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Influence of bacterial adhesion on copper extraction from printed circuit boards

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ABSTRACT

In order to analyze the influence of the contact mechanism in the bioleaching process, bacterial attachment on the Printed Circuit Boards (PCB) surface was avoided using a partition system. The partition system was obtained with a semi-permeable membrane of 12–14 kDa MWCO. A PCB sample of 500–1000 μm particle size was placed inside a partition system for 144 h to compare the copper (Cu) extraction rate by *Acidithiobacillus ferrooxidans*, with the Cu extraction of a system without partition. The results demonstrated that when the contact mechanism was avoided, there was a decrease of 25% in the Cu extraction. When the contact bioleaching was enabled, 1.46 g of Cu was extracted from the initial 1.61 g of Cu (∼91% extraction). When the partition system was used, only 1.10 g of Cu was extracted (∼68% extraction). Bacterial adhesion experiments proved that within the first hour of the experiment, 4.30×10^7 cells were attached per gram of PCB, supporting that bacterial adhesion was responsible for the higher Cu extraction rate. The results for bacterial adhesion tests were consistent with Derjaguin–Landau–Verwey–Overbeek theory.

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1. Introduction

Worldwide, it is estimated that more than 25 million ton of electronic waste are discarded per year [1]. Electronic devices are assembled with several components that have high concentrations of heavy metals that are well known to harm human health and produce negative environmental impacts [2]. From the wide range of waste electrical and electronic equipment (WEEE), Printed Circuit Boards (PCBs) and spent batteries are the electronic wastes containing the highest concentration of metals [3]. In Table 1, a chemical characterization of the metals found in PCB at different particle size is shown. This high generation of waste containing a high concentration of metals has become an attractive alternative source for metal extraction [4].

In recent years, the usage of microorganism to leach the metals from the electronic waste has been implemented in order to produce a more efficient and environmental friendly metal extraction [3,5,6]. *Acidithiobacillus ferrooxidans* (*A. ferrooxidans*) is the iron oxidizing bacteria which has been the most studied bacteria in the field [7]. Previous studies have shown that *A. ferrooxidans* can interact with PCB through three different mechanisms to generate metal dissolution [8,9]. According to the latest studies, those three mechanisms are defined as contact bioleaching, non-contact bioleaching, and cooperative bioleaching. The first bioleaching mechanism, the contact mechanism, is generated due to the bacteria attachment to the PCB surface, in order to oxidize the metal [8,10–12]. In the second mechanism, the bacteria are not attached to the PCB surface. Instead, non-attached bacteria oxidizes the Fe^{2+} in the solution to Fe^{3+}. Fe^{3+} will then be the oxidizing agent in order to solubilize the metal contained in the PCB particles [7–9]. The last mechanism, the cooperative mechanism, is a combination of the previous two mechanisms (i.e. the contact and non-contact mechanisms). The attached bacteria and the oxidizing agent Fe^{3+} in the solution cooperate, to oxidize the metal in the PCB particles [9,13]. Even though several experiments have supported the efficiency of metal extraction from PCBs, there is still a lack of information about the influence of each mechanism in the bio-reaction.

Experimental approaches have been used to distinguish the differences between the influence and importance of each bioleaching mechanism; but a consensus has yet to be reached [8,11,13–15]. A separation of the leaching bacteria from solid particles during the bioleaching process has been used, in order to differentiate the influence of the contact mechanism. The separation is achieved by installing a partition system using a semi-permeable membrane, to avoid the bacteria attachment to the solid particles

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Table 1
Metal contents in PCBs, with different size distributions.

Metal	Liang[a]	Yang[b]	Ilyas[c]
	Content (%w/w)		
Cu	12.60	25.06	8.90
Zn	5.60	0.04	8.20
Pb	3.10	0.80	3.15
Ni	2.40	0.002	2.00
Al	1.40	N.D.[e]	0.75
Fe	1.20	0.66	8.00
Ag	0.0033	N.D.	0.0030
Au	0.0014	N.D.	0.0013

[a] Size range from 100 to 200 μm [22].
[b] Size range below 500 μm [30].
[c] Size range from 50 to 150 μm [39].
[e] N.D. – not determined.

[16]. Experiments using a partition system have been conducted to analyze the influence of the contact mechanism on the bioleaching of zinc sulfide ores and electrode powder from spent batteries [13,17,18]. Different kinds of membrane can be used as a partition system. When the influence of the bacterial attachment was analyzed in zinc sulfide ores, a nucleopore polycarbonate filter with a 0.2 μm cut off membrane was used to separate bacteria from the mineral ore. A higher metal extraction rate was obtained when the filter was not used, and the bacterial attachment was allowed [13]. Different results were obtained when electrode powder from spent batteries was isolated from the bioleaching bacteria with a dialysis membrane, with an 8000–15,000 Da of molecular weight cut off (MWCO). It was demonstrated that when the bacterial attachment was disabled, the bioleaching of Co, Li, and Zn was not affected; but under the same conditions, Mn showed a significant reduction in extraction [17,18]. Both authors concluded a need for further studies related to the influence of the contact mechanism. These conclusions suggest that the extraction of some metals may (or may not) be affected by the contact mechanism. To the best of our knowledge, no research has been conducted, focusing on the influence of the contact mechanism on the PCB bioleaching process; and no research has been conducted to compare the Cu extraction rate under both of the bioleaching mechanisms. A better understanding of the contact mechanism can have implications for methodology development, to improve the Cu extraction from PCBs. In the present study, the influence of the contact mechanism in the Cu extraction from PCBs was therefore analyzed by using a partition system. The conditions selected to conduct the present experiment were chosen in accordance with the conditions that showed the highest efficiency extraction rates proposed by previous literature in the PCB bioleaching (i.e., initial pH [6,13], pulp density [6,19], particle size [20], temperature [7,21], and incubator rpm [13,22,23]).

2. Materials and methods

2.1. Microorganism and media

The bacteria used in the present study were *A. ferrooxidans* (KCTC 4515). The microorganism was provided by the Korean Research Institute of Bioscience and Biotechnology. Bacteria were cultured in DSMZ medium 882, with a pH adjustment to 1.8 with H_2SO_4, at 95% solution in water (Acros Organics™). The DSMZ medium 882 contains $(NH_4)_2SO_4$, 132.0 mg L^{-1}; $MgCl_2·6H_2O$, 53.0 mg L^{-1}; KH_2PO_4, 27.0 mg L^{-1}; $CaCl_2·2H_2O$, 147.0 mg L^{-1}; $FeSO_4·7H_2O$, 20.0 g L^{-1}; $MnCl_2·2H_2O$, 62.0 μg L^{-1}; $ZnCl_2$, 68.0 μg L^{-1}; $CoCl_2·6H_2O$, 64.0 μg L^{-1}; H_3BO_3, 31.0 μg L^{-1}; Na_2MoO_4, 10.0 μg L^{-1}; $CuCl_2·2H_2O$, 67.0 μg L^{-1}; deionized (DI) water, 1000 mL. The temperature and the rpm of the incubator were fixed at 30 °C and 150 rpm respectively (WIS-20 wisecube® incubator, Germany). The concentration of bacteria cultured by this process was determined to be 7.75×10^{10} cell mL^{-1}, using a Burker–Turk counting chamber (Paul Marienfeld GmbH& Co., Germany).

2.2. Waste electrical and electronic equipment (WEEE)

The electronic waste selected was PCB, with a particle size of 500–1000 μm and 2000–4000 μm. The PCB was obtained from local recycling markets in Seoul, South Korea. The waste was crushed, and fractionated in dry sieving. A hammer mill at 2000 rpm was used to crush the PCB, using a 4.0 mm exit screen.

The concentrations of metals in the two different PCB particle sizes were analyzed. Table 2 shows the chemical characterization for each particle size. An increase on the metal concentration in the sample occurs while reducing the particle size, which was consistent with a previous study [23]. In this study, only the size range between 500 and 1000 μm was used in the bioleaching experiments. Due to the negative influence of higher concentrations of PCB pulp densities during bioleaching processes [23], a total amount of 1.2 g (4.0 g L^{-1}) of 500–1000 μm PCB was used for the present experiment. *A. ferrooxidans* was not previously adapted for this experiment, because it is believed that when the influence of the cell contact is analyzed, the adaptation of the bacteria does not affect the results [22].

2.3. Partition system

To study the influence of the contact mechanism, a partition system was used for the present experiment [16]. The partition system was made by a semipermeable membrane, with a MWCO of 12–14 kDa (Spectra/Por® 4 membrane, Spectrum® Laboratories, Inc. CA. USA). The setup of the partition system for this experiment is shown in Fig. 1. Inside the semipermeable membrane, 1.2 g of PCB and 10 mL of DSMZ medium 882 were added. Outside the membrane, 30 mL of bacterial suspension (7.75×10^{10} cell mL^{-1}) and 290 mL of DSMZ 882 medium were placed. The reaction temperature and shaking speed were fixed at 30 °C and 150 rpm, respectively. The experiment was conducted for 7 days, and the oxidation–reduction potential (ORP) and pH were measured every day (HI 2211 Hanna Instrument & Thermo Scientific Orion Star 4, respectively).

2.4. Metal concentration analysis

An aliquot of two mL was filtered through a 0.45 μm nylon syringe filter (Corning Incorporated, Corning, Germany), for ICP analysis of Cu and Fe concentrations. Additionally, the Fe^{2+} contents were analyzed through the *o*-phenanthroline method (HS-3300, Humas Co., South Korea). The Fe^{3+} was calculated by mass balance between the Fe and Fe^{2+}. It is important to note that the water losses in the system due to evaporation significantly affect the

Table 2
Metal contents, according to the size range of PCBs used in the present study.

Metal	500–1000 μm	2000–4000 μm
	Content (%w/w)	
Cu	40.181	36.856
Fe	0.445	0.078
Pb	1.990	0.060
Sn	4.504	0.005
Au	0.017	0.013
Ag	0.108	0.012
Ti	0.034	0.004

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