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Prior electro-mechanical separation to improve metal recovery from ceramic-rich electronic waste using bioleaching

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Abstract. PCBs, as one of the most valuable streams of e-waste, are a considerable source of precious metals, but also contain considerable amounts of plastic and ceramic. These non-metallic fractions interfere with and can inhibit the efficiency of metal recovery, particularly for precious and rare earth metals, which are present in e-waste in very low concentrations. In this work, electro-mechanical pre-treatment was applied in order to remove ceramic and plastic fractions from e-waste prior to the application of the bioleaching process. Metal content with and without mechanical separation, as well as metal dissolution and behaviour in the bioleaching process were compared. The results obtained illustrate the beneficial effects of separating the metallic from the non-metallic fraction prior the bioleaching process for the recovery of precious, rare earth and base metals from e-waste.

Keywords: Electronic Waste, Printed circuit board, Bioleaching, Mechanical Separation

Introduction

Electronic waste (e-waste) is a global challenge, due to its ongoing fast-growing demand, but also its hazardous content. It was estimated that this waste stream will have reached 53MT in 2021 (Singh et al. 2020). However, in addition to these challenges, e-waste provides an opportunity as a major secondary source of precious and rare metals for a circular economy, with economic and environmental benefits for the conservation of natural resources, with a reduction of eco-cost in the mineral industry. Printed circuit boards (PCBs) are one of the most targeted fractions of e-waste due to their high value and content in rare metals. Whereas their metal content represents around 40% of solid waste, their ceramics and plastics comprises the majority of their composition (Ribeiro et al. 2019). Several methods, which rely on gravity, density or conductivity are available for mechanical separation of metallic and non-metallic fraction of PCBs.

Electrostatic separation is an electric conductivity-based method suitable for fine particles (0.6-0.12 mm) (Zeng et al. 2012). With low energy consumption, this is an environmentally friendly method, which provides a high voltage electrostatic field, by which conductive metals are separated from non-conductive plastics and ceramics (Yong et al. 2019).

Within the group of methods used to solubilise metals from solid mixtures that is a fundamental step in metal recycling, bioleaching is a promising technology, which is more environmentally friendly and sustainable than conventional methods such as pyrometallurgy and hydrometallurgy. However, the presence of non-metallic materials can affect the process efficiency due to reduced accessibility to the metals, but also to their potential inhibitory effects on bacterial growth and activity. The presence of plastics and ceramics decreases the availability and contact of biochemical reagents with target metals. Therefore, mechanical separation and elimination of ceramics and plastics is being investigated to improve the efficiency of metal solubilisation and recovery in bioleaching applications.

In this work, preliminary electrostatic separation was applied to a sample of ceramic-rich e-waste, to extract the metal fraction from plastics and ceramics. The biological metal solubilisation from this sample was compared to the metal solubilisation obtained with an identical but un-treated sample. Bioleaching efficiency was evaluated for both samples, by monitoring different parameters during the process to assess the effects of preliminary separation.

1. Material and Methods

2.1. E-waste and mechanical pre-treatment

The e-waste samples used in this study were obtained from a mixture of component removed from PCBs. Samples were initially milled using an industrial ball mill (Italimpianti Orafi, Italy) for 6 hours with the mesh size 80 that produced a fine powder with particle size in range of 0.177 mm. Following this first stage, half of the sample was submitted to separation of the metallic fraction from the non-metallic one, where plastic and ceramic particles were separated from metals using an electrostatic separator

Table 1. Metal content of non-pretreated e-waste before electro-mechanical separation (mg metal/g PCB) determined by XRF

Fe	Cu	Si	Al	Pb	Ca	Sn	Mg	Ti	Ba
164.8	110.2	95.3	89.6	36.6	31.1	16.5	13	11	10.2
Mn	**Zn**	**Ni**	**Sb**	**As**	**K**	**Cr**	**Zr**	**Ag**	**Ta**
9.3	7.2	6.9	4.1	3.2	2.3	1.9	1.7	1.6	1.1
P	**Rb**	**Bi**	**Au**	**Hg**	**Co**	**Nb**	**Sr**	**Tl**	**Mo**
1.1	0.9	0.7	0.5	0.3	0.2	0.1	0.1	0.1	0.1

(Bunting, UK) operated dry and in combination with magnetic separation.

2.3. Bioleaching

Acidothiobacillus ferrooxidans (A. ferrooxidans) was used to solubilise the metals due to its iron and sulfur oxidising ability. The bacteria were kindly provided by Professor Barrie Johnson, Bangor University, Bangor, Wales and cultivated in acidophilic basal salts medium and trace element and 50 mM ferrous iron, as recommended by Wakeman et al. (2008), with pH adjusted to 2. Cultures were inoculated in 250ml flasks containing 100 ml of medium and were grown for four days at 30°C and 100 rpm. After these four days, samples of 1 gr of electro-mechanically pre-treated and non-pretreated e-waste were added individually to separate flasks, and the shaking rate increased to 160 rpm.

2.3. Analytical Methods

The metal content of each sample was determined by X-ray fluorescence analysis (XRF) (Rigku, Nex De XRF). Oxidation Reduction Potential (ORP) and pH of the medium were determined with ORP meter and Thermo Scientific pH meter, respectively. The ORP electrode used a platinum pin sensor with reference to Ag/AgCl.

Fe^{3+} and total iron concentration were determined by spectrophotometry as described by Karamanev et al. (2002), where ferric iron is determined using the 5-sulfosalicylic acid reaction while total iron is determined using the ammonia method.

The final solution composition was determined by Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES; Perkin Elmer Optima 8300) after centrifugation and filtration.

2. Results and discussion

3.1. E-waste characterisation

As illustrated in table 1, rare earth metals (REM) were not detected in the initial XRF analysis of the pre-treated sample, which could be due to their very low concentration. As the e-waste sample used in this study was obtained from a group of components, its composition includes high amount of ceramics, as shown with the presence of silicon and zirconium, and a relatively low amount of copper.

3.2. Bioleaching results

Bioleaching with acidophiles *A. ferrooxidans* relies on the conversion of ferrous iron to ferric by bacteria (Eq.1). In turn, ferric iron reacts with surrounding metals to oxidise and solubilise them while it is itself converted back to ferrous (Eq.2). This creates a redox cycle of iron that can ensure the continuous recycling of the ferric iron reagent in the solution:

$$2\mathrm{Fe}^{2+} + \frac{1}{2}\mathrm{O}_2 + 2\mathrm{H}^+ \rightarrow 2\mathrm{Fe}^{3+} + \mathrm{H}_2\mathrm{O} \qquad \text{(Eq.1)}$$

$$\mathrm{M}^0 + 2\mathrm{Fe}^{3+} \rightarrow \mathrm{M}^{2+} + 2\mathrm{Fe}^{2+} \qquad \text{(Eq.2)}$$

As such, the determination of iron, pH and ORP is significant during bioleaching for optimisation.

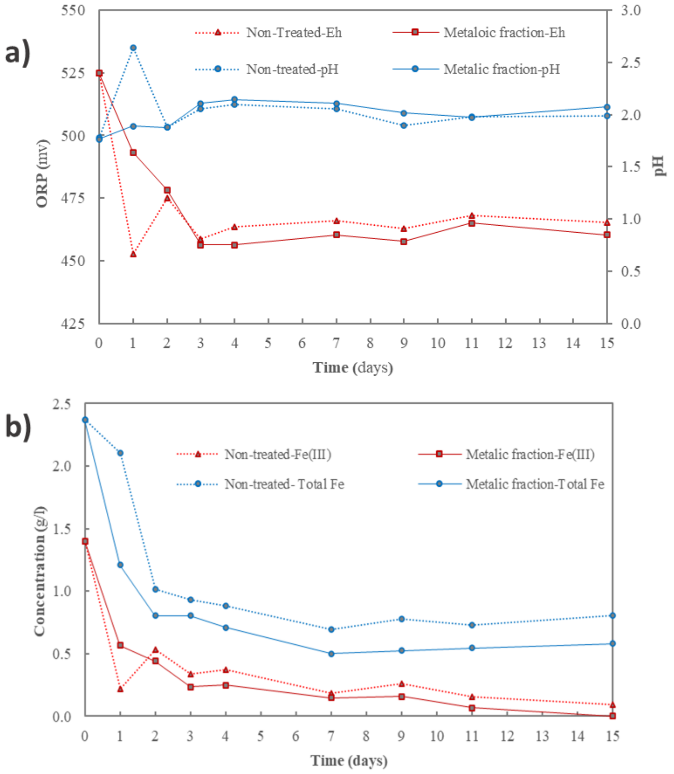

Figure 1. Variation of bioleaching parameters a) pH and ORP b) ferric iron and total iron during bioleaching time course

As shown in figure.1a, where day zero refers to the addition of e-waste, differences in pH and ORP variations can be observed between treated and untreated samples. The presence of organic materials available in the plastic-containing fraction of e-waste, leads to an initial increase in pH, due to the depolymerisation of epoxy by the consumption of proton (Baniasadi et al. 2020). As a result, no increase in pH is detected in the mechanically pre-treated e-waste, which is free from plastics. However, after day three the pH variation follows a similar trend for both pretreated and non-pretreated e-waste samples. The pH decreases after day 1, for the non-pretreated e-waste sample, is due to the chemical hydrolysis of ferric iron according to Eq.3 which produces H$^+$:

$$\mathrm{Fe^{3+} + nH_2O \rightarrow Fe(OH)_n^{(3-n)+} + nH^+} \qquad \text{(Eq. 3)}$$

Following the addition of e-waste to the culture (figure 1.b) ferric iron concentration drops significantly due to its consumption (Eq.1). Apart from this initial drop, the ferric concentration remains higher for non-treated samples during the whole process. This is probably due to the lower amount of metals accessible in the non-pretreated sample, which comprises around 60% of plastics and ceramics.

Following bioleaching of both samples, metal recovery (Table 2) is higher in the pre-treated sample in comparison to the non-pretreated one for most of the metals. This higher efficiency in metals solubilisation is thought to be due to the absence of ceramics and plastics, which provides a more homogenous fraction, with increased interaction with the metals and lower inhibitory effects. A marked improvement can be noticed with the detected increased amount of REM, which are mostly used in PCBs in magnets and superconductors (Hoard et al. 1985). Due to their very low concentration, their recovery is challenging both in bioleaching but also during further metal extraction processes from the bioleachate. Therefore, the higher concentration of REM observed in the bioleachate obtained from the pre-treated sample, in comparison to non-pretreated sample, demonstrates that this preliminary separation process is beneficial for REM recovery from PCBs.

3. Conclusion

A preliminary separation of the metallic fraction from the non-metallic fraction for the bio-recovery of metals from PCBs, is beneficial to the process as it provides a higher amount of metals recovered in solution. This is particularly noticeable for REM, which are of high value in e-waste despite present in low amount. In this study, bioleaching, as a sustainable and environmentally friendly method for metal recovery, is shown to be efficient to recover metals including REM from PCB components, despite high amount of ceramic and plastic materials, which can be removed by preliminary electrostatic separation.

Table 2. Metal recovery in bioleaching process (%)

	Non-treated	Metallic farction
Ag	28.6	14.6
Al	31.9	42.4
Cu	100.0	100.0
Mn	55.4	94.3
Ni	100.0	100.0
Zn	100.0	100.0
Dy	17.0	16.0
Er	18.8	56.2
Y	15.3	27.7

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