Hydrometallurgical Approach to Investigate the Recovery Potential of Gold Available in Waste PCBs

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Abstract

Gold is one of the highly demanded precious metals which have applications in jewellery, investment, electronic and medical industries due to its unique chemical and physical characteristics. Although the demand for gold is continuously increasing, gold producers have failed to meet the existing demand for gold through gold mining. Therefore, seeking out secondary sources of gold is vital. Since gold is one of the major metals used in the electronic industry, e-waste has enormous potential as a secondary source of gold. This study outlines the recovery potential of gold and several other valuable metals quantitatively in Printed Circuit Board (PCB) components of end-of-life computers, namely, microprocessors and Integrated Circuits (ICs), plated connectors in network cards, and plated metallic pins. The research workflow consists of a sample pre-processing and an acid leaching (digestion) process followed by a sample analysis process using an Inductively Coupled Plasma - Mass Spectrometer (ICP-MS). According to the results, the recovery potential of gold is significant in every e-waste component tested under this study.

Keywords: Acid leaching, E-waste, Gold, Metals, Printed circuit boards, Urban mining

1. Introduction

Gold is a transition element situated in group 11 in the periodic table along with copper and silver. The abundance of gold (^{197}Au) in the earth's upper lithosphere is 0.005 ppm [1]. Characteristics such as high malleability, ductility, high thermal and electrical conductivity, corrosion resistivity and rarity have turned gold into the highly desired, precious, and popular metal all over human history [2]. Comparative to the other metals, the demand for gold has an increasing trend. Generally, the jewellery industry accounts for more than 50% of gold consumption [3]. The electronics industry is the third-largest consumer of gold, accounting for nearly 12% of the total gold demand in 2017 [4].

Gold mining is a highly mechanised global industry all over the world. As the three major gold producers, China, Australia, and Russian Federation are account for 1,027.2 tonnes (around 30% of global production in 2019). However, according to the GlobalData, a UK-based data analytics and consulting company, gold production in the year 2020, from the world's eighth-largest producers, fell 6.5%, to 25 million ounces, owing to lower ore grades, asset sales, reduced mill throughput, and lower recoveries [5].

Furthermore, annual demand requires more gold than mined, and the deficit is usually offset by recycled gold (often from the recycling of jewellery). Therefore, recycling from secondary sources is one of the best options to cater for the gold demand in the market. Furthermore, seeking out secondary sources for gold will be a strategic approach for developing countries like Sri Lanka to sustain in the current and upcoming industrial revolutions as gold is essential in the electronic industry. According to the United Nations University (UNU), e-waste is considered as various forms of discarded electronic and electrical equipment that are ceased to be of value [6].

According to the latest global e-waste monitor report, total global e-waste generation and e-waste generation per capita in 2019 is estimated at 53.6 million metric tons (Mt) and 7.3 kg, respectively, and it is a fast-growing waste stream throughout the world with a growing rate of 3-5 % [7, 8].

Moreover, it is predicted that the developing countries in Asia will be producing at least twice as much e-waste as developed countries within the next few years [9, 10].

Almost all electrical and electronic equipment contains metals and plastics. Pure metal and alloy composition is 60 %, while the plastic composition is exceeding 15 % in general e-waste [7]. PCBs are the significant 'electronic' components included in e-waste. Apart from the base metals such as copper, PCBs are a composition of several precious metals, such as gold and platinum [11, 12]. Gold is used as a thin film in contacts, soldered joints and connecting wires [13]. Due to the limitation of natural resources, precious metals such as gold can be recovered through techniques such as acid leaching, cyanide leaching, thiourea leaching, thiosulphate leaching, halide leaching, bioleaching, ion exchange method, borax method, and amalgamation, if the selected e-waste has a considerable concentration of gold [14, 15]. The potential of e-waste as an alternative source for gold will be studied in this study.

2. Materials and Methods

2.1 Sample Collection

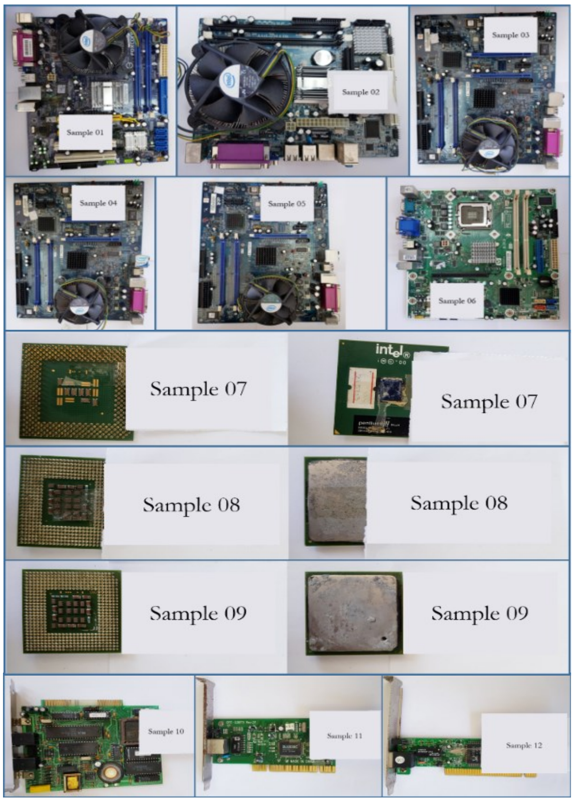

Figure 1: Initial E-waste Samples (01–06: Motherboards, 07–09: Micro-processors, and 10–12: Network Cards).

As shown in Figure 1, 12 e-waste (PCB) samples under 3 categories i.e., motherboards, microprocessors, and network cards discarded by the Department of Computer Science and Engineering, University of Moratuwa were used for this study.

2.2 Sample Pre-processing

Initial PCB samples were dismantled using hand screwdrivers and pliers. Then, 3 types of e-waste components were liberated as shown in Figure 2.

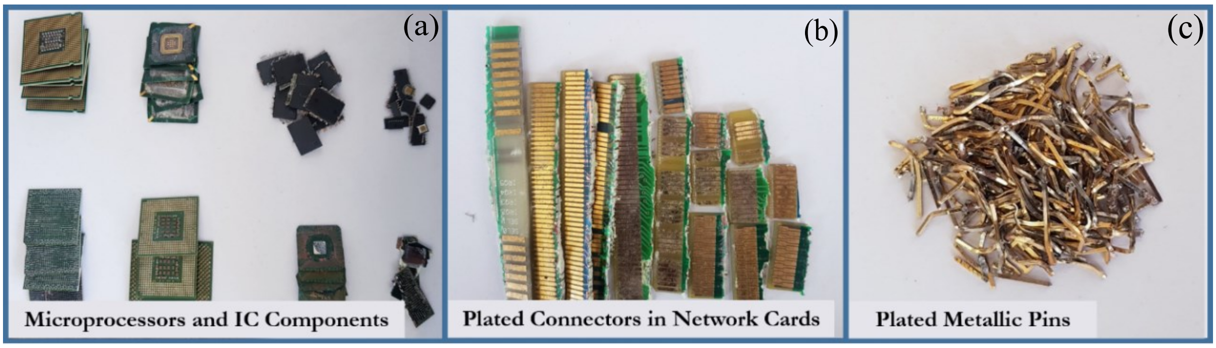

Figure 2: Dismantled E-waste Components ((a) Microprocessors and IC Components; (b) Plated Connectors in Network Cards; (c) Plated Metallic Pins).

An initial manual crushing and a grinding process were used for the size reduction. T.100 type Tema mill (1000 rpm for 5 min.) and a sieve shaker with laboratory test sieves (63 µm BS410/1986) were used for the grinding and sieving process.

2.3 Digestion Process

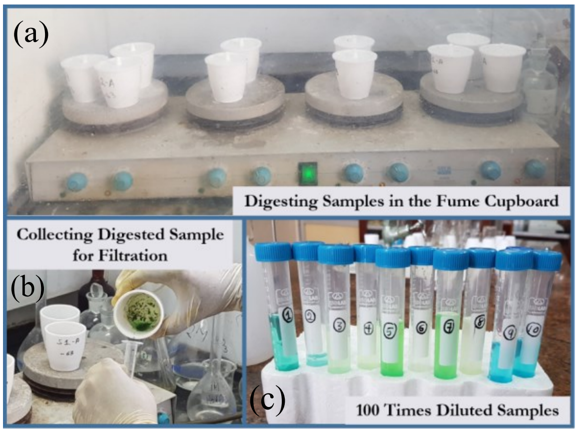

Figure 3: Digestion Process ((a) Digesting samples in the fume cupboard; (b) Collecting digested samples for filtration; (c) 100 times diluted samples).

After the size reduction process, two 0.5 g of each bulk sample were digested separately in Teflon beakers with 4 ml of aqua regia (3 ml of conc. HNO_3 and 1 ml of conc. HCl) at 200 °C for 1 hr.

After the digestion, residue solutions were collected and filtered through 0.45 µm Nylon syringe filters. The filtrates were diluted 100 times with deionised ultrapure water from the Banstead EASYpure® II water system (Figure 3).

Usually, almost all metals, including gold, are oxidised and then solved as ions under aqua regia digestion. Therefore, the actual concentration of selected metals in the sample can be determined using the aqua regia digestion process. Duplications of each sample were digested and analysed using ICP–MS.

2.4 Sample Analysing

The digested samples were analysed through the ICP–MS (ThermoScientific – iCAP RQ) for metal concentrations in the samples. An autosampler unit (TELEDYNE® – ASX-560) was used to feed the sample accurately into the ICP–MS.

Averaged metal concentrations in the digested samples were calculated based on the ICP–MS results.

3. Results and Discussion

Aqua regia dissolves gold, although none of the constituent acids does so alone. Nitric acid is a strong oxidant, which will actually dissolve a virtually undetectable amount of gold, forming gold ions (Au^{3+}).

Hydrochloric acid provides an immediate supply of chloride (Cl^-) ions, which react with gold ions to produce tetrachloroaurate (III) anions, even in solution.

The reaction with hydrochloric acid is an equilibrium reaction that favours the formation of chloroaurate anions ($[AuCl_4]^-$). This results in the removal of gold ions from the solution and allows for further oxidation of the gold. The appropriate equations for aqua regia dissolution are,

$$Au + 3\ HNO_3 + 4\ HCl \rightarrow [AuCl_4]^- + 3\ NO_2 + [H_3O]^+ + 2\ H_2O \quad (1)$$

Table 1: Metal concentrations in digested samples.

Sample Source	Microprocessors and IC Components (MP/IC)		Plated Connectors (PC)		Plated Metallic Pins (PMP)
Size (μm)	**+ 63**	**- 63**	**+63**	**- 63**	**-5000**
^{52}Cr [ppb]	95.10	46.29	72.85	149.73	58.18
^{58}Ni [ppb]	12,685.93	6,028.53	32,227.37	3,335.66	3,736.24
^{59}Co [ppb]	3,521.25	1,600.38	186.23	71.72	12.48
^{56}Cu [ppb]	264,990.23	124,905.45	296,506.11	19,003.21	480,856.82
^{64}Zn [ppb]	857.16	424.00	1,161.19	295.51	100,846.87
^{75}As [ppb]	782.41	351.90	63.16	18.88	3.29
^{114}Cd [ppb]	1,050.00	562.33	44.78	1195.45	306.09
^{197}Au [ppb]	2,162.86	124.61	1,506.92	2,685.56	4,881.05
^{208}Pb [ppb]	3,230.51	1,860.08	1,294.17	1,705.26	5,750.95

$$Au + HNO_3 + 4\ HCl \rightarrow [AuCl_4]^- + NO + [H_3O]^+ + H_2O \quad (2)$$

Apart from the gold, all other elements shown in Table 1 are reacted with aqua regia, similar to the reaction of copper.

$$Cu + 4\ HNO_3 \rightarrow Cu(NO_3)_2 + 2\ NO_2 + 2\ H_2O \quad (3)$$

According to the results (Table 1), copper and nickel concentrations are higher in every sample. Especially, copper content in the Plated Metallic Pin (PMP) sample is significantly high.

Furthermore, it was evident that the concentration of gold is high in waste PCB components listed in Table 1. The highest gold concentration has resulted in gold plated metallic pin sample, and it was 4,881.05 ppb. When considering gold plated connectors in network cards, gold concentration is higher in the -63 μm sample.

Moreover, toxic heavy metals such as Cd and As concentration is significantly high in MP/IC samples than PC and PMP samples as they are used in manufacturing semi-conductors in MP/ICs. Since Pb is used in both solders and alloy pin manufacturing, the concentration of Pb is high in PMP samples than MP/IC and PC samples.

Moreover, Cr concentration is almost low in every sample. Apart from the MP/IC, Co concentration is lower than 200 ppb. As is also showing a similar variation as Co. Generally, As and Co are used in integrated circuits due to their low diffusion rate and semiconducting properties.

4. Conclusion and Recommendations

The metal composition in the components of waste PCBs and their potential as an alternative source for gold were investigated in this paper.

According to the results, it can be concluded that PCB components such as MP/IC, PC, and PMP have enormous potential for gold recovery; therefore, those waste components will be a good alternative source for gold extraction. Therefore, research on non or less toxic methodologies to extract gold from e-waste are recommended, as most gold leaching techniques are based on cyanide leaching. Furthermore, particle distribution under different size reduction processes should be assessed to identify the optimum size reduction process for gold in e-waste.

Since copper and nickel concentration is higher in MP/ICs, plated connectors, and plated metal pins, further research on the economic viability and the eco-toxicology of the extraction of those elements are encouraged.

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