An Assessment of the Potential to Recover Gold from E-waste as a Waste Management Initiative

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Abstract

This study evaluated the potential to extract gold from e-waste mainly focusing on printed circuit boards (PCBs). E-waste was first separated physically and then went through dissolution. Cyanide leaching and Aqua Regia leaching using various precipitating reagents such as zinc (Zn), aluminum (Al), $Na_2S_2O_5$, $FeSO_4$, $NaBH_4$ on Zn and $NaBH_4$ on Al. The process was conducted at pH of 11.8 and 12.4. Gold extracted through cyanidation leaching with $NaBH_4$ on Zn precipitation resulted in gold extraction of 99.0% in comparison to leaching with Aqua Regia with $NaBH_4$ on Zn precipitation to yield gold content of 91.9%. The e-waste processing plant was assumed to process 20000 tons per annum of PCBs with a gold yield of 1.4 tons and total power requirement of almost 203 000 KWhr. A total capital investment of USD 15 million was required with a payback period of 1.04 years and a return on investment of 0.96. E-waste can be utilized as a raw material to recover precious metals.

Keywords
Economic assessment, e-waste, gold recovery, leaching, metals recovery, PCBs, precipitation.

1. Introduction
An increase in the usage of electronic equipment has led to the generation of large quantities of electronic waste (e-waste) (Kang et al., 2005). E-waste includes radios, computers, cell phones, printers and calculators. E-waste is a growing waste source globally with a 3-5% increase annually (Park et al., 2017). E-waste contains different substances which are toxic, non-biodegradable and have negative impact on the environment and health resulting in diseases such as heart failures, cancer and kidney failures (Awasthi et al., 2018). E-waste also contains significant amounts of precious metals such as gold, silver and palladium as well as base metals such as copper and lead.

E-waste management is important in solid waste management as it supports zero landfill initiatives, helps prevent and eliminate toxic scrap (Baidya et al., 2019). Presently a ton of gold produced releases 10000 tons of carbon dioxide to the environment however if recycling methods are used to recover metals from e-waste minimal amounts of carbon dioxide are released (Awasthi et al., 2018). The metal composition of e-waste makes it attractive in terms of metal recovery particularly printed circuit boards (PCBs), which are part of electronic devices where gold is the main component (Awasthi et al., 2018). Through implementation of the 3Rs in waste management: Reduce, Recycle and Reuse, the problem of e-waste can be minimized. E-waste can be utilized as raw material for secondary source of precious and base metals. This study then focused on the assessment for the potential to recover gold from e-waste mainly PCBs as a waste management initiative.

2. E-waste generation statistics

Baidya et al. (2020) indicated that the metal compositions of PCBs is dependent on sources like televisions, cell phones, personal computers and calculators. Table 1 shows metals contained in various components of electronic waste.

Table 1. Metal composition in electronic waste (Baidya et al., 2020)

Metal content (%)	Key boards	Computers	PCBs	Car electronics	Recycling efficiency (%)
Silver (Ag)	0.05	0.009	0.3	0.12	80
Gold (Au)	0.005	0.001	0.008	0.01	99
Copper (Cu)	13.0	7.0	25.0	20.0	90
Zinc (Zn)	3.0	1.2	1.5	1.0	60
Palladium (Pd)	0.0002	0.0004	-	-	60
Aluminum (Al)	18	11	3	-	80
Nickel (Ni)	0.16	0.2	0.5	0.3	0
Lead (Pb)	0.3	1.5	-	1	5
Bismuth (Bi)	<0.0003	<0.0004	0.17	0.01	6
Iron (Fe)	3.0	<0.1	5.0	5.0	80
Antimony (Sb)	0.3	0.5	0.06	0.08	70

2.1 Health effects of e-waste

E-waste has negative impacts on human beings (Awasthi et al., 2018). Arsenic disturbs cell communication and interferes cell growth contributing to cardiovascular diseases, cancer and diabetes (Baldé et al., 2017). Cadmium lowers body metabolism rate leading to bones complications. Chromium causes skin irritations, copper causes throat irritation, affects the liver as well as the kidneys. Lead poisoning causes the impairment of intellectual and verbal activities, paralysis and death. Nickel is carcinogenic in large doses and frequent handling of silver causes a condition that stains skin a blue-grey shade.

2.2 E-waste processing methods

Various methods are used for recovering metals from PCBs. The methods in Table 2 are the ones which are currently being used for processing e-waste.

Table 2. E-waste recovery methods e-waste, energy usage and environmental impact (Bisschop. 2012)

Method	Energy requirement	Metal recovery	Environmental impact
Shredding	Low	High	High
Incineration	High	None	High
Pyro metallurgical recovery	Low	High	High
Thermal depolymerisation	High	None	Low
Plasma arc gasification	High	None	Low
Bioleaching	Low	High	Low

The separation of metals from non-metals requires further processing which involve the use of chemical reagents. There are different methods to separate metals from non-metals in PCBs which involve incineration, acid washing, smelting and physical separation.

2.2.1 Incineration
Incineration is a treatment process that involves the combustion of organic substances (Corsini et al., 2013). Incineration is used to burn off the non-metallic parts of PCBs and retain the metals from the ashes. E-waste incineration causes release of hazardous gases such as dioxins and furans.

2.2.2 Acid washing
Acid washing is used to react with the non-metallic parts of PCBs and recover the metals either from the rich solvent or as precipitates (Ejiogu. 2012). The process of acid washing is difficult to control when including the non-metallic parts of PCBs as it releases hazardous vapors.

2.2.3 Physical separation
Physical separation techniques are used to separate the metals and non-metals from PCBs and are known to have safe and eco-friendly operation (Herat and Agamuthu. 2012). Physical separation technologies are energy intensive and are capable of producing separate streams of metals and non-metals.

2.2.4 Separation of valuable metals
Separation of the valuable metals is when all the metals of interest are separated from the mixture and extracted as pure metals (Kang and Scheming. 2005). The metals selected for recovery in this study is gold. Therefore, a process is needed which can selectively and quantitatively separate gold from the PCBs.

2.2.4.1 Pyro metallurgical methods
Pyro metallurgical methods include incineration, smelting, sintering, melting and cementation (Kraan et al., 2006). The crushed scrap is burned in a furnace to remove plastics to leave a molten metallic residue. The plastic burns and the refractory oxides form a slag phase. A collector metal such as copper or lead can be used, impure alloys are made by smelting the crude metal concentrates. Silver and gold containing scrap materials are treated in a copper smelter (Lepawsky and McNabb, 2010).

2.2.4.2 Bio leaching

Bio leaching is a microbiological process where there is use of bacteria and fungi to extract metals from e-waste. Bacteria such as *Thiobacillus Thiooxidans* and *T Ferrooxidans* and fungi such as *Aspergillus Niger* and *Penicillium Simplicissimum* can be used through metal mobilization (Osibanjo et al., 2012). Efficient metal mobilization through a two-step leaching process is used where biomass growth is separated from metal leaching (Osibanjo et al., 2012). Microbiological leaching uses the bioactivity of microorganisms to transform metals to a dissolved form (Park and Fray. 2009).

2.2.4.3 Hydrometallurgical separation

In hydrometallurgical treatment the main steps are acid or caustic leaching of e-waste. Hydrometallurgical treatment requires a small grain size to increase the metal yield (Robinson. 2009). From the solutions the metals are then isolated and concentrated through solvent extraction, precipitation, ion exchange, filtration or distillation. Leaching solvents used are H_2SO_4, H_2O_2, HNO_3, NaOH and HCI. Hydrometallurgical methods provide high selectivity, high purity output, controlled environment and good recovery. Hydrometallurgical methods depend on dissolution efficiency in order to achieve a complete dissolution of all metals within e-waste.
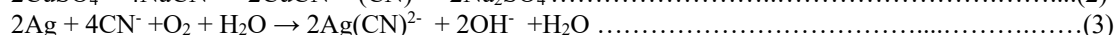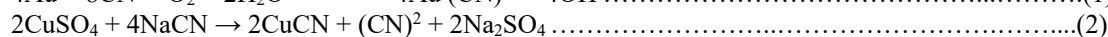
2.3 Thermodynamics of Leaching Agents

The choice of leaching agents depends on capital investment, economics, extraction economics, availability and recyclability (Schluep et al., 2009). In addition, the process applicability, selectivity, toxicity, ore type, control, potential to be up scaled and separation are critical factors. Cu, Ag and Au are noble and the potentials are: $Au + 3e^- = Au^{3+}$; $Cu + 2e = Cu^{2+}$ and $Ag + e^- = Ag^+$. The equilibrium of Au is more positive than that of oxygen reduction reaction. Ag and Cu are highly non-reactive with air. Some metals are unaffected by weak acids and the other metals above hydrogen in the series are easily leached. The leaching of these metals proves difficult as we go down the reactive series. The presence of complexing agents modifies potential/pH diagrams for metal-water systems due to the formation of stable metal complex ions. Table 3 shows leaching agents for the processing and the active substrates.

Table 3. Leaching agents used in e-waste processing

Metal	Lixiviant
Base metals	Nitric Acid
Au and Ag	Cyanide or Thiosulphate
Cu	Sulphuric Acid or Aqua Regia
Pd	Hydrochloric and Sodium Chlorate

2.4 Effect of various parameters on cyanidation leaching

Cyanidation is a leaching method in which the dissolution of alkaline cyanide solutions, the overall reaction is represented as indicated in Equations 1-3.

$4Au + 8CN^- + O_2 + 2H_2O \rightarrow 4Au (CN)^{-2} + 4OH^-$……………………………………...……….(1)

$2CuSO_4 + 4NaCN \rightarrow 2CuCN + (CN)^2 + 2Na_2SO_4$ …………………….………………………....(2)

$2Ag + 4CN^- + O_2 + H_2O \rightarrow 2Ag(CN)^{2-} + 2OH^- + H_2O$ ………………………………...……….…….(3)

2.4.1 pH

An alkaline pH range of 10.5-11 is essential to ensure that most of the cyanide is in the ionic form (Awasthi et al., 2018). An alkaline pH is essential for safety and economic reasons as HCN is a volatile and poisonous gas. The decrease in the leaching rate at high cyanide concentration is as a result of the increase in pH of the solution hence the pH must always be controlled.
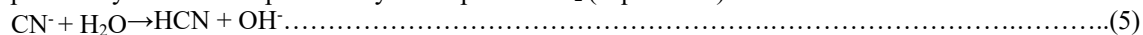
2.4.2 Cyanide concentration on gold dissolution

The rate of metal dissolution increases linearly with increasing cyanide concentration until a maximum is reached (Baidya et al., 2019). Cyanide ions undergo hydrolysis according to Equation 4 and this reaction is undesirable since there is production of toxic HCN fumes.

$$CN^- + H_2O \rightarrow HCN + OH^- \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4)$$
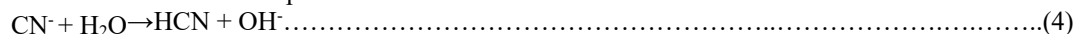
2.4.3 Hydrogen ion concentration during gold leaching

Cyanide solution is kept alkaline during leaching of gold in order to prevent hydrolysis (Equation 5) and to prevent cyanide decomposition by atmospheric CO_2 (Equation 6).

$$CN^- + H_2O \rightarrow HCN + OH^- \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(5)$$

$$CN^- + H_2CO_3 \quad \rightarrow HCN + HCO_3^- \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(6)$$
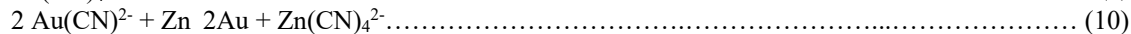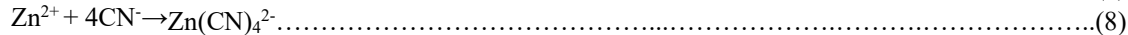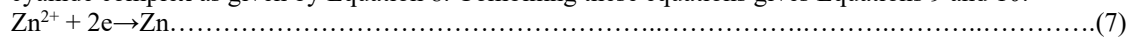
2.4.4 Precipitation of gold with zinc powder

Gold is precipitated out of the pregnant solution by means of zinc powder. The precipitate is then filtered out of the solution, and the filtrate is then smelted with fluxes to recover the gold.

2.4.4.1 Reaction chemistry for gold precipitation with zinc

The anodic oxidation of zinc in aqueous solution is given by Equation 7. In cyanide solution zinc forms a stable cyanide complex as given by Equation 8. Combining these equations gives Equations 9 and 10.

$$Zn^{2+} + 2e \rightarrow Zn \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(7)$$

$$Zn^{2+} + 4CN^- \rightarrow Zn(CN)_4^{2-} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(8)$$

$$Zn(CN)_4^{2-} + 2e^- \rightarrow Zn + 4\ CN^- \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(9)$$

$$2\ Au(CN)^{2-} + Zn\ 2Au + Zn(CN)_4^{2-} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\ (10)$$

2.4.4.2 Effect of cyanide concentration on gold precipitation

The rate of precipitation is independent on cyanide concentration above the critical minimum value (Baidya et al., 2020). The dissolution rate of zinc increases with increase in cyanide concentration and it is important to increase cyanide concentration significantly above the minimum required for precipitation (Baidya et al., 2020).

2.4.4.3 Effect of zinc concentration

The dissolution rate of zinc decreases with increasing Zn ion concentration (Baldé et al., 2017). High zinc concentration result in formation of insoluble zinc hydroxide which can passivate the zinc surface and reduce the precipitation rate.

2.4.4.4 Effect of temperature on zinc dissolution

Higher temperatures increase the rate of zinc dissolution and hydrogen evolution, with an associated decrease in precipitation efficiency (Bisschop, 2012). The addition of Pb (II) reduce zinc consumption and improve precipitation efficiency (Baidya et al., 2020).

2.4.4.5 Effect of pH on zinc dissolution

The pH of the pregnant solution influences the redox potential, which shifts in the negative direction with increasing alkalinity (Corsini et al., 2013). The cementation process improves when there is an increase in pH 11.5-11.9. Precipitation is reduced to <pH 8 and the precipitation rate drop at pH>12 due to too much hydrogen evolution (Bisschop, 2012).
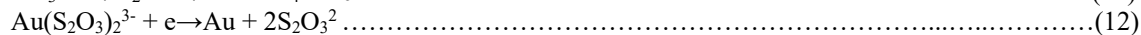
2.5 Thiosulphate leaching

The leaching with thiosulphate is an alternative to cyanide leaching. Thiosulphate leaching is the only process which is used directly to leach gold from certain gold containing sulphide ores without a pretreatment step such as roasting, high pressure oxidation, bacterial leaching and also without using large amounts high cost leaching agents (Ejiogu., 2012). The gold in leach solution is cemented with sodium borohydride, zinc dust, or with sodium sulphide. The effect of thiosulphate concentration on gold extraction increases with the increase in thiosulphate

concentration ≤1.0M and then the extraction decreases with further increase in thiosulphate concentration. The extent of gold extracted has shown a minimum at 0.6 $Na_2S_2O_3$ (Corsini et al., 2013).

2.6 Precipitation of gold
2.6.1 Precipitation with sodium borohydride
Gold can be precipitated by reduction onto Zn, Al or Fe powder with sodium borohydride as represented by Equations 11 and 12.

$$BO_3^{3-} + 7H_2O + 7e \rightarrow BH_4 + 10OH^-\text{………………..……………………………..…………(11)}$$
$$Au(S_2O_3)_2^{3-} + e \rightarrow Au + 2S_2O_3^2\text{…………………………………………...…..…………(12)}$$

2.6.2 Precipitation with sodium sulphide
A large amount of metal powder is required to provide sufficient surface area to reduce gold. Copper also co-precipitates from solution and must be recycled to leach. Basic electrochemical show that Au (I) thiosulphate cannot be readily reduced to metallic gold in the potential region where copper dissolves (Herat and Agamuthu., 2012). Nevertheless, the presence of both copper and silver in solution enhances gold deposition at a low over potential.

2.7 Leaching with Aqua Regia
The Aqua Regia was made upon mixing 1 volume of concentrated nitric acid with 4 volumes of concentrated hydrochloric acid. No heat is evolved when mixing but the Aqua Regia at once starts to emit chlorine gas which continues to be generated for a number of days. A closed Aqua Regia vessel can develop enough chlorine pressure to burst hence the bottle needs to be stored in a fume hood. Aqua Regia attacks the gold with formation of $[AuCl_4]^-$ complex ion as represented in Equation 13. Gold is first oxidized by nitric acid to Au^{3+}, which is then removed by complexing with the chloride ions.

$$Au + 6HNO_3 \rightarrow Au^{3+} + 3NO^{3-} + 3H_2O + 3NO_2 + 4Cl^- \rightarrow HCI + [AuCl_4]^-\text{………………………….(13)}$$
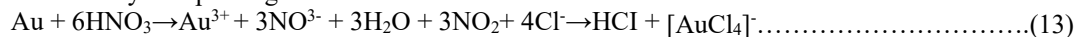
3. Materials and Methods
3.1 Materials
The materials that were required for this study included: PCBs containment gadgets, balance, pliers, nitric acid, magnesium nitrate, magnetic stirrers, cloth bag, graphite rod, voltage source, stop watch, distilled water, meter and voltmeter and Aqua Regia. In addition, a 250 mL flask, balance, universal indicator, filter paper, stop watch and lime. Sodium cyanide (NaCN), sodium nitrate ($NaNO_3$), silver nitrate ($AgNO_3$), oxalic acid, nitric acid and hydrochloric acid were also required.

3.2 Methods
3.2.1 Dissolution of PCBs to determine metal compositions in a PCB extract
A 5kg mass of PCBs was weighed and cut into small pieces. Afterwards, 4L of distilled water were mixed with 400 mL nitric acid (HNO_3). The PCBs were placed in a cloth bag and a graphite rode was inserted in the bag. A current of up to 12A, voltage of up to 15V was passed through while a stop watch was used to take time taken by the process to reach maximum current level. The stop watch was stopped when the maximum current was achieved. The remains in the bag were taken out, dried and weighed and the weight loss in the scrap was calculated. The current, voltage and time were measured in order to calculate the total energy consumed for dissolution. The experiment was repeated twice.

3.2.2 Recovery of gold using cyanide leaching then precipitation
The experiment was done to recover the metals from solution through cyanide leaching and precipitation.

3.2.2.1 Cyanide leaching
A sample of 100 mL of the 99g remaining solution of PCBs was put in a 250 mL flask and then pulped. Afterwards, 0.5g of lime was added to achieve a pulp pH of 10.5, followed by 1.54g of sodium cyanide. Mechanical agitation was carried out for 24 hours, with regular withdrawal of solution samples to monitor the dissolution rate and reagent

consumption. At the end of the leach period, the pulp was filtered and the solution was taken for precipitation. The amount of sodium cyanide added was 1.54g with a conversion factor of 0.77.

3.2.2.2 Zinc precipitation

A sample containing 100 mL of the pregnant leach solution at pH of 11.9 was placed in a beaker. The free oxygen in the leach liquor was removed by heating the solution for an hour without boiling. Afterwards, 10g zinc powder was added to the leach liquor in order to allow the gold to precipitate out of solution. The mixture was left for 3 hours in order to precipitate the maximum amount of gold from the pregnant leach solution. The precipitation efficiency was improved by addition of a few drops of sodium (II) ions in the form of sodium nitrate. The precipitate was filtered out of solution. The precipitate was washed by hydrochloric solution to remove residual zinc with a ratio of HCl to H_2O of 1:10.

3.3 Recovery of metals using Aqua Regia leaching then precipitation
3.3.1 Leaching

A sample containing 100 mL volume of 1M nitric acid was mixed with 300 mL of HCl in a beaker under a fume hood. The mixture was boiled until the colorless liquid changed color to lime. The hot liquid was then added to 100 mL and mixture was then boiled until it changed to a thick paste. 100 mL HCl diluted 1:1 with water was added to the paste and boiled again for 30 minutes. The solution was allowed to stand for 2 hours and then filtered and leach pregnant solution was then taken for precipitation.

3.3.2 Precipitation with sodium metabisulphite

A sample containing 100 mL of sodium metabisulphite solution was diluted with 20 mL of distilled water in order to remove the excess HNO_3 and boiled for 20 minutes. An excess amount of 15g sodium metabisulphite was added to the solution while stirring until dissolution of the precipitant had stopped. Additional sodium metabisulphite was added and a white cloud produced which was an indication of more gold precipitating. The mixture was left to cool and mixed in order to precipitate all the gold out of solution. The solution was decanted and the residue which looks like black mud was smelted with borax flux at 1200 °C in a furnace.

3.3.3 Precipitation with ferrous sulphate

A sample consisting 10g of ferrous sulphate powder was added to 100 mL of the leach pregnant solution. A sample containing 2mL oxalic acid was added to the solution to enhance the precipitation process. A precipitate was formed and more ferrous sulphate was added until sulphur dioxide odor was produced which was an indication that precipitation was complete. The solution was allowed to stand overnight so all the gold can be settled at the bottom. The upper precipitant was then filtered and melted with flux.

4. Results and Analyses
4.1 Dissolution of PCBs to determine metal compositions and energy usage

The e-waste was dissolved to determine the metal composition. Reactions which took place are described by Equations 14-18. A summary of the amount of metal extracted and the energy requirements are shown in Table 4. The average metal composition was 38.7%

$$HNO_3 \rightarrow H^+ + NO_3^- \quad \text{...} (14)$$
$$NaNO_3 \rightarrow Na^+ + NO_3^- \quad \text{..} (15)$$
$$Na^+ + H_2O \rightarrow NaOH + H_2 \quad \text{..} (16)$$
$$H_2O \rightarrow H^+ + OH^- \quad \text{...} (17)$$
$$H_2O + 2OH^- \rightarrow \tfrac{1}{2} O_2 + H^+ \quad \text{..} (18)$$
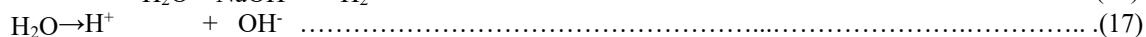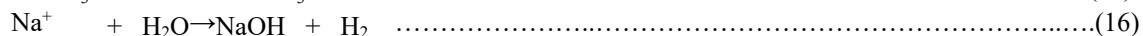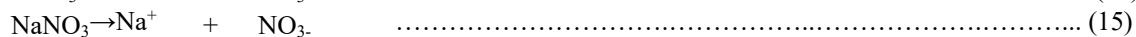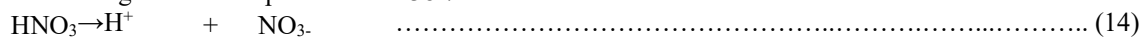
Table 4. Metal recovery from the e-waste and the energy requirements

Exp number	Initial mass of scrap (g)	Volts (V)	Amps (V)	Time (min)	Power(Kwhr)	Metal content (%)

| 1 | 160.0 | 7.2 | 8.3 | 295 | 0.30 | 38.1 |
| 2 | 158.0 | 8.3 | 9.8 | 225 | 0.31 | 39.2 |

4.2 Cyanide leaching and precipitation with zinc and aluminum

The leaching process was allowed a longer residence time of 24 hours, Zn powder demonstrated to be an enhanced precipitating agent than Al (see Figure 1). Zinc powder precipitated 99.0% of the gold whereas aluminum powder precipitated 51.5% of the gold at pH 11.8 (see Figure 1). When the pH was adjusted to 12.4 by adding sodium carbonate, there was a remarkable increase in the amount of gold precipitated by Al by 60% (see Figure 1). The gold precipitated by Zn was unaffected by increasing the pH. A hydroxide layer is formed on the surface of the Al which passivates the precipitation process on lower pH.
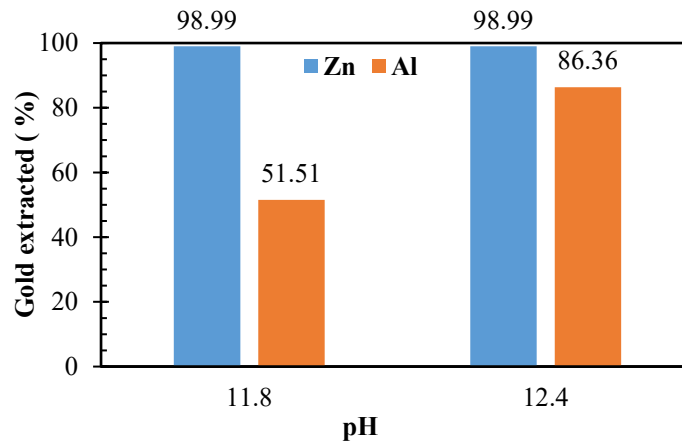

Figure 1. Gold extracted through cyanidation using zinc and aluminum precipitant

4.4 Gold leaching with Aqua Regia and precipitants

Various precipitants were used to recover gold which included $Na_2S_2O_5$, ferrous sulphate, $NaBH_4$ on Zn and $NaBH_4$ on Al at pH of 12.4. The highest gold recovery of 91.9% was obtained when $NaBH_4$ on Zn was used as a precipitant, followed by $Na_2S_2O_5$ with an 82.6% recovery, then $NaBH_4$ on Al with a 62.5% recovery then ferrous sulphate with a 39.8% recovery (see Figure 2). Thiosulphate leaching sodium borohydride ($NaBH_4$) on Zn proved to be a better precipitating agent than $NaBH_4$ on Al. The cause for the lower recovery was centered on passivation of Al on lower pH of <13 by forming a hydroxide layer. Thiosulphate dissolved less gold than cyanide into solution. The lower recovery was due to lower residence times, passivation by cupric sulphide formed by the reaction between cupric ions, thiosulphate ions and the oxidation of cuprous thiosulphate complex ions.
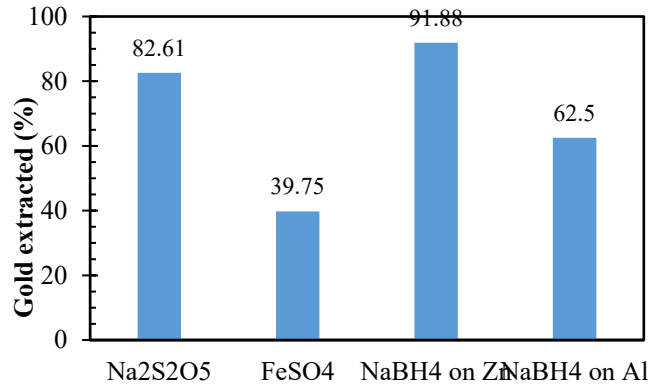
Figure 2. Amount of gold extracted using Aqua Regia and various precipitants

5. Process Design

The process design highlighted the material and energy balances giving a full description of the process for extracting gold from e-waste as indicated in Figure 3.

5.1 Material balances

An overall material balance was used to determine the quantities of raw materials required and products produced using the conversation of mass. The general conservation equation for the process system can be written as represented by Equation 19.

Input + Generation - Output - Consumption = Accumulation…………………………….……..(19)

The overall mass balance is a material balance calculated over the whole process. In order to match an annual feed of 20 000 tons, the laboratory experiment have a scaling factor of $125exp^6$. The results for the mass balances are shown in Table 5 for an annual production.

Table 5. Annual scaling quantities for e-waste value addition

Input / year	Quantity (tons)	Output /year	Quantity (tons)
E-waste	20000.00	Cu	1875.00
H_2SO_4	2500.00	Au	1.35
$Na_2S_3O_2$	1250.00	Ag	875.00
Cyanide	625.00		
NaCI	1250.00		
Zn	125.00		
CI	250.00		

5.2 Energy Balances

According to the First Law of Thermodynamics the conservation of energy is described by the Equation 20.

Energy out = Energy in + Generation - Consumption - Accumulation ………………………….(20)

For the electrical equipment, power was calculated from the relationship between the voltage across the equipment and electrical current through them. The calculated power consumed is shown in Table 6 and was calculated in accordance to Equation 21.

Energy = Voltage x Current x Time …………………………………………………………..(21)

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Table 6. Power consumption summary

Equipment	Power Requirements (KWh)
Shredder	125 000
Crushers	75 220
Electrostatic separator	2 000
Magnetic separator	202
Concentrator	400
Total	202 822

The recovering of metals from e-waste has its own energy balance and so are the leaching, precipitation and the generation process. Following the conservation of energy, Equation 22 applies. Based on the Principle of Conservation of Energy and taking a basis of calculation of per hour.

$$\Delta H + \Delta K + \Delta P = Q + W \ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(22)$$

Assuming that at steady state ($\Delta K=0$), no change in elevation ($\Delta P=0$). Total energy input=202 822kWh + Q = ΔH_{tot}
Enthalpy change of reaction = Enthalpy change of formation of products - Enthalpy change of formation of reactants.

$$\Delta H_{tot} \text{ (reaction)} \ = \ \Delta H_f(Cu) + \Delta H_f(Pb)+\Delta H_f(Ag)+\Delta H_f(Au)-(\Delta H_f(Cu(NO_3)_2) +$$

$$\Delta H_f(Pb(NO_3)_2) + \Delta H_f(Ag(NO_3)) + \ f(Au(OH)_3)) = 3838.8 \text{ kJ/kg (Crushed PCBs)}\dots\dots\dots\dots.\dots\dots..(23)$$

5.3 Process description
The process description highlighted the process taking place during e-waste value addition which included PCBs sampling, dismantling, separation techniques and cyanide recovery.

5.3.1 PCBs sampling and shredding
The process involves shredding of the PCBs into 5.0 x 5.0 cm plates followed by crushing into an average diameter of 1.5 mm. This is done so as to increase the surface area when methods such as leaching are carried out. The process of PCBs dismantling is particle size reduction.

5.3.2 Separation techniques of the PCBs
Three separation techniques of PCBs particles into their different components based on their properties were employed to get a high percentage of the separation yield.

5.3.2.1 Electrostatic separation
An electrostatic separator is a device for separating particles by mass in a low energy charged beam. Electrostatic charges are used to attract or repel crushed PCBs material. The same electrostatic separator can use force of attraction to sort the PCBs particles, conducting PCBs particles stick to an oppositely charged object such as a metal drum, thereby separating them from the particle mixture. The same electrostatic separator uses repelling force to change the trajectory of falling objects to sort them into different places. This way, when a mixture of PCBs particles falls past a repelling object, the particles with the correct charge fall away from the other particles when they are repelled by the similarly charged object.

5.3.2.2 Eddy current separation
An eddy current separator uses a powerful magnetic field to separate non-ferrous metals from PCBs after all ferrous metals have been removed by arrangement of magnets. The device uses eddy currents to effect the separation. The eddy current separator is applied to a conveyor belt carrying a thin layer of mixed e-waste. At the end of the

conveyor belt is an eddy current rotor. Nonferrous metals are thrown forward from the belt into a product bin, while non-metals simply fall off the belt due to gravity.
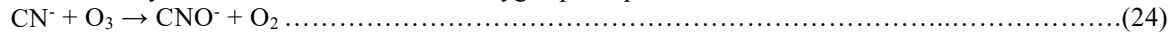
5.3.2.3 Magnetic separation
Magnetic separation is a process in which magnetically prone materials are extracted from a mixture using a magnetic force. During magnetic separation crushed PCBs material are fed onto a moving belt which passed underneath two pairs of electromagnets. The first pair of electromagnets is weakly magnetized and serves to draw off any iron particles present.
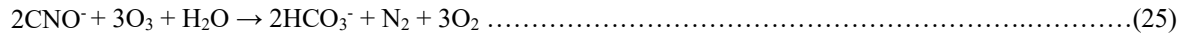
5.4 Cyanide absorption
Activated carbon (C) is a form of carbon processed to with small, low-volume pores that increase the surface area available for CN adsorption and has a surface area of 400-500 m^2. Complete cyanide removal is at ambient temperatures by passing pre-aerated solutions of cyanide at pH 8-9. The efficiency of the activated carbon is enhanced by adding cupric ions to the solution. This behavior is explained by the preferential adsorption of $Cu(CN)_{2-}$ over CN^- on activated carbon. The activated carbon absorbed was between 7.5-7.8 g CN^-/kg.C.

5.5 Cyanide ozone oxidation
Ozone oxidation of cyanide was used for treating cyanide. Cyanide oxidation with ozone is a two-step reaction similar to alkaline chlorination. Ozone is a strong oxidizing agent with an electrode potential of +1.24. Cyanide is oxidized to cyanate, with ozone reduced to oxygen per Equation 24.
$$CN^- + O_3 \rightarrow CNO^- + O_2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(24)$$
Then cyanate is hydrolyzed, in the presence of excess ozone, to bicarbonate and nitrogen and oxidized per Equation 25.
$$2CNO^- + 3O_3 + H_2O \rightarrow 2HCO_3^- + N_2 + 3O_2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(25)$$
The reaction time for complete cyanide oxidation is rapid with 10-30 minutes' retention times. The second-stage reaction is slower than the first-stage reaction. The reaction is carried out in the pH range of 10-12 where the reaction rate is constant. Temperature does not influence the reaction rate significantly. The metal cyanide complexes of cadmium, copper, nickel, zinc and silver are destroyed with ozone. The presence of copper and nickel provide a catalytic effect in the stage one reaction but can reduce the rate of the stage two reactions. Iron, gold and cobalt complexes are very stable and are partially oxidized. Ultraviolet light in combination with ozone can provide complete oxidation of these complexes. UV oxidation is limited to clear solutions since waste streams are passed through a light-transmitting chamber and exposed to intense UV light. UV in combination with ozone results in the formation of OH• radicals which are strong oxidizing agents capable of oxidizing iron cyanide complexes. Suitable light sources emit in the range of 200-280 nanometers are required. Ozone will absorb in this band. Figure 3 gives a summary of stages in gold recovery from e-waste.

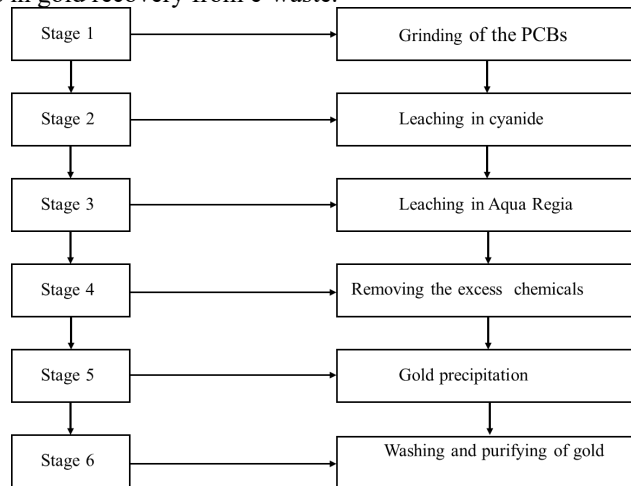| Stage 1 | → | Grinding of the PCBs |
Stage 2	→	Leaching in cyanide
Stage 3	→	Leaching in Aqua Regia
Stage 4	→	Removing the excess chemicals
Stage 5	→	Gold precipitation
Stage 6	→	Washing and purifying of gold

Figure 3. Stages in gold recovery from e-waste

5.5 Process improvement
The study managed to come with an improvement in the designing of the process on the addition of the electrostatic separator will increase the purity levels of recovered metals. Another improvement is the use of activated carbon together with ozone in the treating of cyanide. The combined use of these two techniques ensured that a contaminant free gold is produced and also protecting the environment against the negative impacts of cyanide.

6. Economic Analyses
For the commercial success of the gold recovery from e-waste, estimation of manufacturing unit cost and calculation of annual net cash flows were done to determine the economic feasibility of the study using profitability estimators such as payback period, breakeven point and return on investment.

6.1 Capital investment
Capital investment consists of fixed capital and working capital required for the process is USD 15 000 000.00. The capital investment is the sum of fixed capital and working capital. The fixed capital cost is the money needed to supply the necessary manufacturing and plant facilities. Capital investment comprises of direct and indirect costs. The direct costs and indirect costs for the methods are given in Tables 7 and 8 respectively, with Table 9 showing the equipment costs.

Table 7. Direct costs for the e-waste recycling process

Description	Cost (USD)
Equipment	3 590 000.00
Land	1 500 000.00
Buildings	1 500 000.00
Vehicles	2 000 000.00
Instrumentation and control	410 000.00
Piping and electrical equipment	1 000 000.00
Services facilities	1 000 000.00
Total	11 000 000.00

Table 8. Indirect costs for e-waste recycling

Indirect costs	Cost (USD)
Engineering and supervision	8 00 000.00
Construction expenses	1 700 000.00
Contingency	5 00 000.00
Total	3 000 000.00

Fixed capital is a sum of direct costs and indirect costs and this gives USD 14 000 000.00.

Table 9. Summary of equipment cost

Equipment	Number required	Cost (USD)
Filter	10	1400 000.00
Dryer	8	200 000.00
Conveyor belt	20	30 000.00
Vibrating feeder	10	60 000.00
Reactor	8	1600 000.00
Screening machine	7	50 000.00
Eddy current separator	2	80 000.00
Magnetic separator	2	70 000.00
Electrostatic separator	2	80 000.00
Total		3 590 000.00

Working capital is needed for the operation of the plant. The working capital for the recycling process is USD 1 000 000.00. Capital investment is the total sum of fixed capital and working capital and this gives a total of USD 10 500 000.00. Sales represent the revenue of the e-waste recycling process.

6.2 Sales calculations
The feed stock of the process is 20 000 tons / yr. The summary of metal prices is given in Table 10. Total sales of metals is USD 24 867 155.00.

Table 10. Metal prices (www.mining.com/market-data)

Metal	Price (USD)	Amount recovered (%) (year/oz. exp6)	Total (USD)
Au	380.0/oz. (29.2% purity)	66.1	16 500 051.00
Ag	20.0/oz. (15.0% purity)	0.05	8 237 012.00
Cu	3.2/oz. (60.0% purity)	30.9	1 300 920.00

6.3 Total costs
Total costs are the costs for operating the e-waste plant and selling the gold. Total cost comprises manufacturing costs and general expenses and are calculated as represented by Equation 26 on annual basis.
Total costs = Manufacturing costs + General expenses + Plant overheads………………………………….. (26)
Manufacturing costs are divided into direct/variable and indirect/fixed costs. A summary of the direct manufacturing costs is given in Table 11.

Table 11. Direct manufacturing costs

Component description	Cost (USD)
Catalyst	1 00 000.00
Transport expenses	900 000.00
Operating labor	1 500 000.00
Power and plant maintenance	2 500 000.00
Total	5 000 000.00

Fixed manufacturing costs are expenses which remain constant from year to year and do not change with production rate (Table 12). These included depreciation, loan interests and insurance. Depreciation is as a loss of value of fixed assets. Equipment and vehicles are estimated to have a useful life of five years, a salvage value of USD 559 000.00 and is calculated as indicated by Equation 27.

$$D = (V - V_s) / t_u = 5\ 590\ 000 - 559\ 000)/5 = USD\ 1\ 006\ 200.00 \dots\dots\dots(27)$$

Where D is the depreciation, V is the initial value of the assets, V_s is salvage value and t_u is the useful life.

Table 12. Fixed manufacturing costs

Description	Cost (USD)
Depreciation	1 006 200.00
Insurance	1 500 000.00
Rentals	693 800.00
Total fixed manufacturing costs	3 200 000.00

Table 13. Total manufacturing costs

Item	Cost (USD)
Direct cost	5 000 000.00
Indirect cost	3 200 000.00
Plant overheads	1 200 000.00
Total manufacturing costs	8 400 000.00

General expenses were estimated to be USD 2 000 000.00 and the total production costs are a sum of the manufacturing costs and the general expenses which are USD 10 400 000.00.

6.4 Profitability evaluation

The profitability evaluation for establishing an e-waste processing plant was done using profit, return on investment and payback period as indicated in Table 14.

Table 14. Summary of profitability analysis

Profitability measure	Formulae	Calculation	Value
Profit	Sales - Total product cost	USD24 867 155.00 - USD 10 400 000.00	USD14 467 155.00
Return on investment	Profit /Investment	USD 14 467 155.00/ USD 1500 000.00	0.96
Payback period	Investment / Profit	USD 1 500 000.00 / USD 14 467 155.00	1.04 years

6.5 Break even analysis

Break even analysis is used to determine the point at which revenue received equals the costs associated with receiving the revenue. The break-even for e-waste study was calculated as indicated in Equation 28. The breakeven chart is shown in Figure 4.

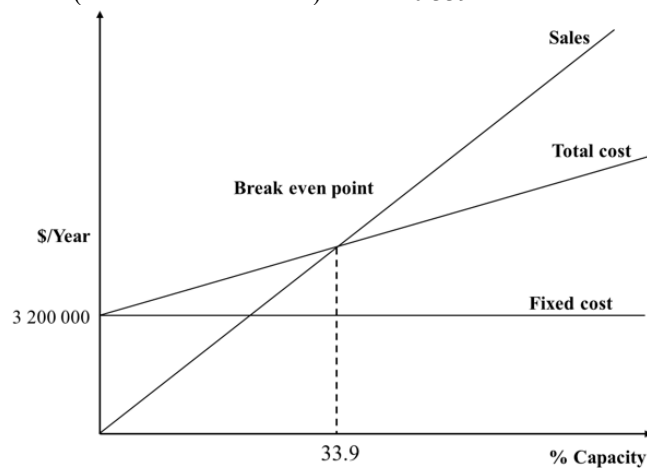Break even   = Fixed costs / (Sales - Variable costs)   = 0.339………………………………………..(28)

Figure 4. Break even chart for gold recovery from e-waste

7. Conclusion

Gold can be recovered from e-waste as a value addition strategy. From this study, 38.9% was recovered from the electronic waste mainly composed of the PCBs. Physical separation and hydrometallurgical processing of the e-waste using cyanidation and zinc precipitation resulted in a gold yield of 99.0 % at pH of 11.8 and 12.4. An economic evaluation of gold recovery for an e-waste input of 20 000 tons/year indicated capital investment requirements of USD 15 million. A return of investment of 0.96 was realized, with a payback period of 1.04 years and a breakeven of 33.9% of throughput capacity.

Acknowledgements

References

Awasthi, A. K., Wang, M., Wang, Z., et al., E-waste management in India: A mini-review. *Waste Management and Research*, vol. 36, no. 5, pp. 408–414, 2018.

Baidya, R., Debnath, B., Ghosh, S. K., Analysis of E-waste supply chain framework in India using the analytic hierarchy process. In: Sadhan KG (ed.) *Waste Management and Resource Efficiency*. Singapore: Springer, pp.867–878, 2019.

Baidya, R., Debnath, B., Ghosh, S. K., et al., Supply chain analysis of e-waste processing plants in developing countries. *Waste Management and Research*, vol. 38, no. 2, pp. 173–183, 2020.

Baldé, C. P., Forti, V., Gray, V., et al., *The Global E-waste Monitor 2017*: Quantities, Flows and Resources. Bonn, Geneva, and Vienna: United Nations University, International Telecommunication Union, and International Solid Waste Association, 2017.

Bisschop, L., Is it all going to waste? Illegal transports of e-waste in a European trade hub. *Crime Law Society Change*, vol. 58, pp. 221-249, 2012.

Corsini, F., Rizzi, F., Gusmerotti, N. M., Frey, M., Extended Producer Responsibility and the Evolution of Sustainable Specializations: Evidences from the e-Waste Sector. *Business Strategy and the Environment*, 2013.

Ejiogu, A. R., E-waste economics: a Nigerian perspective. *Management of Environmental Quality: An International Journal*, vol. 24, no. 2, pp. 199-213. European Commission, 2011.

Herat, S., Agamuthu, P., E-waste: a problem or an opportunity? Review of issues, challenges and solutions in Asian countries. *Waste Management and Research*, vol. 30, no. 11, pp. 1113-1129, 2012.

Kang, H. Y., Schoenung, J. M., Electronic waste recycling: a review of U.S. infrastructure and technology options. *Resources, Conservation and Recycling*, vol. 45, no. 4, pp. 368- 400, 2005.

Kraan, S., Nijssen, C., Dols, N., Huijbregts, C., *Is what you see, what you get?* European Union Network for the Implementation and Enforcement of Environmental Law, 2006.

Lepawsky, J., McNabb, C., Mapping international flows of electronic waste. *The Canadian Geographer*, vol. 54, no. 2, pp. 177-195, 2010.

Osibanjo, O., Rae, I., Scheringer, M., Have, C., Chapter 6: Chemicals and Waste. In: Ullstein, B., Mattos, H. de, Hawkins, C., McMullen, C.P., Jabbour, J., Scharlemann, J. (Eds*.). Global Environment Outlook-5. Environment for the future we want*, 168-192, 2012.

Park, Y. J., Fray, D. J., Recovery of high purity precious metals from printed circuit boards. *Journal of Hazardous Materials*, vol. 164, no. 2-3, pp. 1152-1158, 2009.

Robinson, B. H., E-waste: An assessment of global production and environmental impacts. *Science of the Total Environment*, vol. 408, pp. 183-191, 2009.

Schluep, M., Hagelüken, C., Meskers, C. E. M., Magalini, F., Wang, F., Müller, E., Kuehr, R., Maurer, C., Sonnemann, G., *Market potential of innovative e-waste recycling technologies in developing countries*, 2009.

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