Journal of Environmental Chemical Engineering 6 (2018) 1288–1304

Contents lists available at ScienceDirect

Journal of Environmental Chemical Engineering

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

Novel technologies and conventional processes for recovery of metals from waste electrical and electronic equipment: Challenges & opportunities – A review

Garima Chauhan[a], Prashant Ram Jadhao[b], K.K. Pant[b], K.D.P. Nigam[b,*]

[a] Department of Chemical and Materials Engineering, University of Alberta, Canada
[b] Department of Chemical Engineering, Indian Institute of Technology Delhi, New Delhi 110016, India

A R T I C L E I N F O

Keywords:
Waste electrical and electronic equipment
Metal extraction
Conventional processes
Leaching
Novel technologies
Chelation technology

A B S T R A C T

Challenges of sustainable development, particularly 'living within limited infinity' and 'scarcity of natural resources' have urged scientific community to develop innovative processes that integrate into complex technology and reduce ecological disturbances. Present study provides a state-of-art review on waste electrical and electronic equipment (WEEE) ranging from an analysis of relevance, government initiatives, management strategies, conventional methods of metal recovery and novel alternatives. WEEE generation and its management tools have been a subject to various review articles, however resource(s) recovery from WEEE has not been hashed out intricately in literature. Presence of significant amount of precious/rare metals makes WEEE a secondary resource of metals and therefore warrants special attention relative to general solid waste management strategies. Various hydrometallurgical and pyrometallurgical approaches have been reported for efficient metal recovery from WEEE; still a decisive assessment of conventional approaches has not been sufficiently explicated. Therefore, a comprehensive analysis of literature is essentially necessitated in order to create a common framework of knowledge in this emerging research area. This review article critically analyses the technical feasibility of conventional practices for metal recovery from WEEE and suggests that conventional processes may not meet the industrial feasibility because of secondary pollution possibilities and high economics. Hence, emerging trends in the field of metal extraction from WEEE have been discussed which has not been reviewed yet, to the best of our knowledge, in any review articles. It is believed that this review may provide an insight to look into novel technologies such as chelation technology, use of ionic liquids, and other alternative technologies for resource optimization and waste management.

1. Introduction

Revolutionary transformation from agriculture to industrial economy and fast paced unveiling of new electronic gadgets coupled with affordable prices have defined a new era where obsolete electrical and electronic equipment (EEE) have become the most prominent solid waste stream. Waste Electrical and Electronic Equipment (WEEE) and Electronic Waste (e-waste) are the two more frequently used terms for discarded EEE appliances [1]. E-waste refers to discarded electronic goods (e.g. computers, mobile telephones), whereas WEEE additionally incudes non-electronic appliances (e.g. refrigerators, air conditioning units, washing machines) [2]. In present study, the solid waste stream

Abbreviations: AM, arithmetic mean; ARF, advance recycling fee; BaA, benzo-anthracene; BaP, benzo-pyrene; BAN, basel action network; BDE, decabromodiphenyl ether; BFRs, brominated flame retardants; BPhs, bromophenols; CAGR, compound annual growth rate; Chr, chrysene; DTPA, diethylenetriaminepentaacetate; EDTA, ethylenediaminetetraacetic acid; EEE, electrical and electronics equipments; EOL, end-of-life; EPA, Environmental Protection Agency; EPR, Extended Producer Responsibility; ETBC, electronics TakeBack coalition; WEEE, waste electrical and electronic equipment; F_{COL}, fraction of the annual amount of WEEE generated which is collected for recycling; F_{EXP}, fraction collected for recycling which is exported to non-OECD countries; GM, geometric mean; HQ, hazard quotient; ICME, international council on metals and the environment; ICT, information and communications technology; M_{EXP}, amounts of WEEE exported from the country; M_{GEN}, amount of WEEE generated domestically by its own population; M_{IMP}, amounts of WEEE imported to the country; M_{NET}, net amount of WEEE generated; MeO-PBDEs, methoxylated PBDEs,; NTA, nitrilotriacetic acid; OECD, organization for economic co-operation and development; OHPCB, hydroxylated PCB congeners; OH-PBDE, hydroxylated PBDEs; PAHs, polycyclic aromatic hydrocarbons; PBDD/Fs, polybrominated dibenzo-p-dioxins and dibenzofurans; PBDEs, polybrominated diphenyl ethers; PCBPs, polychlorinated biphenyls; PCDD/Fs, polychlorinated dibenzo-p-dioxins and dibenzofurans; PGM, platinum group metals; POAL, pressure oxidative acid leaching; POPs, persistent organic pollutants; (S,S)-EDDS, (S,S)-ethylenediaminedisuccinic acid; SVTC, silicon valley toxics coalition; UNEP, United Nations Environmental Program; UNU, United Nations University; WEEE, waste electrical and electronics equipments

* Corresponding author.
E-mail address: kdpnigam@chemical.iitd.ac.in (K.D.P. Nigam).

https://doi.org/10.1016/j.jece.2018.01.032
Received 18 October 2017; Received in revised form 30 December 2017; Accepted 18 January 2018
2213-3437/

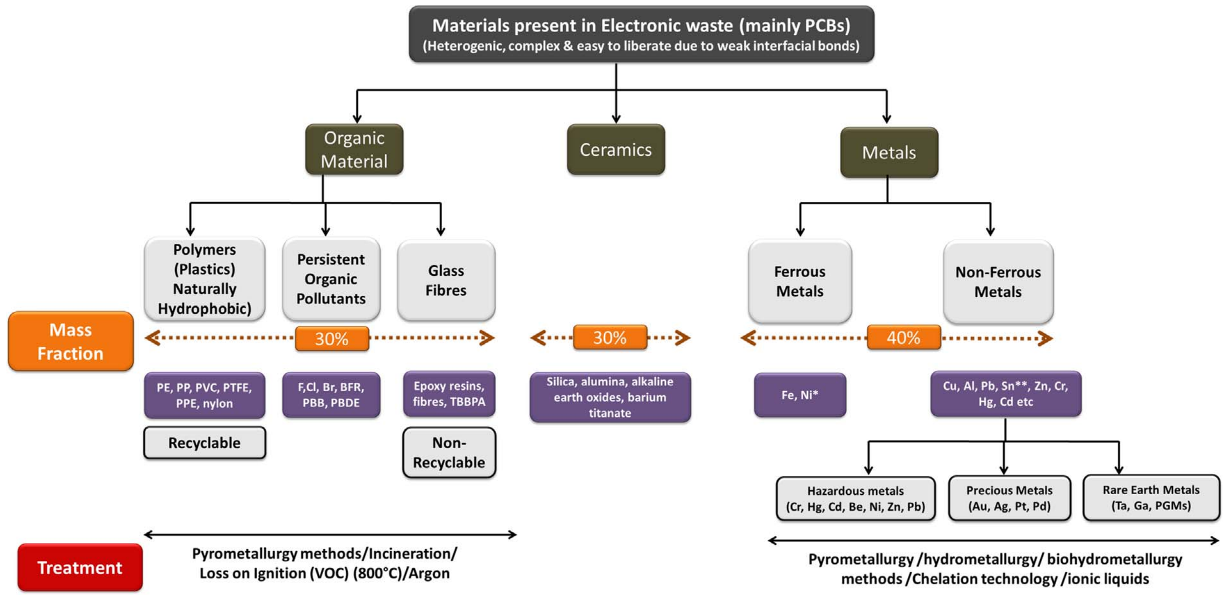

Fig. 1. Composition and mass fraction of organic materials, metals and ceramics in end-of-life WEEE (Kaya, 2016).

originated from EEE is referred by the term 'WEEE' inclusively. WEEE is a complex mixture of more than 1000 toxic substances which can be principally categorized into three groups: organic materials, metals and ceramics [3]. Fig. 1 demonstrates the WEEE composition and percentage fraction of three dominant categories in end-of-life (EOL) WEEE.

Plastics (C—H—O and halogenated polymers) such as Polycyclic aromatic hydrocarbons (PAHs), Polybrominated diphenyl ethers (PCBPs), Polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs); Persistent organic pollutants (POPs) such as Brominated flame retardants (BFR), dioxins and dibenzofurans and glass fibers such as epoxy resins are included in organic materials. A large fraction of base metals (Al, Cu, Fe, Sn), rare metals (Ga, Ta), precious metals (Ag, Au, Pd, Pt) and hazardous metals (Be, Cd, Cr, Hg, Ni, Pb, Zn) is present in WEEE which contribute to the increased toxicity levels of ecosystem. Silica, alumina, alkaline earth oxides, barium titanate etc. are listed in ceramic group. The global volume of WEEE generated is anticipated to reach 130 million tons in year 2018 from 93.5 million tons in year 2016 at a compound annual growth rate (CAGR) of 17.6% [4]. Asia led the global WEEE generation with production of 16 million metric tons of WEEE in year 2014. On the other hand, Europe secured the first place in the category of the highest per inhabitant WEEE quantity with 15.6 kg per person [5]. Several studies are available in literature to estimate rate of WEEE generation [6–8] based on recycling and export analysis [9,10], consumption and used methods [11,12], market supply method [12], life span distribution analysis [13] and material flow analysis [14,15]. These reports may vary widely due to differences in methods and assumptions taken for different studies and therefore, defining an exact amount of WEEE generation is difficult. It can be anticipated that the factual amount of this solid waste stream is much higher than predicted one using different estimation studies and needs sincere attention in the context of WEEE management.

Motivations to address WEEE include fastest arising waste stream, presence of significant amount of metals and other pollutants, environmental fate of heavy metals, severe health hazards of informal recycling and economic benefits associated with successful recovery of metals. Numerous studies and reviews on WEEE have already been presented, however these review articles are largely restricted to reporting scattered data on WEEE generation [16–18], environmental and social impacts of WEEE [19–21], future perspectives on WEEE generation [10] and various management strategies/tools [22–25] with very few attempts to critically assess the conventional [3,26] and advanced methods [27,28] for metal recovery from WEEE. Recently, Pérez-Belis et al. [29] presented a review on WEEE trends and management; however metal recovery and resource optimization was not included in this study also. Therefore, an in-depth review on existing metallurgical practices for WEEE processing is essentially necessitated in order to create a common framework of knowledge in this emerging research area. Also, a strong need was felt to address the novel green alternatives of conventional practices for metal recovery from WEEE which has not been reviewed yet, to the best of our knowledge, in any review articles. Present study provides a comprehensive review about WEEE ranging from an analysis of the relevance, existing approaches for resource recovery and research outlook to develop novel green technologies as better ecotechnie alternatives of conventional practices. Various hydrometallurgical and pyrometallurgical methods have been reviewed in brief to recover metals from WEEE. New green alternatives such as chelation technology, ionic liquids and other alternative technologies have also been proposed for the first time in detail to provide an elaborated outlook for effective management of WEEE and successful recovery of metals.

2. WEEE processing routes

Ample generation of WEEE, non-rigorous management strategies and lack of consumer awareness lead to a cavalier fashion of WEEE disposal into the environment. Fig. 2 presents a flow scheme of WEEE generation, its disposal, transportation and processing. It can be depicted from Fig. 2 that there are four different routes of WEEE processing i.e. (1) landfilling and incineration (2) transboundary shipment (3) material recycling and (4) direct reuse/remanufacturing.

2.1. Route 1

Landfilling and incineration, in spite of causing high risks to health and environment, are still being carried out in an unprofessional manner for WEEE disposal. The US Environmental Protection Agency (EPA) and UNs estimate that only 15–20% of WEEE is recycled, the rest of these consumer electronics go directly to landfills and incineration [30]. Landfilling of WEEE (though in a controlled manner) has become a major concern for North America, Europe and Australia in order to avoid any harmful effect on ecosystem. Landfill leachate may potentially transport toxic metals and persistent organic pollutants into food chain and cause acute and chronic health effects. It should also be noteworthy that WEEE are collected along with municipal waste in