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An economic analysis of the recovery of gold from CPU, boards, and connectors using aqua regia

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ABSTRACT

The recovery and recycling processes for the management of electronic wastes should be determined accurately. The processes applied to e-waste recycling are continually developing. These processes are applied using different methods, and thus, economic analysis is required in order to select the preferred choice. In particular, the aqua regia process for the recycling of gold can usually be implemented efficiently. In our study, the inputs and outcomes of the physical separation and chemical reactions that are conducted with the aqua regia for CPU, board, and connectors in the real scale plant were discussed. The rent, equipment, and labor costs, as an expense, have mainly been determined in the economic analysis of the aqua regia, and \$16.55 is calculated as kg waste per month. However, the benefits obtained from CPU, board, and connectors were determined as \$274, \$104, and \$94 for kg waste per month, respectively.

Keywords: Gold recovery; E-waste; Aqua regia; Economic analysis

1. Introduction

It is necessary to consider both the environmental impact that results from mining operations and the efficiency use of resources in the management of natural resources [1]. The environmental activities based on wastewater treatment, emissions control, and pollution prevention issues focus particularly on recycling and reuse processes. The economic value of the materials obtained from wastes is quite variable, but they all contribute to environmental protection. A lot of paper, plastic, glass, electronic waste, etc. are recycled and economically evaluated. Astronomical amounts of electronic waste sold in the United States of America are being stored in businesses' and consumers' homes awaiting disposal [2]. Recycling electronic waste is one option customers can choose to dispose of it. It has many positive externalities, including conserving landfill space, saving energy, decreasing greenhouse gas emissions, reducing toxic chemicals in the municipal waste stream (lead, mercury, and arsenic), and preserving natural resources. The increasing growth in the generation of electronic waste encourages a variety of research on waste reduction [3]. However, electronic waste such as TVs,

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mobile phones, PCs, laptops, tablets, home appliances, electrical components, DVDs, and calculators are quite diverse, and they possess a metal content between 38 and 50% [4]. In particular, printed circuit boards (PCBs) are an important subset of the overall e-waste stream due to both the high value of the materials contained within them, and their potential toxicity [5]. Electronic waste mainly includes Fe, Cu, Al, Pb, Ni, Ag, Au, and Pd, but gold is a priority in the recovery process applied [6]. Therefore, the wastewater generated from the gold recovery process contains high concentrations of toxic metals. The amount of metals in electronic waste is given in Table 1. The amount of precious metal produced from recycling is very clear.

For example, precious metals such as gold and silver can be obtained at both a higher quality, and with a lower environmental impact from electronic products, rather than from traditional mining. Due to a decrease in mining capacity, prices of precious metals have skyrocketed in recent years. Additionally, increasing amounts of rare metals are being used in electronics. These metals can be sold and reused when salvaged during the recycling process [8]. The industry could decrease production costs if it could safely and inexpensively recover these metals from outdated electronics and reuse them in new products. This could ultimately result in consumers paying less for their electronics. In addition, CPUs containing high amounts of gold and connectors that are significant components of electronic waste are important sources in recycling studies [9].

Three hydrometallurgical processes for industrial wastes are applied. The main separation techniques are: solvent extraction, electro-oxidation, and leaching–precipitation. The recovery of the gold from solid wastes generated in the electronic industries consists of thermal degradation, two-stage leaching with nitric acid solution to remove the silver and other metals, and then using aqua regia (Latin for "royal water") to dissolve the gold, selective solvent extraction of the gold with diethyl malonate, and the reduction of the gold from the organic phase [10].

Several methods for the recovery of precious materials from electronic waste are applied. The selection of the recycling process depends on the type of material and its complexity, the metal content, and the volume of e-waste. Physical, hydrometallurgical, and electrometallurgical methods are used for the recycling of the e-waste [7]. The initial step in the recycling and recovery process is mainly to classify, evaluate, and separate the type of material according to both the metal content and recoverability [11]. The next step in the recycling process is the removal of the critical components from the e-waste in order to avoid the dilution of, and/or contamination of toxic substances during the downstream processes. Mechanical processing is the next step in e-waste treatment. This is normally an industrial large-scale operation in order to obtain the concentrates of the recyclable materials in a dedicated fraction, and also to further separate the hazardous materials [12]. The typical components of a mechanical processing plant are the crushing units, shredders, magnetic- and eddy-current, and air separators. The gas emissions are filtered and the effluents are treated in order to minimize the environmental impact. The chemical stripping of the precious metals from e-waste or i-waste material normally requires acids, which is usually cyanide. The secure handling of these substances is extremely critical. For gold recovery from the motherboards CN process, *aqua regia*, the nitric process, and pyrolysis and hydrometallurgy can be used. The acid solutions are possible for gold recovery in high yields [13].

Aqua regia is a highly corrosive, fuming yellow or red solution. The mixture is formed by freshly mixing concentrated nitric acid and concentrated hydrochloric

Table 1
Composition of metals from different e-waste samples [7]

E-waste	Weight (%)					Weight (ppm)		
	Fe	Cu	Al	Pb	Ni	Ag	Au	Pd
TV board scrap	28	10	10	1.0	0.3	280	20	10
PC board scrap	7	20	5	1.5	1	1,000	250	110
Mobile phone scrap	5	13	1	0.3	0.1	1,380	350	210
Portable audio scrap	23	21	1	0.14	0.03	150	10	4
DVD player scrap	62	5	2	0.3	0.05	115	15	4
Calculator scrap	4	3	5	0.1	0.5	260	50	5
PC mainboard scrap	4.5	14.3	2.8	2.5	1.1	639	566	124
Printed circuit boards scrap	12	10	7	1.2	0.85	280	110	–
Printed circuit boards	5.3	26.8	1.9	–	0.47	3,300	80	–

acid | usually in a volumetric ratio of one to three, respectively. The recovery of precious metals from electronic scrap has been an important area not only from an economic point of view, but also for the recycling rare natural sources and reducing the e-waste to prevent the environmental pollution [14]. After the recovery of gold, the wastewater resulting from gold recoveries causes secondary pollution to the environment [15].

Unlike in mining activities, the recovery process is highly efficient and environmentally friendly. However, there are no detailed studies related to the efficiency of the aqua regia process. In this study, the economic analysis of gold recovery through the aqua regia process was investigated on the CPU, the boards, and the connectors consisting of electronic waste. In the aqua regia process, the cost of rents, equipment, energy, labor, chemicals, water and wastewater, and revenues, taking into account the actual cost required for a business, is determined.

2. Material and methods

The e-waste recycling facility was established in Eyup/Istanbul. E-wastes such as PCBs, CPUs, and connectors were admitted, and applied hydrometallurgical recovery methods were used. The PCBs, and connectors for the CPUs, have been classified and analyzed. Initially, they are subjected to physical methods of electronic waste disassembly decontamination, dismantling, crushing, and grinding processes. The waste was grounded in the cutting mill to a particle size fraction <0.5 mm. Then, aluminum and plastics by means of air in the cyclone separator is separated. In magnetic separators, waste in the magnetic fraction is separated from the non-ferrous metals. The energy expended during physical methods, labor, and expenses have been identified.

The facility for the recovery of the gold hydrometallurgical methods was applied. The aqua regia can dissolve gold because each of its two component acids carries out a different function. The nitric acid is a good oxidizing agent. The chloride ions from the hydrochloric acid from the coordination complexes with the gold ions are removed from the solution. Reducing the concentration of the Au^{3+} ions shifts the equilibrium towards the oxidized form. The reactions involved are as follows:

$$HNO_3 + 3HCL \rightarrow NOCL + 2H_2O + 2Cl \tag{1}$$

$$Au(s) + 3NO_3^-(aq) + 6H^+(aq) \rightarrow Au^{3+}(aq) + 3NO_2(g) + 3H_2O \tag{2}$$

$$Au^{3+}(aq) + 4Cl^-(aq) \rightarrow AuCl_4^-(aq) \tag{3}$$

To this end, the $FeSO_4$ aqua regia process was used for the neutralization. The aqua regia is an acid solution whose mixture is formed by freshly mixing concentrated nitric acid and hydrochloric acid optimally in a volume ratio of 1:3, and can dissolve precious metals such as gold and platinum.

The computer circuit board scrap, CPU, and connectors were first treated with one part concentrated nitric acid and two parts water at 70°C for 1 h. This step dissolved the base metals, thereby liberating the chips from the boards. After the solid—liquid separation, the chips, intermixed with some metallic flakes and tin oxide precipitate, were mechanically crushed to liberate the base and precious metals contained within the protective plastic or ceramic chip cases. The base metals in this crushed product were dissolved by leaching again with the same type of nitric acid—water solution. The remaining solid constituents, crushed chips and resin, plus the solid particles of gold, were leached with the aqua regia at various times and temperatures. The gold was precipitated from the leachate with ferrous sulfate [16].

For a real economic analysis approach, the two stages in the recycling process, all processes are handled. In the first stage, the collecting, sorting, testing, disassembly, size reduction, and cost for the separators were put forward. In the second stage, labor, energy, chemicals, water–wastewater, equipment, and building costs were taken into consideration. The operating income for the recycling of the materials and gold sales were projected [17]. The equations are given for the cost and revenue of operating:

$$\text{Operating costs of the process} = \text{waste} + \text{energy} + \text{transportation} + \text{equipment} + \text{rent} + \text{labor} \tag{4}$$

$$\text{Total cost} = \sum(\text{each process costs}) \tag{5}$$

$$\text{Income} = \text{sales of recyclable products} + \text{gold for sale} \tag{6}$$

In Table 2, the cost and revenue is used for the calculation of the unit prices. The electricity, water, labor, and equipment costs per process values calculated from the annual data are used.

For an accurate economic model, the amount of capital and operating costs should be determined. An

Table 2
Unit costs of expenditures for the recycling process

Energy cost ($/kW h)	0.1
Operating time (d/year)	250
Labor salary ($/h)	6.2
Rent expense ($/$m^2$ month)	3.2
Recycled waste (tons/year)	5.2
Chemicals ($/L)	0.25
Wastewater costs ($/$m^3$)	110

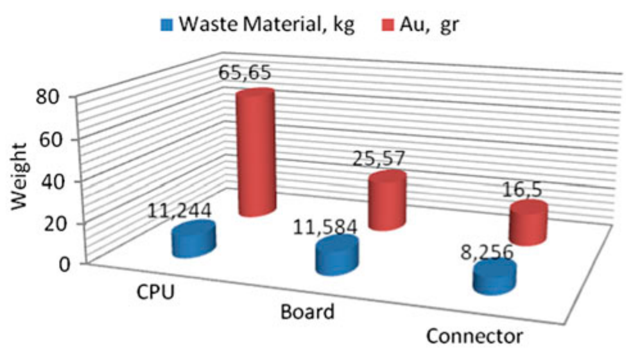


Fig. 1. The amount of gold obtained from the recovery of CPU, boards, and connectors.

income summary should be prepared for the process and should be considered for investment support. An income summary should be prepared for the process and should be considered for investment support to create the cost of capital the investment cost of each piece of equipment in the process flow diagram. The variable model for the estimation of the operating costs is determined using the material balances. The unit cost of electronic waste, rent, chemicals, energy, and labor is estimated through plant requirements, such as pricing. The income summary should be introduced by making all the monthly income and expense statements. The sectorial and regional support for the facility investment should be determined. Both energy-reducing investment and operating costs of the support should be provided to both labors [18].

3. Results and discussion

The incomes of the process are determined, firstly, for the economic analysis of the aqua regia process. The amount of gold waste accepted into the facility is known approximately, but considering the variable amount of waste is redetermined. Determining the treated waste and the average weight of the amount of gold is shown in Fig. 1.

The CPU, board, and connectors supplied at the plant were highly variable in weight. However, the amount of gold obtained by processing the electronic waste from the CPU, board, and connector was 5.85, 2.2, and 2 g/kg, respectively. When compared to the amount of gold (3–9 g/t ore) obtained from gold mining, it appears to be a very efficient process [19]. Also, a small amount of copper and palladium were obtained in the process, but gold sales are the fundamental income.

Taking into account the unit prices given in Table 2, the monthly expenditure for the electronic waste recycling process was calculated and given in Table 3. In particular, money spent on labor, equipment, and rent was observed as higher.

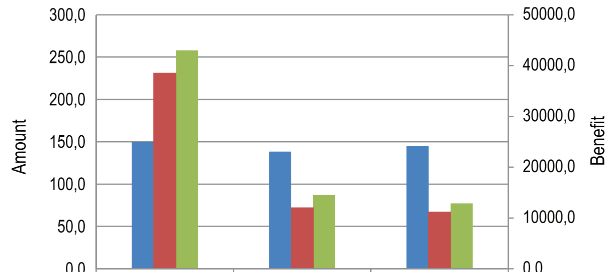
Considering the distribution of the expenditure for the aqua regia process, it seems to account for the

Table 3
Cost of expenses for the economic analysis of aqua regia processes

	Rent	Equipment	Energy	Chemicals	Labor	Water	Wastewater	Total ($)
Expense ($/month)	1,750	2,100	300	490	1,975	95	460	7,170

Table 4
Incomes on economic analysis of recycle process

E-waste	Amount (kg/month)	Au (gr)	Au ($/gr)	Total ($/month)
CPU	149.6	873.70	47	41,063.8
Board	138.4	305.56	47	14,361.5
Connector	145.2	290.23	47	13,640.8



	CPU	Board	Connector
Amount, kg	149,6	138,4	145,2
$/kg e-waste	257,9	87,2	77,4
Benefit, $	38587,3	12070,5	11237,4

Fig. 2. Economic analyses of e-waste recycle.

rent, equipment, and labor, which is approximately 75% of the costs. The cost of chemicals used in the process, and those of energy and water–wastewater amounts were determined to be close to each other. Rent and labor costs spent for the recycling process can be changed for different locations and cities that should be considered. However, water, wastewater, chemical, and energy costs do not show significant differences.

The costs for aqua regia process remain unchanged for CPU, board, and connector, the obtained amounts of gold varies. Therefore, the amount of recycled gold and revenues are calculated separately for each waste. The calculated monthly incomes and changes based on waste are given in Table 4.

The total monthly income for processing the CPU in was quite high, and varied depending on the price of gold. The amount for processing electronic waste, income per waste, and the benefit data for one month is shown in Fig. 2.

When the income of the aqua regia process is analyzed, profitable recovery is provided, and the costs for the disposal of electronic waste will no longer exist. Because of the CPU, board, and connectors, environmental problems may occur and the recovery will be necessary to reduce emissions [20].

4. Conclusion

While providing relatively high amounts of gold recovery, high costs have been calculated for the disposal of solutions and residual materials. The recovery of gold from CPU, board, and connector via the aqua regia process has been found quite profitable. The most economical solution for the recovery of precious metals from electronic waste also discussed along with the solutions that create a minimum of waste are required.

Both waste management and recycling activities should be considered firstly in terms of environmental characteristics. This must be decided by the results of economic analysis and feasibility studies.

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