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Bioleaching of metals from printed circuit boards supported with surfactant-producing bacteria

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HIGHLIGHTS

- Bioleaching of metals from printed circuit boards by BSAC-producing bacteria was estimated.
- Aeration increased the release of all metals in medium with sulphur and biosurfactant.
- Increase in Cu, Pb, Ni and Cr removal rate was observed at 37 °C in acidic medium.

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ABSTRACT

This study has evaluated the possibility of bioleaching zinc, copper, lead, nickel, cadmium and chromium from printed circuit boards by applying a culture of sulphur-oxidising bacteria and a mixed culture of biosurfactant-producing bacteria and sulphur-oxidising bacteria. It was revealed that zinc was removed effectively both in a traditional solution acidified by a way of microbial oxidation of sulphur and when using a microbial culture containing sulphur-oxidising and biosurfactant-producing bacteria. The average process efficiency was 48% for Zn dissolution. Cadmium removal was similar in both media, with a highest metal release of 93%. For nickel and copper, a better effect was obtained in the acidic medium, with a process effectiveness of 48.5% and 53%, respectively. Chromium was the only metal that was removed more effectively in the bioleaching medium containing both sulphur-oxidising and biosurfactant-producing bacteria. Lead was removed from the printed circuit boards with very low effectiveness (below 0.5%). Aerating the culture medium with compressed air increased the release of all metals in the medium with sulphur and biosurfactant, and of Ni, Cu, Zn and Cr in the acidic medium. Increasing the temperature of the medium (to 37 °C) had a more significant impact in the acidic environment than in the neutral environment.

1. Introduction

Technological innovation and modern business marketing strategy results in the development of electronic products that are cheaper, better and more readily available than older versions. As a consequence, much electronic equipment becomes outdated and redundant quicker than ever and is consigned to waste [1]. Electronic scrap is now the fastest growing waste category [2]. According to UN Environment Programme estimates, about 20–50 million Mg of electric and electronic scrap is generated yearly, and the volume of electronic waste is increasing three times faster than other types of municipal waste [3]. In the UK 50,000 tonnes of printed circuit board (PCB) scrap is currently generated every year, with only 15% subjected to any form of recycling [4].

PCBs are integral elements of many electronic systems, including computers and other consumer electronics as well as devices used in military and medical applications. They constitute about 3% of the total weight of electronic scrap. Their main components are non-conducting substrates or laminates, conductive circuits printed on or inside the substrate and mounted components (chips, connectors, capacitors) [1].

Printed circuit boards are composed of polymers, ceramics and metals. About 28–30% of the content is metal, with 10–20% copper, 1–5% lead, 1–3% nickel, and 0.3–0.4% precious metals like silver,

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platinum and gold [5]. Many other elements (Ga, In, Ti, Si, Ge, As, Sb, Se and Te) may be found in chips, with An, Pb and Cd in solder joints, and Ga, Si, Se and Ge in semiconductors, and tantalum in capacitors [1]. Other materials in PCBs are plastics (19%), bromine (4%), glass and ceramics (49%), isocyanates, phosgene, and acrylic and phenolic resins [5]. Ceramics present in PCBs include silica, alumina, alkaline Earth oxides, mica and barium titanate [1].

In the US and the EU the main way of treating PCB scrap is by incineration or by landfill (and more than 70% is disposed without recycling) [1,2]. For example, in 1997, 3.2 million tonnes of US electronic waste was landfilled [1]. This poses a problem due to the toxic properties of both the metallic and non-metallic PCB components [1]. The toxicity of PCB waste is connected with the presence of brominated flame retardants (BFR), PVC plastic and heavy metals – metals with elemental densities above 7 g/cm^3. During landfilling, pollutant-containing leachate may contaminate groundwater and soil. On the other hand, incineration of waste PCBs may result in the release of potentially hazardous byproducts into the atmosphere, such as dioxins, furans, polybrominated organic pollutants and polycyclic aromatic hydrocarbons, as a result of burning BFR, epoxy resins and plastics [3].

Legislation, including the Waste from Electrical and Electronic Equipment (WEEE) directive, necessitates the increasing recovery and recycling of materials found in scrap electronic components [4]. It has been claimed that the purity level of precious metals in waste PCBs is more than 10 times higher than that of rich-content minerals, making them a potentially economically viable mineral resource [3]. However, the recycling of electronic scrap is rather difficult because of its complexity and the heterogeneity of electronic components [5].

Scrap PCBs are classified into three categories, according to the precious metal content: H (high), M (medium) and L (low) grade scrap. For scrap PCBs classified as low grade, the traditional smelting technique appears to be uneconomic. The approximate value of metals found in medium grade PCB scrap is £0.07/kg for silver, £0.13/kg for copper, £1.63/kg for gold and £0.8/kg for palladium. The total value for all metals is £2.74/kg [4].

The traditional techniques for electronic waste treatment – both pyrometallurgical and hydrometallurgical – often require great energy consumption, are high cost and low efficiency, and cause serious secondary pollution [5,6]. Pyrometallurgy, based on incineration, smelting in a plasma arc furnace or blast furnace, drossing, sintering, melting and high temperature reactions in a gas phase, is used for the recovery of non-ferrous metals as well as precious metals from waste PCBs [3]. Hydrometallurgical processing of PCB waste usually includes both chemical leaching and electrochemical processing [1]. This involves a series of acid or caustic (cyanide, halide, thiourea, thiosulphate) leachings of the waste. The obtained solutions are subjected to precipitation of impurities, solvent extraction, adsorption and ion-exchange in order to purify and concentrate the metals [3,7].

Some other technological approaches have been used in order to recover valuable components from electronic waste. One method is an application of a mixture of nitric acid and hydrochloric acid, although a large amount of waste gases and acid solutions are produced in this process. In the US, a method based on solvolysis has been developed. It allows recovery of both metals and plastic materials (such as epoxides) and, additionally, the extraction of halogens and brominated hydrocarbon derivatives [4]. A dissolution of PCB scrap in sulphuric/nitric acid leachants followed by electrolytic copper recovery is used commercially in the US [1]. In Germany, a mechanical process involving shredding, granulation, magnetic separation, classification and electrostatic separation has been commercialised by Fuba [4]. A consortium based at Imperial College, London, has developed the use of non-selective leachants to dissolve the metal content of PCB scrap. This consortium's method involves chemical leaching with electrogenerated chlorine in an acidic aqueous solution of high chloride ion activity. As a result, a multi-metal leach electrolyte containing all of the available metal content is obtained. Additionally, metal recovery via electrolytic membrane cells with discrete metal separation has been demonstrated [4]. Kim et al. [8] applied a similar method and reported that the leaching rate of the metals increased with an increase in density, temperature and time in reactor and that the dissolution kinetics of copper with electro-generated chlorine followed an empirical logarithmic law controlled by surface layer diffusion.

Table 1
The concentration of metals in the electronic waste.

Metal	Concentration (mg/kg)
Cd	1.9
Cr	72.4
Cu	41,237.3
Ni	13,244.7
Pb	14,129.9
Zn	12,471.4

In some areas (though mainly in the mining industry to date), hydrometallurgical processes are being replaced with biohydrometallurgical (bioleaching) techniques [6]. The advantages of biological methods are low operating costs, reduced environment pollution, minimisation of the volume of end-products and highly efficient effluent detoxification [3].

Bioleaching technology offers many advantages over conventional methods, including its relative simplicity, less exacting operational requirements, low energy input, reduced need for skilled labour, and environmental friendliness. However, it requires a longer period of operation compared to other methods, such as chemical leaching [3,9]. For these reasons, techniques facilitating and improving the bioleaching process should be of interest. Additionally, there is a need for research on seeking the available source of active bioleaching biomass [3,10].

There are some suggestions in the literature that the addition of surfactants, complexing agents or other additives may positively influence bioleaching with mesophilic bacteria [7,11]. It has been observed that the addition of citric acid increases copper solubility in the bioleaching solution from 37 wt% to 80 wt% [7].

This research has evaluated the possibility of achieving heavy metal bioleaching from printed circuit boards by applying, respectively, a culture of sulphur-oxidising bacteria and a mixed culture of biosurfactant producing bacteria and sulphur-oxidising bacteria. The impact of selected process parameters, such as temperature and aeration, on bioleaching effectiveness has also been estimated. This is the first step to metal recycling.

2. Materials and methods

2.1. Waste characteristics

The printed circuit boards were obtained in crumbled (fined) form. The grain fractions of the crumbled printed circuit boards used in the experiment were as follows: $d < 0.063$ mm – 2.8%, 0.063 mm – 1.6%, 0.01 mm – 22.0%, 0.25 mm – 22.6%, 0.5 mm – 4.0%, 1 mm – 9.6%, 2 mm – 37.4%. The relative humidity of the waste was 0.84%. Table 1 shows the concentration of metals in the waste.

2.2. Bioleaching media

The experiments were carried out using two bioleaching media.

The M-I medium was a mixture of municipal activated sludge and municipal wastewater with a solids concentration of about 3–4 g dry weight/L. Indigenous sulphur-oxidising bacteria were