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Biomining – biotechnological systems for the extraction and recovery of metals from secondary sources

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Abstract

Biomining is the common term used to define processes that utilize biological systems to facilitate the extraction of metals from ores. Nowadays, a biomining concept can be defined as a two stage combined biological systems (1st stage bioleaching and 2nd stage biosorption) in order to perform the extraction and recovery of the metals from secondary sources such as industrial and mining waste, waste electrical and electronic equipment (WEEE), bottom ash and end of life vehicles. Overwhelming demand and limited sources of metals have resulted in searching new sources so that attentions have been shifted from mining process towards recycling of secondary resources for the recovery of metals. There are several metallurgical processes for metal recovery from the secondary sources such as pyrometallurgical processing, hydrometallurgical and bio/hydrometal-lurgical processing. Biomining processes are estimated to be relatively low-cost, environmentally friendly and suitable for both large scale as well as small scale applications under the bio/hydrometallurgical processing. Thus, the process involves physical separation (pre-treatment) and biomining (bioleaching and biosorption) and hydrometallurgical processes for recovery of base metals, rare earth elements (REEs) and precious metals from e-waste was evaluated.

Keywords: Biosorption, bioleaching, bio/hydrometallurgy, critical metals, WEEE, secondary sources.

1. Introduction

The life cycle of electronic products has been reduced significantly in recent years (Oh *et al.,* 2003). Due to rapid growth of information technology around the world paired with the arrival of new design and technology at regular intervals in the electronics sector, an early obsolescence of many electronic items used around the world today is taking place (Herat and Agamuthu, 2012; Gu *et al.,* 2016). Waste electrical and electronic equipment (WEEE or e-waste) is one of the fastest growing solid waste streams around the world which is growing at a rate of 3% to 5% per annum or approximately three times faster than other waste streams in the solid waste sector (Schwarzer *et al.,* 2005). It is estimated that the total amount of WEEE was 41.8 million megagram (MMg) in 2014 (Baldé *et al.,* 2015). The composition of generated WEEE in 2014 was: lamps (1.0 MMg), screens (6.3 MMg), small IT (3.0 MMg), small household equipment (12.8 MMg), large household equipment (11.8 MMg) and of cooling and freezing equipment (7.0 MMg) (Baldé *et al.,* 2015). The EU was the largest WEEE generator with a total of 9.8 MMg, along with the United States (7.1 MMg) and China (6 MMg) in 2014 (Baldé *et al.,* 2015; Wang *et al.,* 2016). An overview of the WEEE generation in 2013 by selected countries is shown in Figure 1 (StEP, 2015; Eurostat, 2016). Therefore, the treatment of WEEE is a fundamental issue for not only developed countries but also low and middle income countries such as India, South Africa, Ghana, Nigeria, Brazil, Turkey, China etc.

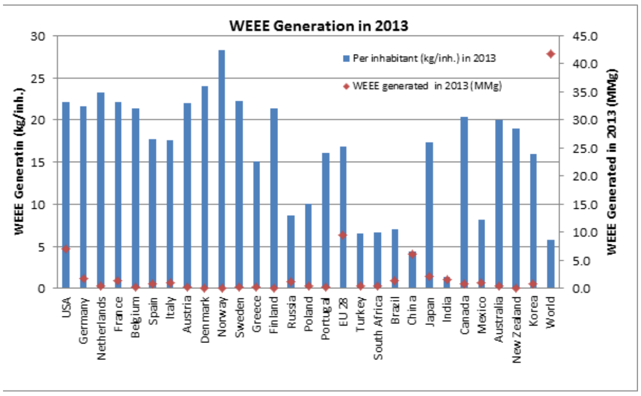

Figure 1. WEEE generated per selected country in 2013 (StEP, 2015; Eurostat, 2016; Kucuker, 2018)

WEEE contains significant quantities of base metals, precious metals (PMs) and rare earth elements (REEs) with high economic potential. The critical elements such as rare earth elements (REEs) and precious metals are the essential materials of WEEE and have increasingly importance in the transition to a green, low-carbon economy. The extraction of critical metals, which often contributes extensively to the value of WEEE, is therefore crucially important (Tuncuk *et al.,* 2012). Several treatment options based on conventional mechanical, pyrometallurgical, hydrometallurgical and biometallurgical processes have been proposed in previous studies for recovery of metals from WEEE (Tuncuk *et al.,* 2012). The most important factors affecting the selection or development of a WEEE treatment process can be listed: quantity of precious metals and REEs in wastes; metal losses; environmental impact and amount of WEEE/scale of operation (Tuncuk *et al.,* 2012). The process should be designed according to these factors (Kucuker and Kuchta, 2012). For instance, base metals in WEEE can be successfully sorted using mechanical treatments. However, several studies reported that mechanical treatment processes are not useful for the effective recovery of precious metals, which are often lost by remaining attached to other components, or in dust fractions as a result of shredding actions (Meskers and Hagelüken, 2009; Meskers *et al.,* 2009; Marra, 2017; Kucuker, 2018).

It can be inferred that the search for efficient, low cost and environmentally friendly processes as well as the refining of the available technologies for the leaching and recovery of base metals and, in particular, REEs and PMs is essential. Since the bulk of hydrometallurgical studies and bio/hydrometallurgical (bioleaching and biosorption) are essentially limited to lab-scale tests, further research should also focus on the development of a combined process with bio/hydrometallurgical aspect.

In this view, the aim of the study is the development of a biomining concept for the recovery of valuable and critical metals from WEEE using bio/hydrometallurgical processes (bio/leaching and biosorption), to generate operational and cost data with the ultimate aim of commercialization.

2. Rare earth elements as critical metals

The rare earth elements are a group of Lanthanides: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu) while scandium (Sc) and yttrium (Y) share the similar psychical and chemical properties (Schüler *et al.,* 2011).

The metallurgical sector has the largest in-use REE stocks (Figure 2) with rising demand particularly for Nd and Pr in magnets. Current processing attempts to recover those elements individually. The next highest REE stock is the information technology (IT) sector, which primary uses Nd, Pr, Dy, Gd and Tb. Further significant in-use stocks include audio systems (mostly Ce), glass additives (Ce and La), nickel metal hydride batteries (Nd, Pr, Dy and Tb), catalysts (predominantly La), automobiles (Nd and Pr), and wind turbines (Nd and Pr) (Du and Graedel, 2011; Westphal, 2015). Together, these nine product sectors constitute nearly 88% of the total in-use REE stocks (Du and Graedel, 2011). With current and predicted supply shortages and the geopolitical situation resulting from Chinese monopoly, the EU has characterized REEs as have a high "supply risk" (EU Commission, 2014). High-tech applications and clean energy production will further accelerate the demand for REEs, such as neodymium and dysprosium as "critical" metals (Figure 3) (Rademaker *et al.,* 2013; European Commission, 2014; Kucuker, 2018). U.S. Mineral Commodity Summaries (2015) reported that the global mine production of rare earth metals is 110,000 tons with 95% of global REEs production from China. The Chinese government currently limits the export of REEs to 35,000 tons annually while the REEs demand of other countries was estimated by 80,000 tons in 2015 (Jha *et al.,* 2016). This restriction of supply resulted in the development of new projects to recovery of REEs from secondary sources (Kucuker and Kuchta, 2012; Westphal, 2015; Jha *et al.,* 2016). Recycling is often considered as one of the ways to reduce REEs supply risk (Rademaker *et al.,* 2013; Westphal, 2015; Jha *et al.,* 2016).

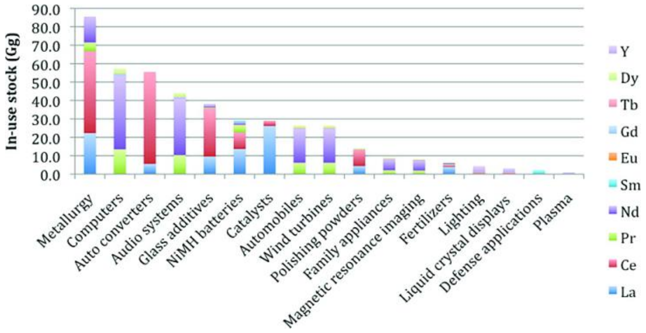

Figure 2. Key applications of rare earth elements (Du and Graedel, 2011)

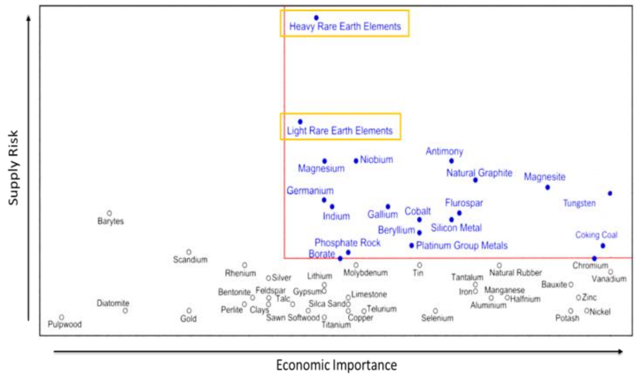

Figure 3. Criticality matrix, marking the most critical elements (EU Commission, 2014)

3. Metallurgical processes for recovery of REEs

In the past, the relatively low prices of REEs, their complex and dissipative use with no incentive to develop industrial recycling technologies had hindered the development of potential recyclable pathways. In recent years, supply issues and in particular sharply rising prices for most REEs have created economically new REE recycling incentives (Rademaker *et al.,* 2013). In particular, REE recovery from Nd-Fe-B magnet scrap is being largely examined (Rademaker *et al.,* 2013). Several separation and extraction technologies e.g. hydrometallurgical, pyro-metallurgical, electrochemical, and combinations of these are being explored as described in Table 1.

4. Biomining concept for metal recovery

Biomining is considered as the technologies that utilize biological systems to facilitate the extraction and recovery of metals from ores (Brierley and Brierley, 2013; Johnson, 2014; Johnson, 2015; Kucuker *et al.,* 2016). In recent years, there has been growing interest in the recovery of metals through biomining among researchers (Figure 4). However, limited research has been carried out on the metal recovery from secondary sources using biomining approach. Nowadays, biomining can be defined as a two stage combined biological processes (1st stage bioleaching and 2nd stage biosorption) in order to extract and recover the metals from primary and secondary sources such as ore, industrial and mining waste, WEEE, bottom ash and end of life vehicles.

Table 1. Advantages and disadvantages of different Nd magnet recycling methods (Adopted and modified from Das *et al.,* 2008; Kotrba, 2011; Binnemans *et al.,* 2013; Habib, 2014; Kucuker, 2018)

Method	Advantages	Disadvantages
Direct re-use in current form/shape	Most economical way of recycling (low energy input, no consumption of chemicals) No waste generated	Only for large easily accessible magnets (wind turbines, large electric motors and generators in hybrid and electric vehicles) Not available in large quantities in scrap today
Reprocessing of alloys to magnets after hydrogen decrepitation	Less energy input required than for hydrometallurgical and pyro metallurgical routes No waste generated Especially suited for hard disk drives (little compositional change over the years)	Not applicable to mixed scrap feed, which contains magnets with large compositional variations Not applicable to oxidized magnets
Hydrometallurgical methods	Generally applicable to all types of magnet compositions Applicable to non-oxidized and oxidized alloys Same processing steps as those for extraction of rare earths from primary ores	Many process steps required before obtaining new magnets Consumption of large amounts of chemicals Generation of large amounts of waste water
Bio/hydrometallurgical methods	Low operating cost Minimization of the use of chemicals, high efficiency at low metal concentrations No metal toxicity issues	Early saturation i.e. when metal interactive sites are occupied, metal desorption is necessary prior to further use The potential for biological process improvement (e.g. through genetic engineering of cells) is limited because cells are not metabolizing No potential for biologically altering the metal valence state
Pyrometallurgical methods	Generally applicable to all types of magnet compositions No generation of waste water Fewer processing steps than hydrometallurgical methods Direct melting allows obtaining master alloys Liquid metal extraction allows obtaining REEs in metallic state	Larger energy input required Direct smelting and liquid metal extraction cannot be applied to oxidized magnets Electro slag refining and the glass slag method generate large amounts of solid waste
Gas-phase extraction	Generally applicable to all types of magnet compositions Applicable to non-oxidized and oxidized alloys No generation of waste water	Consumption of large amounts of chlorine gas Aluminum chloride is very corrosive

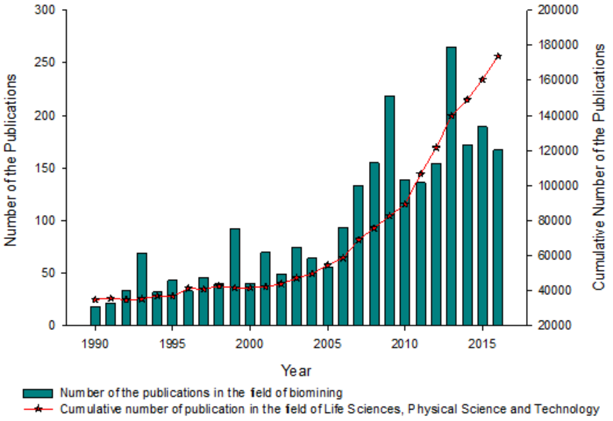

Figure 4. Numbers of papers appearing with ‘biomining’ in the topic and cumulative number of papers in the field of science as listed in the ISI Web of Science database for years between 1990-2016 (database searched 16.01.2017) (Kucuker, 2018)

A new approach of leaching metals from secondary sources such as WEEE and bottom ash by acidophilic bacteria was occurred. In the past two decades, the attention of researchers has been focused on the development of techniques for WEEE recycling (Kucuker and Kuchta, 2012; Gurung *et al.*, 2013). In this context, bio/hydrometallurgical techniques which are reportedly more environment friendly, predictable, and easily controlled than traditionally applied processes due to mild working conditions can be investigated for the recovery of valuable metals from WEEE (Kucuker and Kuchta, 2012; Gurung *et al.*, 2013).

Recovery of critical metals from aqueous solution is the second essential step in bio/hydrometallurgical operations. Biosorption studies generally focus on the removal of heavy metal ions from industrial effluents, where the detoxification of these solutions prior to disposal is the primary goal (Schiewer and Volesky, 2000; Vieira and Volesky, 2000; Diniz and Volesky, 2005; Kucuker and Kuchta, 2012). Biosorption is a metabolism independent process that takes place in the cell wall of microorganisms e.g. algae, fungi, yeast, bacteria, biowaste (wood and garden waste) (Mao *et al.,* 2009). Since biosorption often employs dead biomass, this can enable the researchers to work on biosorption with extreme conditions, such as high temperature and low pH (Das, 2010).

Some recent developments focus on the treatment of WEEE using biomining technologies. Since it has been observed that the WEEE has substantially appreciable quantities of base metals, precious metals and rare earth elements (REEs) with potentially high economic values. A major challenge is how to recover these metals from WEEE or other domestic and industrial metallic waste materials separately, for example using selective biomineralization or biosorption technologies (Kucuker and Kuchta, 2012; Johnson, 2014). On the other hand, motivation factors for biomining application for metal recovery from WEEE can be given as follows: to avoid costs associated with smelting and refining; an innovative and cost effective approach.

4.1. An integrated bio/hyrometallurgical process design under biomining concept

Biological recovery of metals from several post-consumer wastes through a process known as “bioleaching and biosorption” offers attractive advantages compared to conventional metal processing technologies. The technological readiness level of bio-based processes for secondary sources, such as WEEE, is however low. Bioprocessing of waste for metal recovery attracts interest to meet the twin objectives of resource recovery and pollution mitigation (Lee and Pandey, 2012). Several researchers experimented several novel eco-innovative strategies using biomaterials to recover valuable metals from electronic waste (Bharadwaj and Ting, 2011). According to literature survey, a schematic flowsheet was illustrated with available processes for recovery of metals from WEEE (Figure 5). Thus, the process includes physical separation (pre-treatment) and bio/hydrometallurgical (bioleaching and biosorption) process for the recovery of REEs and precious metals from Printed Circuit Boards (PCBs) under a biomining concept.

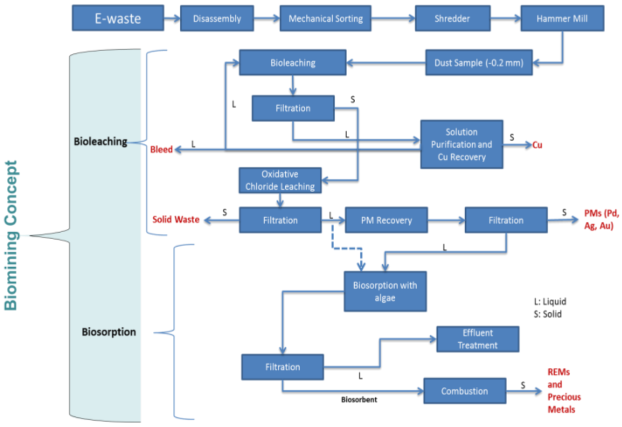

Figure 5. The process flow sheet proposed for the recycling system linking bio/hydrometallurgical and biosorption processes for recovery of REEs and precious metals from WEEE (Kucuker and Kuchta, 2012; Kucuker, 2018)

Base metals, precious metals (PMs) and rare earth elements (REEs) accumulate in PCBs with high economic potential (Kucuker, 2018). Therefore, this study focused on the metal recovery from PCBs. The main motivating factors for biomining application for metal recovery from PCBs are the low costs compared to the associated with smelting and refining and the development of an innovative and eco effective approach. The bulk of hydrometallurgical studies and bio/hydrometallurgical (bioleaching and biosorption) are limited to lab-scale tests, further research should also focus on the development of a combined process with bio/hydrometallurgical aspect to generate operational and cost data with the ultimate aim of commercialization (Kucuker, 2018). In addition, the research activity highlighted that bioleaching and biosorption processes required prolonged time for treatment and provided lower loading rates compared to chemical processes. These limitating factors could hinder the process scale-up. In order to solve these problems, the future research activities should focus on the development of hybrid technologies based on the integration of both chemical and biological processes. More research is needed to evaluate the environmental impacts of the metal recovery from WEEE using the integrated biomining process (Kucuker, 2018).

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