Gold Recovery from PCBs by Acetic Acid and Hydrogen Peroxide

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by

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Report Submitted to:

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Abstract:

E-waste processing in Agbogbloshie, Ghana, is simple and harmful to people and the environment. Since waste PCBs have high value and are cheaply sold, I reviewed seven methods to recover gold from PCBs, chose, and optimized the safest one: acetic acid and hydrogen peroxide. I optimized this method by studying the concentrations of different chemicals, volume ratio, and time. If Agbogbloshie's society chose to process it, our primary recommendation is to adopt this method because of its high safety compared to the other methods.

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Chapter 1: Introduction

E-waste has been an increasing issue in the whole world due to electronics' mass production and consumption. Countries have been regulating the processing of e-waste; therefore, businesses have been exporting their waste to countries with fewer regulations. Ghana is one of them. The e-waste in Ghana has been an issue that the people are affected by in a negative way. The people in the most prominent e-waste location in Agbogbloshie, Ghana, have been burning insulation polymers to recover the copper from copper. E-waste is an economic resource that they can benefit from, and it is in an enormous volume there. People could make much more money out of the e-waste if they focused on valuable objects. One of those is printed circuit boards. Our partners in Ghana noticed that people from other countries have been purchasing PCBs at a meager price from workers in Agbogbloshie.

Meanwhile, if the PCBs are processed there, recovering metals like gold can bring much more value. The gold recovery process can be done chemically by hydrometallurgical leaching. This project proposes a method to recover gold from PCBs, creating a sustainable e-waste process center in Agbogbloshie.

In our project, the ME-ECE MQP group and I could develop a process to help our partners in Ghana. My role in this project was to understand gold beneficiation processes in Ghana and the e-waste processing conundrum. Besides, to propose a safe method of gold recovery from electronic waste that inexperienced person may do. We have done this project with our partners, the workers in Agbogbloshie in Ghana, to learn the current limitations and recycling practices through Mr. Boye. Our goal was to propose a step forward in e-waste processing that helps the community.

Our goal in this project is to find an efficient and safe method to extract gold from the PCBs that lowers the risks toward humans and the environment. The selected chemical procedure must be safe that a person without a scientific background can perform it at the e-waste location Agbogbloshie, Ghana, with minimal supervision. Then, optimize the procedure by studying different factors and their effects to recover the most gold out of the PCBs.

To accomplish our goals and satisfy our partners' needs, many related topics must be studied and reviewed, i.e., e-waste definition, e-waste processes, e-waste effects on society and nature. Furthermore, I familiarized myself with African cultures, history, and their views on nature. That is by studying and understanding these topics to design the project as our partners would like. I could develop an efficient process that satisfies their requests by prioritizing and respecting their culture.

Chapter 2: Background:

This chapter explains what e-waste is, the obstacle of e-waste, what is being done globally with e-waste, and its processing impact on living creatures and nature, and the importance of nature in African cultures. Understanding these topics in the context of e-waste allows connecting the dots of the project with the bigger picture.

2.1 What is E-waste?

The first step toward this project accomplishment is understanding what we are working with: E-waste. There are two definitions of E-waste: general and specific. The general one is every electronic or electric device near or at the end of its useful life. The second definition is the electronic devices that have potential value and can be reused, refurbished, or recycled (International Cooperation, 2021). As technology gets better and improved, new devices are being purchased to obtain better ones. These compulsive purchases have resulted in massive amounts of e-waste. The best examples in our lives are personal devices like laptops and cell phones. People who can afford new devices change theirs' usual from 2 to 3 years. When these devices are considered e-waste, the most precious part of them is the printed circuit board. Printed circuit boards are used to connect parts inside a device, such as CPU and RAM. It can be made from plastic with metals like gold and copper to connect the elements on it. In sum, what e-waste means is disposed of electronic devices and machines that can be dissembled, processed, and economic value can be got out of (International Cooperation, 2021). Therefore, because we know that Africa has a rising issue of e-waste disposal and processing and how it is causing too many issues to the environment and people (Yeung, 2019), developing a process that gets the most value out of e-waste can be helpful; especially if it is safe for users and the environment.

2.2 E-waste recycling in Africa:

The African economy is skyrocketing, which leads to an increase in the import of electronics. More importantly, developed countries have been sending their electronic waste to countries in Africa that accept their waste for money. All these reasons result in high e-waste in Africa. For example, only in one day, about 500 containers of e-waste like computers and televisions arrived in Nigeria. Some of them are being mislabeled, so they get accepted by Nigerian customs (Okorhi, Omotor, & Aderemi, 2019). However, the lack of laws and treaties regarding e-waste results in a release of hazardous substances, which puts people and the environment at health risk. There is a lack of safety protocols, legislations, and regulations. As in 2014, only Cameroon and Nigeria have passed laws against e-waste (Baldé, 2014). That is because much of the e-waste comes can be hazardous. However, people in Africa know the value of e-waste and its economic potential. It is not logical to force them to stop actions like processing cables to get the copper inside it without a safer alternative.

Electronic waste in Agbogbloshie, Ghana, is much more valuable to be recycled into raw material. What is done now is the recycling process is by burning the plastic on wires to get the copper out. However, this process is not effective with other materials such as gold and silver. Nevertheless, even if it works with them, it produces too many toxic gases. So, what needs to be done is to find a process that recycles valuable metals efficiently and environmentally friendly to avoid informal processing consequences. Many countries have been trying to accomplish more sustainable and regulated processing, like Romania, China, and Nigeria.

In Nigeria, efforts were put to make the e-waste business to make it sustainable and improved. E-waste has been flowing into Nigeria at a high rate. As a result, the Nigerian government saw it as a chance for socioeconomic development by encouraging recycling processes. However, many of the e-waste containers they receive are not safe for processing in their country without proper and technologically advanced methods. 47 containers out of 127 were sent back to their origin because of containing hazardous waste in a one-day inspection. Nevertheless, the inspection process is complicated, and many containers may pass (Okorhi, Omotor, & Aderemi, 2019). Nonetheless, most of the cleared e-waste is recycled in the informal sector, making it more dangerous because the people who work in it are not professional.

In Ghana, for instance, e-waste is unregulated. Unregulated e-waste processing is highly hazardous since some e-waste parts may include radioactive elements. Also, the people in Ghana obtain aluminum from electronic waste to produce equipment like cooking pots. On the other hand, the process they use is toxic and hurts the environment by its dark smoke (Asante, et al., 2012). The techniques include mechanical shredding and the use of open flames to plastics which release undesired gases. Although these obstacles may emerge from recent e-waste processing, it is impossible to stop those people from hurting themselves and the environment by the metal recovery by burning without a valuable alternative, since e-waste provides a financial resource to many people. Hence, the need for a developmental project that provides a financially fair and environmentally friendly existence.

Figure 1, A Ghanaian man standing in an e-waste center surrounded by the burning of wastes. (The Guardian Gallery, 2014).

There is a vast e-waste recycling center in Agbogbloshie, Ghana, which is polluting the environment. Our Ghanaian partners informed us that they have been selling valuable parts of this waste, such as printed circuit boards that contain gold for pennies on the dollar, while they can get much more profit if they could process these parts by themselves.

The electronic waste arrives in Ghana at the Port of Tema, and then it is sent to the Agbogbloshie dump. Most of this waste is from Western Europe and the USA (Yeung, 2019). 51% of the E-waste is being shipped to countries that are not members of the Organization for Economic Co-operation and Development, which is illegal (Chan, 2014). Besides, 70-85% of the waste sent to Ghana is non-repairable, and the e-waste can be traced to be one single source according to The Basel Action Network (Burrell, 2016). The European businesses avoid any OECD sanctions regarding their waste processing in Europe by exporting it. The OECD aims to "shape policies in the world that foster prosperity, equality, opportunity and well-being for all" (OECD, ND). Shipped e-waste items are rarely developed or used in projects that help the local communities. That is because 25% to 75% of the devices that Africa receives are useless (Chan, 2014). Electronic waste is being sent to Ghana because it will cost the west vast amounts of money to recycle it in their countries formally. Therefore, they export it to developing countries where it can be processed and recycled illegally and cheaply (Cho, 2018). Also, infrastructure and safety protocols are not regulated or observed by any institution. Rapid changes in Africa, like high the appearance of this source of money, e-waste, by simple actions like burning some of them or selling to a merchant, must affect the people's lives and cultures. By changes, I mean how the appearance of e-waste can improve the people's living situations, their interaction between local workers and international companies affected them, and how they may be forced to leave some of their cultures due to a financial issue. Nature, for instance, is one of the most important aspects of African cultures. Besides, most of the previously mentioned changes are directly related to nature which may not be respectful to their cultures. To avoid that, I studied some of the anthropology of nature in Africa, which can help to familiarize the problem.

2.3 Anthropology of Nature in African Cultures:

We, as humans, have changed the way we look at nature. Since the first day of human consciousness, humans' and nature's relationship was love, admiration, and thinking about nature as sacred grace (Asante & Mazama, 2009). This holy relationship has changed in the past couple of centuries. Despite all its positive consequences, the Industrial Revolution made us extract natural resources like trees, coal, and metals as much as possible to produce massively. Besides, the imperialist raising in the 19th and 20th centuries targeted African countries to export goods. As a result of that, we degrade our vision of nature from being sacred to mere objects. If naturalist philosophers who appreciate nature like Thoreau were in power now, their statements could even degrade from being human after the Industrial Revolution. Those who treat nature as a resource just like how they de-spiritualized it. Thoreau wrote his book, Walden, after reflecting on the degrading human-nature relationship (Alfred, 2010). Nature would be much better if we considered the other consequences of the modern vision on nature, e.g., air pollution and throwing waste into nature. Working with the post-industrialist philosophy can be selfish not only for the people who do not control decisions that destroy the environment and are pushed by profit, but also for animals, humans, and all creatures of the future. We are aware of global injustice and capitalism's adverse outcomes, and global warming and pollution. We must make the situation better for both people and the environment, not one over the other.

Nature is essential in African beliefs and cultures. In West Africa, due to the rain forests and rivers, the most worshiped gods are of nature (Asante & Mazama, 2009). Therefore, the African cultures see the world as an energy, life, and harmony source, a connection between the spiritual and the human world. This sacredness of nature is represented in various forms. For instance, many trees around West Africa are appreciated and respected. Trees like Baobabs and Iroko have fences and pots around them. Aspects like spirits of nature and divinities are widely shared in ancient African culture. Even animals are well respected in Africa. Snakes, for instance, have temples in Benin, and people bow to them as a way of respect. It is stated that African believe that it is necessary to understand and respect nature because of humans and nature's interactions, the most common experience of one's life (Asante & Mazama, 2009). Hence, other than sustainability, safety, and caring for the environment, nature is already sacred in African culture. As a result, I prioritized environmental safety to select chemical reagents in PCBs' processing to choose the least harmful.

2.4 Processing of PCBs:

To process the PCBs, we ended up with a method of three steps to recover gold. The process has three stages: Shredding, grinding, chemical recovery. Shredding reduces the size of the PCB from full size to smaller pieces to ease the grinding process. Grinding parts is a step where the shredded are minimized to minute parts.

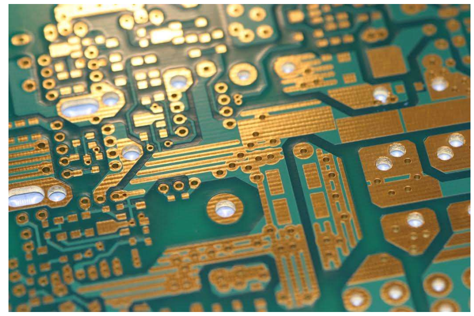


Figure 2, the picture shows PCB and gold within it. (Dzone, 2016)

The grinding process may increase the chemical processing efficiency of gold recovery because of the increase of the surface area.

To develop a whole process of gold recovery, beginning with full printed circuit boards to having the gold separated from them, our colleagues in the ME and ECE project built a machine that pulverizes and crushes PCBs down to the desired size safely, Figure 3. The grinded PCBs become subjects of my part of the chemical leaching.

Figure 3, the grinder that our colleagues built to process PCBs.

The chemical processing part is where components of PCBs may separate. There are many forms of metal separation procedures, pyrometallurgy, electrometallurgy, and hydrometallurgy, which I will focus on. It is a process to recover metals using liquids. Modern hydrometallurgy is a process that was invented in 1887 with two methods; one of them is the cyanidation for gold ores (Habashi, 2005). Hydrometallurgy is a multistep process that is leaching, filtration, and precipitation.

On the other hand, pyrometallurgy uses heat to separate metals, and electrometallurgy uses electricity. Figure 4 shows the cyanidation process of gold hydrometallurgy, which can be used for secondary sources of gold. As shown previously, there are many alternative chemical combinations to recover gold from PCBs that are much less toxic. Knowing that is possible, it is more helpful to look at other countries' methods of dealing with e-waste. This can explain what is happening worldwide and what can help those who work directly with e-waste.

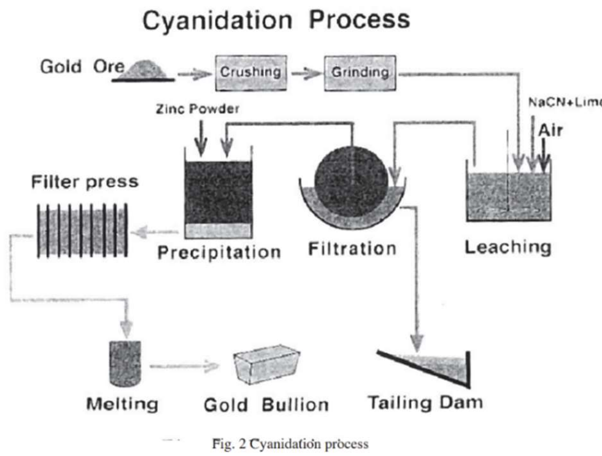


Figure 4, The hydrometallurgy process of recovering gold from ores using Cyanide. (Japan Oil, Gas and Metals National Corporation, 2005).

2.4 E-waste processing in the world:

Our project is not the first of its kind. Many countries around the world have been processing e-waste. Also, most of them have been struggling with informal processing and its adverse effects like pollution. China, India, and Romania are examples of these countries. The informal processing they are trying to manage is done by individuals without any supervision and does not follow any safety requirements.

Regardless of China's and India's high pace in industrial development, both countries have no regulations about electronic waste processing. Meanwhile, the consumption of electronics has been massively increasing. As a result, mountains of e-waste are collected and unused. Also, China used to accept 70% of the electronic waste exported worldwide, although processing limitation (Cho, 2018). However, they stopped doing so in January 2018 due to concerns for their environment. The Chinese government ban on e-waste import has caused obstacles in many countries around the world with recycling. Their new policy has led to an increase in the waste being sent to developing countries like Ghana. Fifty million tons are being disposed of every year (Yeung, 2019).

China has started to regulate E-waste stores and promote the principles of "Reduce, reuse, recycle" (Lines, Garside, Sinha, & Irina, 2016). However, these did not affect other than the formal e-waste management locations. Regulations of the Chinese government on e-waste worked inversely since the legal channels of e-waste processing were facing strict environmental and health standards. In contrast, the informal ones did not have any. China's regulation attempted to westernize their e-waste industry. The western style they adopted has failed because it was not made to the Chinese market's reality (Lines, Garside, Sinha, & Irina, 2016). This reality is that informal stations are cheaper than formal competitors as they do not have many requirements. However, formal processors are more prominent to governments because of their obedience to regulation. India, like China, tried to enforce laws against informal e-waste channels. These informal channels process 95% of the processed e-waste in India. India has tried to enforce a western recycling system that formalizes informal processers and regulates their processes. However, it was enforced and succeed only on large-scale informal processers.

Romania is working on e-waste management as well. There are 2,000 waste processing centers in Romania to recycle and recover e-waste. They face pressures from the European Union to improve aspects of their management of e-waste, such as regulation and monetary incentives. The European Union has set a goal to increase the volume of e-waste that should be processed. Also, the European Union wants to formalize the collecting and to report what is being collected. This pressure faces exhaustion from the Romanian people since many rely on recycling as an economic source. People in Romania have a lack of interest in the management improvements like environmental issues. Also, the informal workers do not report and may not follow the required procedures. The workers cannot afford not selling fixable waste, and the people cannot afford to buy new devices due to the economic hardships they face (Pacesila, Ciocoiu, Colesca, & Burcea, 2016).

In general, countries have been trying to make e-waste processing formal vendors and limit informal processing. The problem with informal waste is not only environmental or that it may not be as efficient. Most e-waste's informal processers are working on a small scale and at a much lower cost. This makes formalizing e-waste processing harder. In addition, the low prices of informal processers make them more robust in competitions with large-scale collectors and processers. These factors may increase the number of those informal small-scale processers, allowing higher levels of pollution, injuries, and toxicity. However, the informal processers in all the previously mentioned countries are in a similar position regarding the impacts caused by this casual and risky processing; Ghana is similar to them.

2.5 The impacts of E-waste processing:

Since basic informal e-waste processing is done by non-experts and done without safety and proper disposal, e-waste processing can have a much harmful impact on the environment, the direct workers, and the societies living nearby processing locations. Related impacts can be severe that they can last lifelong for the environment and people.

2.5.1 E-waste processing effects on the environment:

E-waste being exported from rich to poorer countries is not done to help them develop their economy, but for their interest of avoiding OECD sanctions. Therefore, not doing the process in an advanced way results in environmental and health crises to their society. In Robinson's paper E-waste: An assessment of global production and environmental impacts (2008), a review of the contaminants and their fluxes with e-waste and their ecological impacts was offered. E-Waste is chemically and physically distinct from other forms of municipal or industrial waste. E-waste, in general, contains valuable metals, like platinum group metals. E-waste also may have potential environmental contaminants, like Pb, Sb, Hg, Cd, Ni, polybrominated diphenyl ethers, and polychlorinated biphenyls. E-waste processing has many different methods to recover some value; burning E-waste is one of them. Although it is an easy process to get metals, it may generate dioxins, furans, polycyclic aromatic hydrocarbons, polyhalogenated aromatic hydrocarbons, and hydrochloric acid.

The paper provided an example of the city of Guiyu in China. It is the largest recycling site globally (Robinson, 2008), whereas Agbogbloshie is the largest e-waste dump (Yeung, 2019). In

Guiyu, e-waste is being processed by burning and apply heat. These processes have resulted in high amounts of contaminants like PBDE, Chlorofluorocarbon, Americium, Antimony, and Arsenic (Robinson, 2008). These contaminants can be inhaled while burning.

Besides, many chemicals are being disposed in soil or water. One way of contaminating them is by disposing of the hydrometallurgical aqueous waste containing toxic metals regardless of the dangerous solutions. It was mentioned in the study that disposal of contaminants in the aquatic system leads to the appearance of many contaminant chemicals; for instance, PBDE was found to be 766 ng/g in craps and 16,000 ng/g in sediments (Robinson, 2008). Also, in the same river, it was found that it has 0.4 mg of lead, eight times higher than the expected, and many other elements.

Air is a significant pathway for contaminants. Because the pollutants have many ways to move into the air: water vapor, or dust, they can be absorbed by the skin, inhaled, or ingested. One example of air contaminants is PBDE was found in the recycling site 300 times its amount in Hong Kong (Robinson, 2008). Nonetheless, a collection of dust in Guiyu had much higher amounts of metal like lead, copper, and zinc. This leads to a danger to the people living nearby and more risk to the workers there.

There is no doubt that the site's workers and people suffer from environmental contamination. These factors result in another issue: everything is being produced and manufactured near the area with a high concentration of contaminants that further distribute the danger. Thus, the environmental impact of e-waste processing is not affecting anyone more than the workers and their society. Their processing of rich countries' exported e-waste can be dangerous to the workers and profitable to later. Hence, developed methods of recycling e-waste are needed.

2.5.2 E-waste processing related injuries:

Because the workers on e-waste mostly are not professionally trained, they may suffer from life-long work injuries. Workers have in Agbogbloshie show an example of how dangerous working with e-waste is. According to Adanu et al. (2020), many e-waste workers in Africa are not formally educated and young. Therefore, the technologies used in recycling, such as burning wires, are potential risk of physical injuries. A statistical study was conducted with 112 men working in Agbogbloshie working on four types of e-waste related jobs: Collecting, sorting, dismantling, and burning (Adusei, et al., 2020). The study shows that every one of the subjects has an injury that is caused by working there. 34.8% of the study subjects do not have any formal education, 32.1% have primary education, 11.6% have secondary education, and 19.6% have junior education. 14.6% of them have scars caused by working in e-waste locations, 93.6% have severe rashes, and 23.1% have burns caused by working there. Thus, it is evident that the recent actions being done regarding e-waste are hurting individuals physically. These injuries can be due to a lack of training and not using proper safety procedures and tools.

2.5.3 E-waste processing impacts on human health:

Having the processing center in Accra, Ghana, has negatively affected people due to the methods used there, like open-burning and mechanical shredding. This caused that the recycling workers' health is worse than their peers of the same age. It was found that e-waste recycling workers in Ghana contend that their bodies have high iron, antimony, and lead levels. The experiment was done on the workers' urine and these elements' drinking water levels (Asante, et al., 2012). The heavy elements in workers' urine indicate one of the consequences of the pollution that is done in Accra. According to Robinson (2008), E-waste recycling locations are polluted in all ecological parts: soil, air, and water. Fishing spots located near the recycling factory are contaminated. Nevertheless, agriculture and manufacturing are contaminated, which makes it dangerous for locals and importers.

The current processing methods of e-waste affect the people adversely from pollution and contamination. A suggested factor is that the processes chosen are the most accessible and most harmful due to the worker's age and education. (Adanu, Gbedemah, & Attah, 2020). But contaminations and pollution may be not a priority to the workers due to their financial needs. Adanu et al. (2020) suggest that e-waste is not a waste but a great business opportunity. However, technologies that are helpful for sustainable recycling are financially hard to obtain in a developing country. There is a financial hardship to get new recycling technologies. For the people of Agbogbloshie to work in the current environment of burning to recycle metals is destroying the whole societies around the site. Inappropriate recycling of e-waste releases heavy metals into the air and affects vegetation and humans. Nevertheless, animals can consume some of the waste. Since it has many toxic metals and its indigestibility, it may build up and toxify humans further.

Figure 5: Cows eating from the e-waste dumpster may pass on toxic metals to society. (The Guardian Gallery, 2014).

China, India, and Ghana are an example of countries that are affected by e-waste informal processing. That is because of the lack of governmental regulations and the technologies that are used in recycling. Heavy metals like lead, cadmium, mercury, and nickel do not degrade in the human body; they are essential for metabolism but only in minimal amounts. Having these heavy metals results in severe adverse repercussions. For instance, they can be transferred from the air into breastfeeding, which puts even unborn babies in danger of toxification (Asamoah, Essumang, Muff, Kurcheryavskiy, & Søgaard, 2018). These results of e-waste processing are gruesome, and many of them can be avoided if they can get more economic value from e-waste in a safer way.

2.6 Chemical Recovery of Gold from PCB project:

Recoverable material of e-waste was valued at around $65 billion in 2016 (Cho, 2018). Now, this can be significant potential to start a project like ours. According to Hector Boye, our partner's representative, e-waste processers burn wires to recycle copper, and PCBs are sold to Western companies. 80% of the waste PCB value is in gold and palladium (Yia, Fana, Xiec, Mina, & Zha, 2016). We can provide a higher economic value to the community by recycling other precious metals than copper, specifically gold, from PCBs. Having a safe and beneficial gold recovery process of PCBs will provide a fair amount of money to the community instead of selling them cheaply. Also, proposing a processing method can reduce the volume of gas pollution caused by burning significantly.

We have studied several methods to extract gold from the waste printed circuit boards. Some of the procedures were stated to be sustainable and efficient. On the other hand, most methods are toxic for humans and the environment, but efficiency and cheapness are prioritized. We aimed in our method selection process to have a balance between least toxic and most efficient.

Finding a safe-to-use method for PCBs' gold recovery will decrease the pollution from electronic waste in Agbogbloshie. It may initiate a local economy based on sustainable development without high proficiency nor supervision. Our project will help the people of Ghana to improve both their income and their safety.

2.7 E-waste processing technique:

After the PCBs are shredded and ground, they are ready to be processed at a high yield. To learn the best chemical processing procedure to do that, I studied seven methods. These methods are aqua regia, cyanidation, halides compounds, potassium persulphate and formic acid, ammonium, and sodium thiosulfate, dimethylformamide and copper chloride, and acetic acid and hydrogen peroxide. I looked at the difficulty of each one of them, the complexity of chemicals as it may affect their availability, and most importantly, toxicity.

2.7.1 Aqua Regia:

Aqua regia was first invented by the alchemist Jabir ibn Hayyan (721-815 AD) when he distilled different salts with sulfuric acid; sulfur was an essential element believed that all metals are made of it and mercury. The distillation of table salt and saltpeter with sulfuric acid and aqua regia was invented as they contained hydrochloric acid and nitric acid. As an alchemist, this was a considerable achievement because of its importance in gold extraction properties (North Kentukey University).

Its property of dissolving gold used to be highly useful in the extraction process. However, it is perilous and toxic. Only people with high chemical training can use it. It was proposed in research to be a method of gold recovery from circuit boards due to its flexibility, ease for professionals, and low capital requirements (Sheng & Estell, 2007).

The procedure of the aqua regia method has three stages. The PCBs are treated with nitric acid to remove any silver chloride, reducing the recovery rate of gold. The nitric acid treatment will also dissolve tin particles. Then, the PCBs' parts will be leached with aqua regia. The study has examined various factors like temperature, liquid-solid ratio, and time. The found optimized parameters are 1:2 nitric acid to water, 70 C^o, 3 ml per 1 g, and 1 hr. These condition helps minimize the fiberglass decomposition and nitric acid usage. However, if the goal were to recover the most gold, 23 C^o leaching in 3 hours are the optimum conditions. Figure 6 explains the relationship between time versus temperature. According to figure 6, to optimize the gold recovery, a high temperature is needed, making the process even more hazardous. However, this method will not be recommended for our project because of its hazardous waste and the gas pollution resulting from the reaction (Sheng & Estell, 2007).

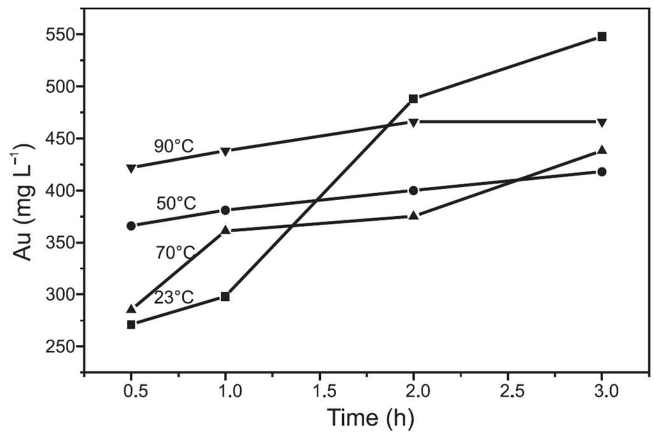


Figure 6, This graph shows the effect of temperature and time on leaching PCBs with Aqua regia. (Sheng & Estell, 2007).

2.9.2 Cyanide:

Cyanide is a cheap method of gold extraction. However, it is very toxic to humans and raises environmental concerns. It is common to extract gold from ores; 90% of the gold production uses it. China, however, started using it to leach gold from e-waste, although its low recovery rate of 60% (Rao, Singh, Morrison, & Love, 2020). It works by exposing the gold particles to cyanide in an aqueous form in the presence of oxygen and water. The following reaction explains the chemistry behind it:

$$4Au_{(s)} + 8\,CN^-_{(aq)} + O_{2\,(g)} + 2H_2O_{(l)} \rightarrow [Au(CN)_2]^-_{(aq)} + 4OH^-_{(aq)}$$

Due to the previous reaction's product, one more step is needed to convert the $[Au(CN)_2]^-_{(aq)}$to its original form of $Au_{(s)}$. This step can be done with what is called the Merrill-Crowe process. It is a process that uses zinc cementations to react with the cyanaurate $[Au(CN)_2]^-_{(aq)}$to reduce the gold particles and precipitate them (Rao, Singh, Morrison, & Love, 2020). The following reaction explains this process:

$$Zn_{(s)} + 2\ Au(CN)^-{}_{(aq)} \rightarrow 2\ Au_{(s)} + Zn(CN)^{2-}_{4\,(aq)}$$

2.9.3 Halogens:

Many halide compounds are proposed to separate the gold of the waste electronic and electrical equipment (Wordsworth, Khan, Blackburn, Camp, & Angelis-Dimakis, 2021). This paper studied Four alternative lixiviants that have been discussed in which four different organic halides used as a leaching agent for metal recovery from electronic waste were employed.

In this research, two different gold substrates were used for analysis; commercially supplied pure gold and dust of WEEE recycling company without prior chemical treatment. Of the four-metal recovery assessed methods: NBS (N-bromosuccinimide), NCS (N-chlorosuccinimide), TCICA ((trichloroisocyanuric acid), and TBICA ((tribromoisocyanuric acid) were discussed in this research. Considering their performance, cost, and environment-friendly chemicals for gold recovery from WEEE, two of them, NBS (N-bromosuccinimide) and NCS (N-chlorosuccinimide), showed quite promising results. They were successful methods on a large scale (Wordsworth, Khan, Blackburn, Camp, & Angelis-Dimakis, 2021). NBS is not the best choice to consider due to its safety consequences. It is a corrosive, irritant, oxidizer, and environmental hazard (National Center for Biotechnology Information, 2021). The use of NBS can be poisonous to the skin and eyes. Furthermore, it can modify amino acids and proteins of the human body, which may be toxic. It also hazardous to the environment as it can biodegrade the soil. Nonetheless, it can release various gases that may affect humans and the environment.

NCS is toxic and harmful if swallowed and causes eye damage. Aquatic life can be detrimental by NCS and last for a long time if disposed in a water body (National Center for Biotechnology Information, 2021).

The other two novel methods, TCICA (trichloroisocyanuric acid) and TBICA (tribromoisocyanuric acid) were used because of their lower toxicity values. Results showed that the NBS solution proved to be the superior reagent, as it showed efficiency >90% compared with the minimum profit in this procedure (22%). In both pure and dust gold, extraction efficiency was 61% and 99%, respectively. Although TCICA is less toxic than NBS and NCS, it is not the safest choice too due to its properties. It may explode if heated or contaminated. Contacting other material may oxidize it powerfully in a violent reaction. TCICA is unstable as it can react with water producing toxic chlorine gas and an explosive compound of nitrogen trichloride. If humans inhaled or contacted their skin or eyes to it, they may be subject to burns or even death (National Center for Biotechnology Information, Trichloroisocyanuric acid, 2021). TBICA is a workplace toxin as it is a strong oxidizing that can oxidize tissues. The bromide ions of TBICA can toxify the nervous system by bromism (The Toxin and Toxin Target Database, 2021).

The other three methods NCS- Pyridine, TCICA- Pyridine, and TBICA- Pyridine showed lower extraction efficiency 36%, 53%, and 29%, respectively. A reason for lower efficiency might be the optimal conditions, as these were only used in the NBS-pyridine method. The minimum profitable yield obtained from NCS and TCICA was 15%, and a WEEE gold recovery plant would have a margin of 10% profit recovery for business implementation (Wordsworth, Khan, Blackburn, Camp, & Angelis-Dimakis, 2021). However, in both NCS and TCICA methods, profit recovery was still low. However, these methods were commercially and economically viable, and their efficiencies could be enhanced by optimizing the molar ratios and other reaction conditions. Thus, considering the extraction process expenses and large-scale viability, three lixiviants NBS- Pyridine, NCS- Pyridine, and TCICA- Pyridine could be cost-effective and commercially viable.

Organic and inorganic halogens like chlorine and iodine were used. However, these halogens have not been widely accepted because of their exceptional handling and toxicity. The more commonly used, economically viable, and less toxic reagents are lixiviants. These lixiviants can convert metals into their subsequent water-soluble salts, i.e., *N*-bromosuccinimide, which can convert gold metal into its soluble salt. Furthermore, for higher efficiency, NBS- pyridine reaction was carried out with gold at room temperature and with a pH of 8.2. It will lead to the formation of an aqueous gold ion (Au^{3+}), which was subsequently reduced and converted into solid gold. The extraction efficiency of optimal NBS – pyridine solution varies between 20%-90%. So, it is concluded that if one ton of CPU waste were used in this gold recovery process, 162g of gold would be recovered. However, due to the toxicity of most leaching reagents, the instability of the yield, and the reagent's higher prices, this method cannot be recommended for the Ghana recycling center.

2.9.4 Potassium Persulphate and Formic Acid:

We want to carry out another experimental method: potassium persulphate and formic acid (Syed, 2006). This method uses 20% v/v formic acid and 20% of aqueous potassium persulfate. The formic acid removes the epoxy layer from the PCBs, which eases the gold removal. The persulfate ions will increase the tendency to dissolve other metals like silver and nickel. Therefore, we can expect metals other than gold to be presented in the yield, for instance, nickel, copper, and silver. Besides, this method is a user-friendly method that enables peeling gold and other precious metals by leaching the PCBs into formic acid and aqueous potassium sulfate. The study provides the best conditions to recover gold which is 20% v/v of each formic acid and potassium persulphate and boiling temperature. Also, this method has little to no toxicity, which helps avoid cyanide or aqua regia to recover gold. However, it depends on other factors, such as the yield, the chemical waste, and chemicals' hazards.

In this method, 20% formic acid will be measured at an unspecified amount. The 20% formic acid will be placed in a 500 ml beaker. The PCBs will be placed in the beaker with the previous solution. The mixture will be brought to boil for 10 minutes to peel the epoxy resin. The PCBs will be washed with distilled water. The 20% potassium persulfate will be measured in an unspecified amount. The solution will be placed in a 500 ml beaker. The PCBs will be added to the beaker. The mixture will be brought to a boil for 20 minutes. The PCBs will be removed from the solution. Then, the solution will be filtered to collect the gold precipitates.

2.9.5 Ammonium and Sodium Thiosulfate:

Thiosulfates and ammonia were studied to compare them to the commercial methods of gold recovery from PCBs using aqua regia and cyanide. This possible alternative method of separating precious metals has far fewer toxicity levels (Kasper & Veit, 2018). However, they admit that the cyanide method yield can get up to 88% of the gold in a PCB in two hours without heating. The researchers, Kasper and Veit, performed both methods, cyanidation, and thiosulfates regarding the use of thiosulfate in gold leaching regardless of thiosulfate's lower yield. The reaction of gold leaching with thiosulfate yield in the formation of $Au(S_2O_3)^{3-}$. This method yields a high percentage of the PCB's gold, 70-75%. If this method is wanted to recover gold, the paper recommends using sodium thiosulfate because it is eight times cheaper than ammonium thiosulfate with a bit of difference in the yield; sodium thiosulfate recovers 70%, and Ammonium thiosulfate recovers 75%.

The procedure of this method is as the following steps. 0.12 M of sodium thiosulfate will be measured. 0.2 M of ammonium will be measured. 20mM of copper sulfate will be measured. All the solutions will be mixed in a beaker until fully dissolved. The PCBs will be added to the previously made solution and left for 4 hours. The PCBs should be in a ratio of 1:25 to the liquid volume. The mixture will be heated to 30 C°. To have the product of $Au(S_2O_3)^{3-}$ stable, copper, which PCBs have, and oxygen, which can be increased by stirring in an open system, must be found in the reaction. The pH will be monitored to be at 10 by using sodium hydroxide and sulfuric acid. Then, the PCBs will be removed by using a funnel.

2.9.6 Mild Aqua Regia:

The first method is called "Mild Aqua Regia." It is based on dimethylformamide, copper (II) chloride, and calcium dichloride. According to the CDC, DFM is dangerous because human skin can easily absorb it, and it can damage the liver if not appropriately handle (CDC, 1990) d. Copper (II) chloride can burn human skin and damage eyes if contacted. However, $CuCl_2$ is not corrosive (NJDHSS, 1999). Calcium dichloride's only concern is that it may cause irritate eyes, nose, and throat if contacted (Pubchem). This method works in three significant steps: leaching, precipitation, filtration, and condensation. The PCBs are leached in the mixture of $CuCl_2$, $CaCl_2$, and DMF. The solution has low concentrations of 1.25 mol/L $CaCl_2$, 0.75 mol/L CuCl2, dissolved in a DMF solution. The optimized reaction situation requires a heat of 75 C°.

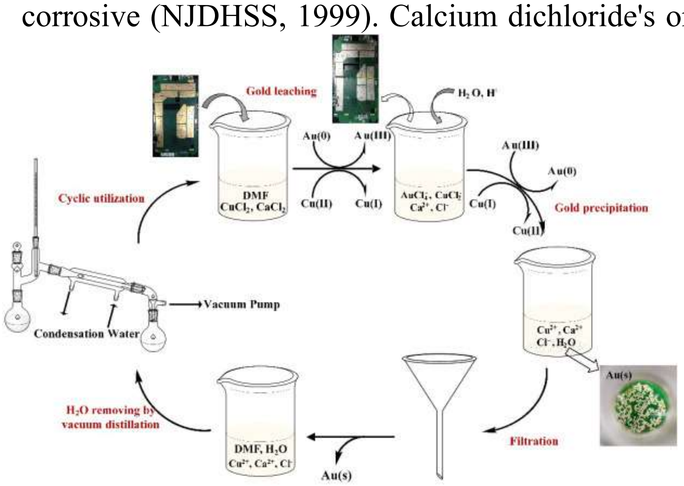


Figure 7: the procedure of leaching PCBs with DMF, mild aqua regia. (Wang, et al., 2020).

This mixture oxidizes gold and reduces copper. Then, adding water turns oxidized gold, Au^{3+}, to gold metal, Au, which precipitates solid gold. The gold can be filtered and separated from the solution. Finally, to use the mixture cyclically, water must be removed from the solution, which can be done by condensation. According to Wang et al., this gold leaching process can reach a rate of 99%. What is unique about this method is that it can be utilized cyclically. Also, this method has a high recovery rate of 99% in a short timing of 100 minutes. Figure 7 shows the process of the mild aqua regia previously explained (Wang, et al., 2020). However, this method is worth the chemicals price because of reusability. Although this high recovery rate of gold may not be performed in Ghana because of the danger of dimethylformamide toxicity and its exothermic decomposition (CDC, 1990). This method also requires additional condensation, which may be difficult on a large scale and require more equipment. It may be adapted later if the recycling project is made more prominent and professional.

Chapter 3: Methodology

In this chapter, I discuss the performed experiments to recover gold from PCBs. Also, I discussed the Proxy of PCBs of SIM cards and explained the reasons for choosing it as a proxy. Also, how this similarity can be proven, what tests, and how to prepare for these tests were explained. Finally, the chosen method was discussed and its factors' effects on gold recovery from PCBs of acetic acid and hydrogen peroxide.

3.1 PCBs Proxy:

Using PCB in the experimental part of the project can be hard to follow. Due to large PCBs, distribution of gold, and harder repeatability due to different devices and models. The size is an issue because if we considered identical PCB sizes, gold might not be the same in all samples of one PCB. Also, the gold on PCBs can vary in every model and device, which affects the repeatability of the experiment.

Therefore, I decided to use SIM cards in the experiments of the project. I claim a significant similarity between SIM cards and PCBs since we focus on the golden part of them. In both, gold is a coating layer that is placed on a copper base. The difference that made us choose SIM cards is that gold and copper amounts are more unified than PCBs. As well as they are smaller, and experiments with them can be controlled better. Relying on all the PCB processing researches, there is no doubt that elements there include copper and gold. Knowing that, I tested the SIM cards twice to ensure that they have the same elements by ICP and UV-Vis. I proved this similarity which, as a result, allowed the method of acetic acid and hydrogen peroxide application on SIM cards.

3.2 ICP spectroscopy and Gold analytics:

ICP-OES stands for Inductively Coupled Plasma Optical. Emission Spectroscopy. It is a device that works by exposing the sample to a gas that contains argon, for example, to excite the sample and ionize its atoms within the plasma (ThermoFisher, 2021). In other words, it is a susceptible technique that traces elements by their exited isotopes. An example of how sensitive ICP is, that it can track even nanograms in one mL (Harris, 2009). Figure 8 shows an experiment on the amount of mercury and Palladium in Hawaiian coffee beans.

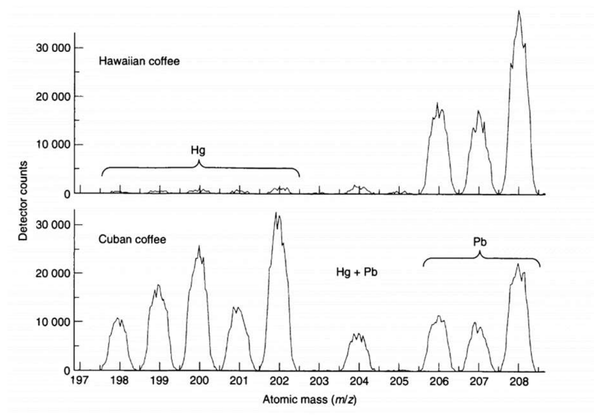


Figure 8: the ICP-MS results of detecting a minimum level of elements. (Harris, 2009).

ICP works by using Argon gas plasma to excite other elements. When the ICP excites electrons of the sample and returns to their ground state, the emitted photons release energy can be measured by their wavelengths respective of the elements that the sample is made from. Then, ICP compares the electronic charge to the targeted element's ionic mass to identify its exact amount in a sample (Harris, 2009). The ionic mass of the element we are looking at is directly related to the prepared standard solutions. It can be done by precise serial dilution. ICP can be helpful also to prove a presence of a particular element we are looking at, which is our case with gold.

3.2.1 Cleaning Glassware for ICP:

To perform the ICP spectroscopy, all used glassware must be exceptionally cleaned because unexpected elements may affect the results due to ICP sensitivity. I used a cleaning method inspired by these two methods of base bath (Harvard EHS) and (Air Quality Research Division, 2013). All glassware used is placed in the base bath, composed of 95% isopropanol and 5% potassium hydroxide, for 60 minutes. It can dissolve any glassware's contaminated surface. Then, all glassware is washed with deionized water with measured purity of 2 MΩ to clean them from the base bath solution. All glassware, then, is rinsed after that with a diluted mixture of 2% metal trace grade of nitric acid and 2% hydrochloric acid to clean any sticky elements (Nelms, 2018). Finally, they are rinsed again with 2 MΩ and then ultrapure water, 18.2 MΩ, which ensures cleanness.

3.2.2 ICP samples Preparation:

To prepare the ICP samples, a metal detection grade of Nitric acid, 99.9999% pure, with ultra-deionized water to concentrate 2%. Then, a serial dilution was done to develop a standard to use in the spectroscopy. As a side of this, a sample of the gold recovered from SIM cards was dissolved in a small amount of Aqua regia, which was diluted later with 2% Nitric acid. The prepared samples of gold are compared using the ICP to the standards I have prepared to know the exact yield of gold from the recovered metals. This procedure is repeated after each trial to test the consistency of the yield.

3.3 Hydrogen peroxide and Peracetic Acid:

A patent on PCB processing suggests that gold can be recovered by combining any suitable acid and an additional oxidizing agent (Foley, 2016). One of the mentioned acids is hydrochloric acid and peracetic acid as an oxidant. Besides, research on metal recovery from PCBs using various acids and hydrogen peroxide, including acetic acid, stated that gold could not be gotten as a soluble solid in any case using this method (Zeba, et al., 2020).

Zeba's paper stated that PCB base metals could be leached by acetic acid in a 99% yield within 5 hours at 40 C^{o}. By that, metals like Zn (II), Cu (II), Ni (II), Fe (III), Sn (IV), Al (III), and Pd (II) react with that solution and dissolve. This leaching process gives precipitations and unreacted metals. Therefore, the gold separates by reacting to the primary metal present, like copper (Zeba, et al., 2020). Their experiment, however, was done with highly concentrated reactants, which were 30% hydrogen peroxide (9.8 mol/L) and glacial acetic acid (17.5 mol/L). It is immoral to have these concentrations recommended to untrained workers or even in a possible high-scale processing location like Agbogbloshie without proper disposal. However, since this method requires chemicals that can be used in a household, it is less dangerous than other chemicals if used in a safe combination of concentrations.

This method cannot be performed in their conditions. Other than the high concentrations, the method includes a high temperature of 40 C^o, making hydrogen peroxide explosive (Clark, 2000). Although the procedure is attractive in terms of the availability of chemicals and low prices, it is hard to perform or recommend due to its high-temperature usage. Our goal is to examine factors like time, concentration, solid and liquid ratio, and reactants' volume ratio to optimize the process in a safe range. I found on YouTube some applications that use similar chemicals to this method which is not studied heavily compared to cyanide or aqua regia. The individuals who performed similar procedures to recover gold do not have any professional background since they were handling their experiments with household material and equipment. This was an optimistic foundation of the method since it is easy to process and recover gold. However, they all were doing very similar steps; only minor factors changed from one to another. Their applications showed that it is possible to be used, but also, the method needs to improve the method and optimize. Understanding the chemistry behind the gold recovery process helps to get the most out of the e-waste with the most profit. I adapted the research of

Zeba et al. and the YouTubers' experiments and decided to test different factors to optimize the gold recovery.

Most of the YouTubers' applications used 12% acetic acid with 3% hydrogen peroxide in a 3:1 volume ratio, respectively, in addition to table salt. Each litter of the solution required 125g of salt in their experiments. The reaction requires stirring to dissolve the salt in the solution and then, Soaking the PCBs for 48 hours to recover gold. Then, the mixture is filtered with a funnel to remove what is left of the PCBs. Then the solution was filtered in a coffee filter to separate gold.

The reactants in this reaction can be hazardous, though, if used in high concentrations without proper precaution. According to PubChem, acetic acid causes can be absorbed by the human body and oxidize tissues (PubChem). Ingestion of 80% of acetic acid can cause brain psych syndrome and prostate cancer. Nevertheless, low concentrations of acetic acid can cause pain and hyperemia. It could be irritating to the eyes and skin if it exceeded 25 mg/m^3. Also, acetic acid can be flammable in concentrations of 4% to 19.9% by volume. Proper use of acetic acid includes but do not constrained to high temperature, smoking nearby, or use in a closed system. Finally, it cannot be disposed of in water bodies in high concentrations due to its effects on aquatic organisms (PubChem).

Hydrogen peroxide can be explosive if heated and flammable. It may be absorbed by human skin, leading to discoloration, redness, and burns if exceeded 10%. It may irritate eyes, noses, and throats. However, 3% hydrogen peroxide is safe even to be used in disinfecting contact lenses directly touching eyes. If the concentration exceeded 90% of hydrogen peroxide, it might cause permanent corneal damage (PubChem).

3.4 Qualitative experiments:

We decided to test all the different factors that affect the gold peeling before focusing on the research's quantitative results. This observational method is included in the project to learn the possible mistakes in the experiment to avoid them. That is since there is no prior application to the proxy of the SIM card I was doing. Besides, I can discard tests with factors that may not work in a targeted way by doing this part. During this part of the project, I tested the following factors to develop the ultimate circumstances of an experiment: using full-size SIM cards, crack the back of the sim cards, cutting them into smaller parts, doubling the salt amount, and changing the liquid ratio from 3:1 to 1:1 of acetic acid to hydrogen peroxide, respectively. I also tested reducing the concentration of acetic acid from 12% to 6%.

3.4.1 Sulfuric Acid Addition as a Catalyst:

Most of the observational trials required two to three days for the gold separation. This will not be beneficial financially to our partners in Ghana because of the waste of their time, and they can make more metal recovery. Therefore, an addition of a catalyst may reduce the time needed for the separation of gold as it increases the concentration of the product of peracetic acid. Sulfuric acid is one catalyst to be used to improve the reaction. Greenspan (1946) suggests that 1% v/v of sulfuric acid can speed up peracetic acid formation.

However, a more recent paper studying the kinetics of peracetic acid formation looked at sulfuric acid's addition in different concentrations (Dul'neva & Moskvin, 2005). They found that the reaction's maximum rate is when the sulfuric acid catalyst is at 5%wt and 0.057 M. This addition prevents the decomposition of peracetic acid after its formation. However, this amount was used for a higher concentration of both reactants, acetic acid and hydrogen peroxide. I saw that the addition of a catalyst had affected their results significantly on forming peracetic acid. I considered adding 10 ml of the 5% sulfuric acid to 50 ml of the solution.

3.5.2 Qualitative experiments results:

In this part, also, I have examined different concentrations of acetic acid and different amounts of salt. I found where the recovery does not work efficiently, which is 9% of acetic acid and 62.5g/L of salt. I tested many methods of filtering the solid products of the reaction, gold. During this part, it was an extreme struggle to find the best filtering method and caused a delay in quantitative analysis. I tried gravitational filtration. It is a method of having filter paper on a funnel over a glass flask. The solution is poured on the filter paper to separate any solids in it. This filtration method took too much time to filter a sample of 10 ml with a high chance of losing the gold.

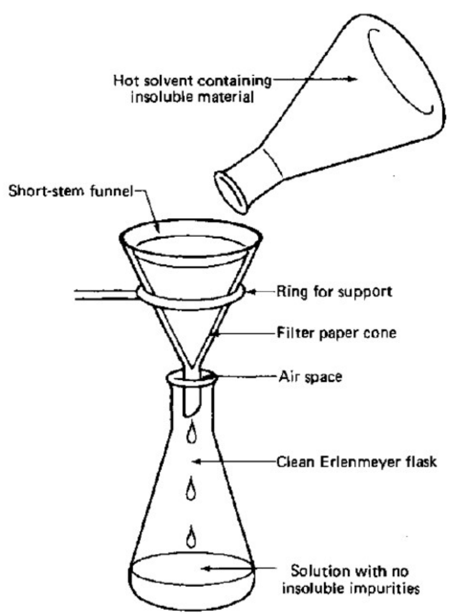


Figure 9, gravitational filtration (Timmakondu, 2012)

The gravitational filter has failed by pressure focused on a little area, and adding a large sample of liquid leads to movement beneath the filter. Adding a large amount leads to losing the product, which takes longer. Of course, a larger size of a funnel and filter will ease the process, but the potential of losing the solid to the filtered solution is still high and may cause a waste of time on refiltration. Another method I examined is vacuum filtration. It is a method where a filter system is on the top connected to a flask on the bottom connected to a vacuum. It may cause high pressure on the flask, which also may cause losing the product.

Finally, I ended up using vacuum pump filtration, figure 10. It is a method that I found more controllable than using regular vacuum filtration. It works by creating a vacuum inside the side-arm Erlenmeyer flask when connected to a running flow of water. As fast the water flows in the pump, the vacuum increases, which causes a negative pressure on the filter and separates the solids.

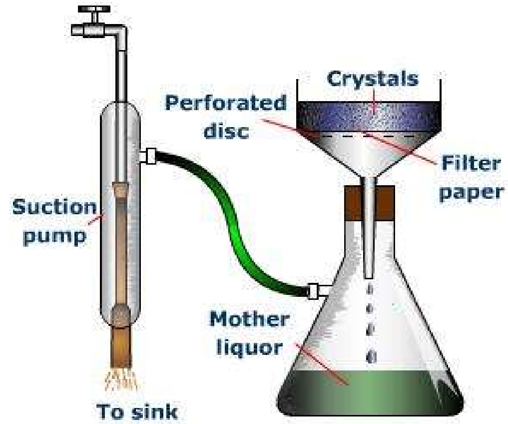


Figure 10, vacuum pump filtration method (UMich).

3.6 Quantitative part of experiments:

After I had an idea and developed a procedure, I started the quantitative part of the experiments. I tested, in this part, different times of 24 and 48 hrs., concentrations of hydrogen peroxide, table salt amount. I fixed the acetic acid concentration since it is the most beneficial during the qualitative part.

Experiment	Stock solution V. (ml)	Conc. AA, V(ml)	Conc. HP, V(ml)	M, NaCl (g)	Conc. SA V(ml)
1, 2	60 ml	12%, 37.5 ml	3%, 12.5 ml	15 g	5%, 10 ml
3,4	60 ml	12%, 37.5 ml	6%, 12.5 ml	7.5 g	5%, 10 ml
5,6	60 ml	12%, 37.5 ml	6%, 12.5 ml	15 g	5%, 10 ml
7,8	60 ml	12%, 37.5 ml	6%, 12.5 ml	7.5 g	5%, 10 ml
9,10	60 ml	12%, 33.34 ml	6%, 16.67 ml	15 g	5%, 10 ml

Table 1, the performed experiments and their factor differences.

Each prepared solution in table 1 was to do two experiments, one for 24 hrs. And the other for 48 hrs. The reactions were cut at 48 hrs. to control the experiments better. I observed in the qualitative experiments that the difference is minute with more extended time. Leaching PCBs for a long time may have a higher yield of the reaction. The SIM cards were cracked from the back in all experiments. This eased the process of peeling the golden part of them. From our perspective, the cracks on SIM cards replicate the step of crushing the PCBs with the device our colleagues MQP. It increases the interaction between the objects, PCBs, or SIM cards, with the solution.

The solutions were prepared by diluting the highly concentrated solution in distilled deionized water, mixed, then added salt. The mixture here was stirred until complete dissolving of the salt. Each vial had 8 ml of the solution. After the desired timing, the solutions were filtered with the vacuum pump filtration process. The filters were heated to ease the separation of golden particles from them and then weighed.

Chapter 4: Results and Discussion

4.1 Gold recovery of SIM cards:

Recovering gold from SIM card leaching is not our primary goal on this project but a proxy to estimate the optimum factors on gold peeling. However, there is some limitation on this proxy. For example, the examined SIM cards were used. The duration of SIM card usage may have affected the amount of metals layer by scratching. Even though SIM cards were tested from the same company, different SIM card models were observed after the leaching, although they seem identical before the treatment. The difference in the types may have caused a difference in the peeling yield and significant inconsistency. All these factors may have affected the final measurements of mass. Overall, these differences may be neglectable by looking at the overall peeling process results to get what chemicals are better and consistent to peel gold.

E1, 24 hrs., 4 sim cards in each, 8 ml of solution:

Sample	Golden parts mass (g)
1	0.0018 g
2	0.0026 g
3	0.0001 g

Table 2, Experiment 1 mass yield.

E2, 48 hrs., 4 sim cards in each, 8 ml of solution:

Sample	Golden parts mass (g)
1	0.0020 g
2	0.0021 g
3	0.0008 g

Table 3, Experiment 2 mass yield.

E3, 24 hrs., 4 sim cards in each, 8 ml of solution:

Sample	Golden parts mass (g)
1	0.0018g
2	0.0015 g
3	0.0005 g

Table 4, Experiment 3 mass yield.

E4, 48 hrs, 4 sim cards in each, 8 ml of solution:

Sample	Golden parts mass (g)
1	0.0010 g
2	0.0014 g
3	0.0007 g

Table 5, Experiment 4 mass yield.

E5, 24 hrs., 4 sim cards in each, 8 ml of solution:

Sample	Golden parts mass (g)
1	0.0028 g
2	0.0017 g
3	0.0016 g

Table 4, Experiment 5 mass yield.

E6, 48 hrs. 4 sim cards in each, 8 ml of solution:

Sample	Golden parts mass (g)
1	0.0021 g
2	0.0020 g
3	0.0019 g

Table 5, Experiment 6 mass yield.

E7, 24 hrs, .3 sim cards in each, 6 ml of solution:

Sample	Golden parts mass (g)	Estimated mass if 4 SIM
1	0.0012 g	0.0016
2	0.0004 g	0.000533 g
3	0.0003 g	0.0004 g

Table 6, Experiment 7 mass yield.

E8, 48 hrs., 3 sim cards in each, 6 ml of solution:

Sample	Golden parts mass (g)	Estimated mass if 4 SIM
1	0.0012 g	0.0016
2	0.0010 g	0.00133
3	0.0003 g	0.0004

Table 7, Experiment 8 mass yield.

E9, 24 hrs., 3 sim cards in each, 6 ml of solution:

Sample	Golden parts mass (g)	Estimated mass if 4 SIM
1	0.0012 g	0.0016 g
2	0.0010 g	0.00133 g
3	0.0004 g	0.000533 g

Table 8, Experiment 9 mass yield.

E10, 48 hrs., 3 sim cards in each, 6 ml of solution:

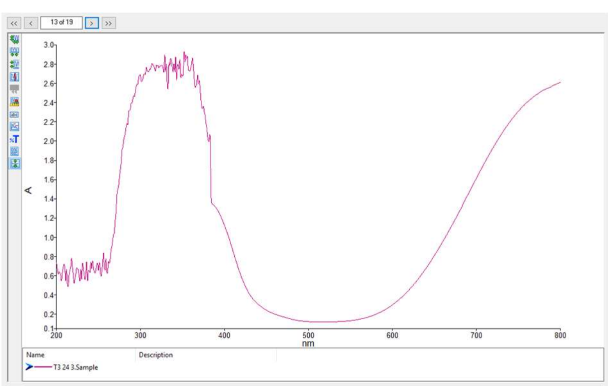
Sample	Golden parts mass (g)	Estimated mass of 4 SIM
1	0.0013 g	0.001733 g
2	0.0012 g	0.0016 g
3	0.0010 g	0.00133 g

Table 9 Experiment 10 mass yield.

4.2 Proves of similarity between SIM cards and PCBs:

By performing the two tests of ICP and UV-vis, we have proven that SIM cards are applicable to be used as a proxy for PCBs. Both object objects, PCBs or SIM cards, may react with acetic acid and hydrogen peroxide in this experiment. Observing the reactions, they look similar, but I needed to know how similar the products are and if the method applies to both in the same way. We are sure about the contents of PCBs since they are widely studied, and copper and gold are majorly present there. Reacting SIM cards with the exact solution of PCBs show a similar coloration. In addition, each gold is separated after the reaction. The uncertainty is if they are following the same method and if they are giving the same products. The similarity can be proved by identifying the chemical product in solutions in both with UV-vis. It is found to fit the expected peak of copper (II) acetate. In addition, ICP testing proved that what we are getting from SIM cards is gold.

4.2.1 UV-Vis results:



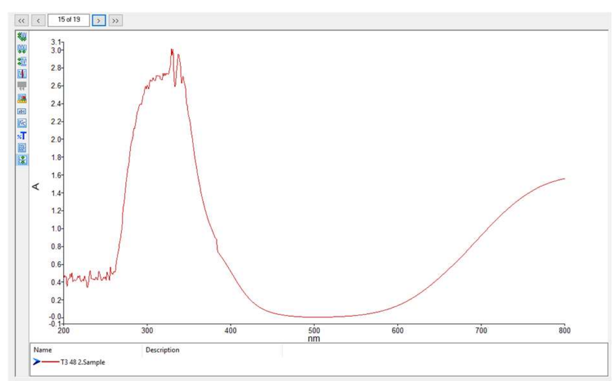


Figure 11: UV-vis spectra with 280-350 nm peaks.

The two attached graphs show the UV-vis reflection of samples 3 of experiment 5 and 2 of experiment 6 solutions. All tested samples reflected a peak in the same range of 280 nm to 350 nm with different absorbance levels (Bull O.S, 2014). These peaks prove that the reaction of SIM cards and the mixture of hydrogen peroxide and acetic produce copper (II) acetate. Since the significant component in PCB of copper is already known, I concluded that the SIM cards have a significant amount of copper beneath the golden part. By reacting that copper layer with the solution, the golden layer above it gets separated.

4.2.2 ICP-OES results:

PCBs have a gold presence in them, and there is no doubt about it. However, to prove the similarity of SIM cards to PCBs, and because there is no reference stating that the golden layer on SIM cards is gold, I performed an ICP test to prove that the golden part is gold.

We have prepared three samples of the golden particles from SIM cards. Gold was dissolved to test in the ICP. Y, weighs 0.0021g. X, weighs 0.0011g. Z weighs 0.0015g.

Sample X, which has 11 mg of golden particles, has 0.469 mg/L of gold. This means that the sample has 15 ml 0.007035 mg.

Sample Y, which has 21 mg of golden particles, has a concentration of 5.187 mg/L of gold. This means that the sample of 15 ml has 0.077805 mg.

Sample Z, which has 15 mg of golden particles, has a concentration of 6.719 mg/L of gold. This means that the sample of 15 ml has 0.100785 mg.

This inconsistency here might be due to a mistake in mass measurement. Although that, the ICP proves that the SIM cards have gold. The SIM cards' recovered golden layer is not pure gold. It is an alloy of metal that includes gold, and it can be recovered by this method. Therefore, we have a very similar condition between SIM cards, and they can be used as a proxy for PCBs.

4.3 The PCB trials:

From our tested experiments, I found out that the optimum solution of peeling gold is 12% acetic acid, 6% hydrogen peroxide, 5% sulfuric acid in a ratio of 3.75:1.25:1, respectively, with 250g/L of NaCl, table salt; E6 the highest value and most consistent. The gold peeling process is being done by reacting the copper part under the golden plate with acetic and peracetic acid. This reaction results in a copper acetate solution. If copper under the gold coating has dissolved as a copper acetate form, the gold separates from that base into flakes in the solution. So, the amount of gold that this method can recover is proportional to the reacting solution's volume and copper.

Figure 12: the NaOH solution after reacting with the coating layer.

We performed three experiments on PCBs to ensure the application of the method. Application on PCB has an additional step of soaking in a sodium hydroxide solution to remove a protective coating layer.

Figure 13, the acid solution after leaching the PCB.

In the first trial, I cut the 38 g of PCB in a size of 2.5 $inches^2$ and soaked them in a 1 M NaOH solution for a day. After that, we get a colorful solution, as in figure 12. Then, I soaked them on 165 ml of the solution with the recommended ratios in a covered beaker. After two days, we find that the solution, figure 13, is as colorful as the SIM cards. I could not recover gold from it. Fortunately, while washing the PCB to dispose them, little gold has been observed and color change in one of the PCBs. Unfortunately, gold particles could not be collected because they appeared on the waste, and some may have been drained.

The second and third trials were done in the same ratio of chemicals. However, the difference is that they were soaked in a 2.5 M solution of sodium hydroxide. After soaking them for 24hrs., the solution had less coloration compared to the 1 M trial. Also, solid precipitation was observed in it. This may indicate that more of the coating is separated from PCBs.

Figure 14: 2.5M sodium hydroxide after the PCB coating precipitates.

The second trial had 34 g of PCBs in 140 ml of the solution, and the third trial had 34g in 140 ml. The second trial has a higher volume of the solution than the PCB's mass. After two days, the mixtures were filtered. Looking at the yields, we find that the second trial, which had a higher volume to mass ratio, had less yield of gold, 0.005g, when we compare it to the third trial, which had a lower volume to mass ratio than the third trial with a yield of 0.0737g. In other words, these two trials' results are 0.02g for the second trial and 0.0526g for the third recovers if they were in 100ml solutions.

Chapter 5. Conclusion:

This study has compared various methods of recovering gold from secondary sources and e-waste like printed circuit boards. I wanted to understand the gold recovery better to recommend a chemical processing of gold to our partners in Ghana. This shall reduce their e-waste processing that requires burning. Also, it will eliminate the selling of valuable PCBs to foreign parties. Hopefully, it helps create an economic system in Agbogbloshie, Ghana, based on sustainable e-waste processing that is safe for workers, society, and nature. I have concluded that the safest method to recover gold from PCBs is a combination of Acetic acid, hydrogen peroxide, and sulfuric acid. their concentrations are 12%, 6%, and 5% respectively, with 250 g/L of salt.

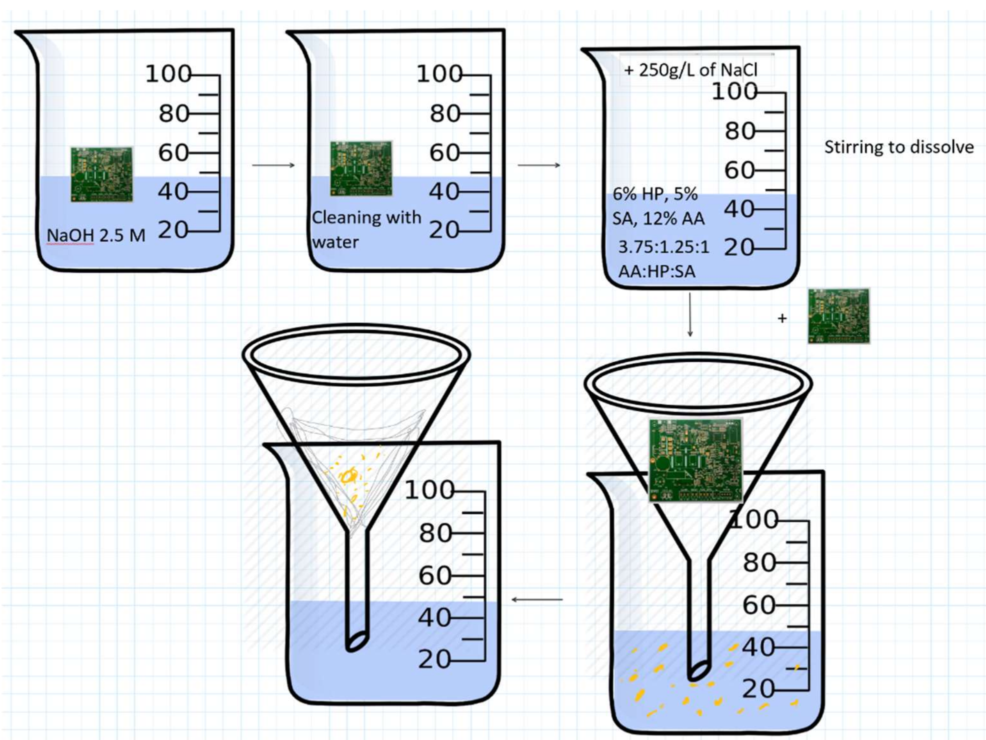


Figure 15, our recommended process of gold recovery from PCBs.

In Figure 15, we have the final recommended process of recovering gold from PCBs. It is made of four steps: coating removal with NaOH, washing PCBs to avoid an acid-base reaction, leaching process, and filtration.

This experiment can provide other valuable products. When aluminum metal is added to the copper (II) acetate, the blue solution after gold separation, the solution instantly starts producing aluminum (III) acetate and copper metal. Figure 16 shows the secondary products after 48 hrs. Figure 17 shows the copper metals that were filtered from them. This additional step adds a substantial profit to the society of Agbogbloshie since both products are profitable. Copper is five times more valuable than aluminum, and aluminum acetate is a beneficial chemical used as an antiseptic agent that may be sold to an interested party. Therefore, our project can be zero waste.

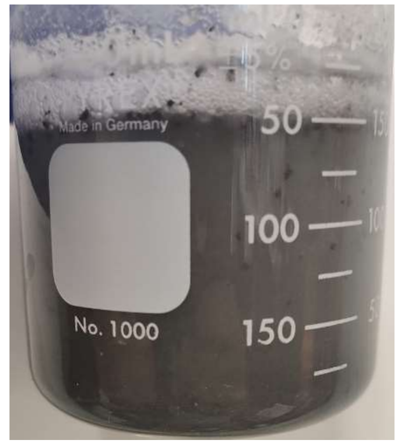


Figure 17, the solution forming aluminum acetate and copper after adding aluminum foil.

Figure 167, Copper metal after filtering the aluminum acetate solution.

5.1 Future research questions:

This research can be taken further by these questions:

- How can the reaction’s waste be processed?
- Is applying this method on a large scale can cost beneficial?
- Is metalizing copper (II) acetate with aluminum to copper metal and aluminum (III) acetate the most user and environmentally friendly method?
- Does an increase in temperature improve the recovery yield? If so, what is the best temperature to experiment safely?
- Does constant stirring of the solution can reduce the required time?
- What is the optimum volume to mass ratio on recovering gold from PCBs?
- How can reduce the catalyst of sulfuric acid increase the recovery yield since it is diluting the solution?
- Can an alternative of this method with a higher yield, i.e., “mild aqua regia,” be adjusted to make it safe?
- Using this method, does the gold separation depend on the final amount of copper acetate?
- Can we make the reaction’s waste reusable using a secondary reaction?
- How to recover other valuable metals? Can we do it without having to depend on reacting the copper base?

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