Resources, Conservation & Recycling 126 (2017) 228–239

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

Review

An overview of the potential of eco-friendly hybrid strategy for metal recycling from WEEE

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ARTICLE INFO

Keywords:
WEEE
Mechanical recycling
Bioleaching
Metal recovery
Microbes

ABSTRACT

Most waste electrical and electronic equipment (WEEE or E-waste) is recycle in the informal sector, even though—many more sophisticated recycling technologies are available. Mechanical recycling, usually the first step, can achieve maximum metal extraction, however has direct or indirect health effects, higher capital costs, and results in the loss of numerous secondary metal resources. The second most commonly used approach is the chemical method, which is much faster than the biological one, but chemical hydrometallurgy is metal-specific and also causes secondary pollution. The third approach—microbial metal recovery—is an eco-friendly and promising technology for WEEE processing. This comprehensive review evaluates and provides details of recent trends and developments in various technologies, including: physical, chemical and biological methods for the recycling and recovery of secondary resource materials, such as valuable metals. Although no single approach by itself is adequate, and as it cannot achieve ecofriendly high extraction rates of metals from WEEE, it is possible to develop a combined process, such as the initial use of mechanical treatment followed by leaching with either easily biodegradable reagents or organic acids produced by microbes—this would be more ecofriendly and economically feasible. Therefore, this article highlights specific gaps in the available technology for solving the e-waste issue, and recommends a hybrid strategy as the best available approach.

1. Introduction

Rapid population growth and technological advancement have increased the purchase, use, and discarding of electrical and electronic equipment's (EEEs), resulting in the generation of a massive amount of WEEE (Akcil et al., 2015; Huisman et al., 2007; Scruggs et al., 2016; Tansel, 2017; UNEP, 2009; Xu and Liu, 2015; Yazici and Deveci, 2015). Globally, an estimated 41.8 million metric tonnes (MT) of WEEE were generated in 2014 (Balde et al., 2015) [Supplementary Information (SI)-Table 1)]. Although many countries have their own specific WEEE management and control regulations, but huge amount of WEEE is illegally shipped from developed nations to developing ones (Chan and Wong, 2013). This WEEE contains many types of hazardous substances (e.g., brominated and chlorinated flame retardants), as well as precious metals (Au, Ag and Pd), also toxic metals [Hg, Pb, Cr, Cd] (Awasthi et al., 2016a,b; Tue et al., 2013). The major portion of this e-waste is processed by traditional or crude methods in the informal sector. These methods are inadequate for extracting valuable metals (Chan and Wong, 2013; Leung et al., 2015; Umair et al., 2015). These crude processing methods consist mainly such as, breaking, acid leaching and open burning which lead to the release of toxic gases and other contaminants into the atmosphere (Fu et al., 2011; Birloaga et al., 2013; Zhang et al., 2014), heavy metals and other pollutants into soil and groundwater (Quan et al., 2014), where they can easily persist for a long time (Awasthi et al., 2016a). Additionally, these pollutants can be transported and accumulated inside plants system, and thence through dietary intake to animals and/or humans, (Awasthi et al., 2016b). The detail information on human health risks associated with informal recycling of WEEE is listed in the in SI-Table 2.

WEEE management has become an active research field, and many researchers studied WEEE issue from different views such as, environmental pollution and human-health perspectives (Awasthi et al., 2016b; Chen et al., 2011; Eguchi et al., 2015; Krol et al., 2016; Ongondo et al., 2011; Sarath et al., 2015; Sawhney et al., 2008; Wang et al., 2013), and have carried out experimental research to achieve the efficient recycling and recovery of resource materials from WEEE at both national and global level (Tan et al., 2015; Zeng et al., 2013). Different recycling methods (mechanical, chemical and biological) are already being applied to remove toxic and/or recover precious metals from WEEE (Jadhav and Hocheng, 2015; Silvas et al., 2015; Yazici et al., 2013).

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http://dx.doi.org/10.1016/j.resconrec.2017.07.014
Received 21 November 2016; Received in revised form 10 July 2017; Accepted 11 July 2017
Available online 19 August 2017
0921-3449/

A number of different approaches have been presented, for separating metals from non-metallic portion, such as electrostatic (Silvas et al., 2015), and magnetic separation; pure metals can be extracted from the mixed metals by vacuum metallurgy. The hydrometallurgy, has also been applied (Yang et al., 2012, 2013; Yazici et al., 2013). However, most of these methods are either not cost-effective or not ecofriendly (Meshram et al., 2015a, 2015b; Savvilotidou et al., 2015). Moreover, these technologies have certain drawbacks: for example—mechanical recycling requires significant capital investment; chemical methods—cause secondary pollution, and biological methods are slow (Ilyas and Lee, 2014a; Jadhav and Hocheng, 2015; Karwowska et al., 2014). Bio-hydrometallurgy has also been applied, to leach valuable metals from waste printed circuit board (WPCBs) (Ghosh et al., 2015; Sahni et al., 2016). Valuable metals can be further recovered from leaching solution through adsorption by using biomass waste including microbial biomass (Gurung et al., 2013).

To the best of our knowledge, limited studies have been done on the recycling and recovery of metals from WEEE using a hybrid approach. This article a comprehensive review of hybrid approach, evaluating various metal recycling methods that have been proposed and/or tested for sustainable environmentally sound WEEE recycling.

2. WEEE recycling methods

The heterogeneous composition of hazardous substances in WEEE make it difficult to find an appropriate recycling method (Vats and Singh, 2014). The primary aims of any WEEE recycling method are to mitigate the negative environmental and public health effects of hazardous substances and to recover valuable materials. For example, WPCBs: firstly, is dismantled and separation are some of the key technologies, normally using mechanical processing to upgrade the needed materials (Lu and Xu, 2016). Wang and Xu (2015) stated that the shredding, electrostatic separation, supercritical extract employed in this stage. Afterward the next step is to screening and processing of metal content, which is very important in terms of environment and economic prospective (Zeng et al., 2013). There are many methods for extracting metals from WPCBs; these methods are include—hydrometallurgy, bio-hydrometallurgy and smelting for pyrometallurgy (Ghosh et al., 2015).

In this section we briefly discuss, mechanical, chemical and biological approaches to processing WEEE.

2.1. Mechanical recycling

The mechanical recycling is most popular WEEE recycling process used throughout the world (Cui and Forssberg, 2003; Dodbiba et al., 2008). Mechanical recycling of WEEE includes—three main approaches, (a) Dismantling: which focuses on removing valuable and hazardous components (Movilla et al., 2016), (b) Upgrading/repairing: which focuses on re-using desirable materials, and (c) Refining: recovering materials and returning them to their normal life cycle (Zeng et al., 2016; Zlamparet et al., 2017).

These mechanical recycling units utilize manual dismantling followed by crushing, screening (rotating screen or trammel), magnetic separation (special low-intensity drum separators), and electrical conductivity [e.g., corona electro static separation, eddy current separation, and triboelectric separation] (Table 1and Fig. 1). In general, two type of dismantling, such as—Selective dismantling can be based on either manually or mechanical. But now days, the informal manual dismantling is frequently practiced in developing countries.

2.2. Chemical recycling

The chemical leaching approach to retrieving the valuable portion of metals from WEEE has been evaluated by many researchers, and some specific techniques are presented in Table 2, and shown in Fig. 2 (Chen et al., 2013; Gonçalves et al., 2015; Marques et al., 2013; Navarro et al., 2014; Pant and Singh, 2013). Chemical leaching process is that uses chemicals and complexometry, such as a ligand that can attach to a specific metal. Many well-known leaching agents eg., halide (Behnamfard et al., 2013), cyanide (Bas et al., 2015; Raphulu and Scurrell, 2015; Wang et al., 2015), thiourea and thiosulfate (Kannan et al., 2014; Ghasem and Khoramnejadian, 2015), and alkali fusion–leaching (Guo et al., 2015) are already being applied in the recycling and recovery of metals from WEEE. Chemical method based leaching of metals from e-waste has been explored by using different acids such as—hydrogen chloride (HCL) (Kim et al., 2011; Jha et al., 2012a), nitric acid (HNO_3) (Bas et al., 2014; Petter et al., 2014), H_2SO_4 (Beolchini et al., 2013; Rocchetti et al., 2013a; Yazici and Deveci, 2013), and sodium hypo-chloride (Guo et al., 2015).

Chemical leaching is also a well-known process for recovering of copper chloride ($CuCl_2$), ferric chloride ($FeCl_3$) and HCL that can remove the valuable portion of metals. Ghasem and Khoramnejadian (2015) found that, 99.92% of the gold can be recovered with the help of HCL/HNO_3 (1:1) at 60 °C in 1 h. Similarly, Rocchetti et al. (2013b) used cyanide or thiourea leaching to extract gold and silver. Other researchers have used solvent extraction and obtained good results in extracting metals such as Copper, Cobalt, Platinum, Rhodium, Indium, Vanadium and Nickel (Raju et al., 2012; Yang et al., 2013; Barik et al., 2014; Zhang et al., 2015).

Kim et al. (2011) examined and observed that, the leaching kinetics of Cu from WPCBs, achieve leaching up to 98% Zn, 96% Pb, 96% Sn, and 71% Cu were using 2.0 M HCl solution within 4 h at 50 °C, and 400 rpm. Jha et al. (2012b) studied the leaching process of Sn from WPCB solder. They noted that 95.79% of Sn was leached out at 50 g/L pulp density using 5.5 M HCl, at 50 °C temperature within 2.45 h without pretreatment (organic swelling). But, the similar Sn recovery was observed at 90 °C using 4.5 M HCl, mixing time 1 h and pulp density 50 g/L. While Pb metal leached out consuming 0.1 M HNO_3 at 90 °C in within 1 h (about 45 min) with pulp density 10 g/L. Pretreatment such as organic swelling of solder from WPCBs removes both solder material from epoxy resin and Cu layers and resulted as dissolution kinetics increases. Yang et al. (2012) applied a combined method for the recovery of ultrafine Cu particles from components of WPCBs. They obtained 96.7% of Cu recovery at 35 °C within a leaching time of 2 h. Silveira et al. (2015) recovered 613 mg of Indium/kg powder of LCD screen (pretreated polarizing film removed), by consumed 1.0 M H_2SO_4, at 90 °C, 500 rpm within 1 h, while Indium (In) (99.8%) precipitated with NH_4OH at pH 7.4. In addition—Table 2 summarizes various metal leaching reagents, outcomes, specific

Table 1
Environmental impact monitoring for the integrated mobile recycling plant (Zeng et al., 2015).

	Waste monitor recycling equipment		Waste PCBs recycling equipment		Integrated emission standard for air pollutants (GB16297-1996)	
	Concentration (mg/m^3)	Emission (kg/h)	Concentration (mg/m^3)	Emission (kg/h)	Concentration (mg/m^3)	Emission (kg/h)
Pb	8.9×10^{-3}	4.7×10^{-5}	0.016	2.0×10^{-5}	0.9	0.005
Hg	1.1×10^{-4}	5.8×10^{-7}	3.6×10^{-5}	4.5×10^{-8}	0.015	1.8×10^{-3}
Cd	4.9×10^{-3}	2.6×10^{-7}	5.5×10^{-5}	6.9×10^{-8}	1.0	0.060
Cu	6.0×10^{-3}	3.2×10^{-5}	4.9×10^{-3}	6.2×10^{-6}	–	–