COPPER RECOVERY FROM PRINTED CIRCUIT BOARDS USING GREEN ELECTROLYTE

NUR LAYLI BINTI WIRMAN

Degree in Engineering Technology
(Energy & Environmental)
with Honours

UNIVERSITI MALAYSIA PAHANG

UNIVERSITI MALAYSIA PAHANG

DECLARATION OF THESIS AND COPYRIGHT

Author's Full Name	:	Nur Layli Binti Wirman
Date of Birth	:	
Title	:	Copper Recovery from Printed Circuit Boards using Green Electrolyte
Academic Session	:	Semester I 2022/2023

I declare that this thesis is classified as:

☐	CONFIDENTIAL	(Contains confidential information under the Official Secret Act 1997)*
☐	RESTRICTED	(Contains restricted information as specified by the organization where research was done)*
☒	OPEN ACCESS	I agree that my thesis to be published as online open access (Full Text)

I acknowledge that Universiti Malaysia Pahang reserves the following rights:

1. The Thesis is the Property of Universiti Malaysia Pahang
2. The Library of Universiti Malaysia Pahang has the right to make copies of the thesis for the purpose of research only.
3. The Library has the right to make copies of the thesis for academic exchange.

Certified by:

_____	_____
(Student's Signature)	(Supervisor's Signature)
_____	_____
New IC/Passport Number	Name of Supervisor
Date: 13 February 2023	Date:

NOTE : * If the thesis is CONFIDENTIAL or RESTRICTED, please attach a thesis declaration letter.

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Degree of Engineering Technology (Energy & Environmental) with Hons.

_____

(Supervisor's Signature)

Full Name : Noor Intan Shafinas Binti Muhammad

Position : Senior Lecturer

Date : 13 February 2023

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

_____

(Student's Signature)

Full Name : Nur Layli Binti Wirman

ID Number : TC19083

Date : 13 February 2023

COPPER RECOVERY FROM PRINTED CIRCUIT BOARDS USING GREEN ELECTROLYTE

NUR LAYLI BINTI WIRMAN

Thesis submitted in fulfillment of the requirements
for the award of the Degree of
Engineering Technology (Energy & Environmental) with Honours

Faculty of Civil Engineering Technology

UNIVERSITI MALAYSIA PAHANG

FEBRUARY 2023

ACKNOWLEDGEMENTS

First and foremost, praises and thanks to the Allah, the Almighty, for the showers of blessings throughout the proposal of senior design project. His blessing on wisdom, strength, health, support and knowledge helps me complete the project proposal and without his guidance this study would not be possible.

I would like to express my deep and sincere gratitude to my project supervisor, Dr. Noor Intan Shafinas Muhammad, for giving me the opportunity to do research and providing invaluable guidance throughout this project. Her dynamism, vision, sincerity and motivation have deeply inspired me. She has taught me the knowledge I am not aware off to be apply in the project as clearly as possible. It was a great privilege and honor to study under her guidance. I am extremely grateful for what she has offered me. I would also like to thank her for her rapport, empathy, and great sense of humor. I am extending my heartfelt thanks her husband and family for their patience during the discussion I had with her on the project preparation period.

I am extremely grateful to my parents and siblings for their love, prayer, caring and sacrifices for educating and preparing me for my future. I am very much thankful for their continuous support to complete this project proposal. My special thanks go to my friend and a few lecturers and staff for the encouragement they gave in my journey to complete this proposal.

ABSTRAK

Evolusi peranti elektrik dan elektronik telah menyaksikan perkembangan yang luar biasa dan seiring dengan perkembangan teknologi. Namun, peningkatan penggunaan peralatan ini telah menghasilkan jumlah bahan buangan elektronik yang tinggi. Penghasilan bahan buangan yang tinggi ini telah menimbulkan masalah kepada komuniti global dan setempat. Walaubagaimanapun, sebahagian besar komponen bahan buangan elekronik ini terbentuk daripada logam berharga, menjadikannya bahan kitar semula yang sesuai untuk pengekstrakan tembaga melalui kaedah elektrolisis. Kajian ini bertujuan untuk menyiasat masa tikdak balas dan arus elektrik yang optimum untuk proses ini. Kesimpulan yang didapati daripada kajian ini mendapati bahawa elektrolisis menggunakan elektrolit hijau, yang beroperasi pada suhu bilik dan tekanan atmosfera telah berjaya mengekstrak tembaga setinggi 85% dengan masa tindak balas 3 jam dan arus elektrik 1.0 mA. Kesimpulannya, menggekstrak tembaga melalui kaedah elektrolisis dengan menggunakan elektrolit hijau adalah alternatif yang lebih mesra alam daripada perlombongan tembaga.

ABSTRACT

The evolution of electronic devices has seen remarkable development and continuous improvement in technologies, but their increased use comes an increase in the amount of e-waste produced. This has become an emerging problem for both global and local societies. However, valuable metals make up the majority of e-waste components, making urban mining through electrolysis a feasible method for extracting copper. This study aimed to determine the optimum reaction time current needed for this process. It was found that electrolysis using green electrolyte, which operates at room temperature and atmospheric pressure, yielded the highest extraction of copper at 85% with a reaction time of 3 hours and a current of 1.0 mA. In conclusion, recovering copper through electrolysis using a green electrolyte is more environmentally friendly alternative than virgin mining.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

PCBs	Printed Circuit Boards
WEEE	Waste of Electric and Electronic Equipment
WPCBs	Waste Printed Circuit Boards

CHAPTER 1

INTRODUCTION

1.1 Background of Study

New work culture has been evolving along the passage of time and the public reliance on electronic equipment has been increasing due to the Covid-19 pandemic situation (Borthakur, 2022). Besides, the Internet of Things (IoT) encourages industries, schools, and other sectors to depend on devices in daily life from work to personal matters. Thus, the evolution of electronic devices has experienced remarkable development and continuous improvement in technologies. As a consequence, it led to unprecedented advances in society (Reyna et al., 2018). Because of the advancement of technology, people's desire to buy many electronic products such as smartphones, tablets, laptops, and gaming device to adopt a modern lifestyle as well as to be in trend causing rapid obsolescence, leading to the increase on the electronic global consumption (Nithya et al., 2021). The online survey data recorded a 56% increase of electronics consumption worldwide of people who own 6 or more devices from the year 2018 to 2021 show people reliance on technology (Morris Tom, 2022). In addition, according to Kumar et al. (2018), the requirement of new software is one of the factor for electronic purchasing. Due to functional needs, rapid adoption of new software may necessitate hardware upgrades. Hence, if the old hardware is not relocated or eliminated, it will become obsolete. To conclude, the drawback for high electronic consumption is a very fast replacement of electronics due to obsolescence (Ardelean et al., 2021).

In ever-increasing humans' reliance on technology, electronic waste (e-waste) disposal has become an emerging problem to both the global and local society. According to the Waste Electrical and Electronic Equipment (WEEE) Forum, a total amount of 57.4 million tonnes of e-waste is expected to be dumped in year 2021 and most of it is unlikely to be recycled. While in Malaysia, the overall e-waste generated in 2017 was about 280 kilo tonnes compared to 230 kilo tonnes in 2014 and is expected to reach 1.1 million

tonnes e-waste volume in 2020 (Yong et al., 2019). Properly recycled e-waste only account to 20% of global e-waste in 2016, while the remaining 80% undocumented might likely be dumped, traded or recycled under inferior conditions (Ilankoon et al., 2018). The majority of the e-waste was dumped via household waste or bulk waste without proper disposal. Commonly, e-waste will be sent to a registered recycling centre for further process either to be reuse, treated or final disposal. E-waste needs to be recycled because waste from electronics can cause serious health impacts to human and on the environment if not properly managed. Furthermore, e-waste still contains valuable and precious metals that can be extracted and recovered after going through certain processes (Environment, n.d.).

Extracting valuable metals from e-waste and conventional mining is different. However, both have their own advantages. Metals extracted from the e-waste were found to be more cost saving compared to conventional mining processes. With the e-waste recycling, materials recovery from e-waste is more profitable due to the energy efficiency in contrast to processing primary raw materials from mining (Tesfaye et al., 2017). There are few types of process for value-added metals recovery such as pyrometallurgy, hydrometallurgy, bio metallurgy, electrolysis, and supercritical fluid method (Yang et al., 2018). In this experiment, the process to recover value-added metal which is copper is electrolysis process. The electrolysis process is a process where the electric current causes a chemical reaction in the electrode with the presence of anode and cathode. It will cause the amount of required product deposited at the cathode from the electrolyte mixed with e-waste.

1.2 Problem Statement

The total e-waste generation of 54 million tonnes, only 9.3 million tonnes which constitute to 17.4% was formally recycled and the remaining 44.7 million tonnes which amount to 82.6% are left untreated (Nithya et al., 2021). Nonetheless, the annual growth rate of e-waste recycling is 0.4 million tonnes per year. Meanwhile, the e-waste generation annual growth rate is 2 million tonnes. Therefore, the recycling rates is insufficient to cope with the growth of e-waste generated. Extracting valuable metals such

as gold, copper, platinum, and other metals from mines are thirteen times pricier than recovering the valuable metal from e-waste. By recovering metals from the waste, it can be reuse for other usage and helps to reduce total cost by lowering the raw material purchase price. Improper disposal of e-waste can deteriorate human health, reduce water, and soil quality and causing other adverse impact on the environment. This is because, e-waste contains components that can cause toxicity such as mercury and lead and it need to be handled by professional unit before disposal. Generally, WEEE can be categorized as precious metals, ductile metals, heavy metals, and scarce metals. Copper is a ductile metal. Nowadays, copper has a potential to be depleted in future. Furthermore, copper demands have been increasing along the rise of technology. For instance, the electric Tesla Model S requires three times more copper wiring than an internal combustion engine (Andrew, 2017). Apart from that, all electrical and electronic devices need copper because of its high conductivity. Thus, the copper market is on the rise. Extracting copper instead of gold and silver might seem mundane to the public. But there is necessity in it.

1.3 Objectives of Study

The objectives of the study are

1. To extract copper from e-waste using electrolysis process.
2. To investigate the optimum reaction time and current needed for the electrolysis process.

1.4 Scope of Study

The purpose of this project is to extract copper from crushed e-waste using an electrolysis process. Furthermore, the scope of this study is to determine the optimum reaction time and the current needed for the extraction process based on a few different changes made to the process. The result will depend on the copper concentration of copper extracted from the electrolyte and will be evaluated using a spectrophotometer after the experiment.

1.5 The Importance of Study

The increasing volume of e-waste is being viewed as a global problem. The conventional and primary method of disposing of e-waste which is incineration and landfills could severely influence the economy and the environment. According to Ismail and Hanafiah (2019), an appropriate disposal method is needed for e-waste as the chemical and physical component of e-waste is different from other waste. Moreover, e-waste contained various valuable metals that can be recovered. The recycling method can be considered the best option to deal with disposal issues. Recycling metal is both economically and environmentally preferable to mining new ore sources. Therefore, the e-waste recycling method that will be used in this study can be considered reasonable because it is more environmentally beneficial and sustainable.

CHAPTER 2

LITERATURE REVIEW

2.1 E-waste

The advancement of technology has contributed to the unprecedented development to the mankind (Reyna et al., 2018). Moreover, the creation of electrical and electronic devices helps in everyday work. As an example, computers, tablets, and smartphones helps to ease communication and work, while washing machines and vacuum robots help in household work. Besides, factors such as the urbanization, literacy rates, middle-class expansion, decreasing pricing, rising interest sparked by aggressive advertisements and a desire to adopt new technologically advanced electronic devices are all contributing to the high volume of electric and electronic equipment (Adeola, 2018). Furthermore, the recent disease outbreaks of Covid-19 has triggered the increased in devices purchasing due to movement control order. The changes in working mode from working in the office to work from home, and from going to school to attend classes into online classes causes a massive purchase of electronics. Additionally, the growth of electrical consumption is due to the advent and emerging technologies (Tesfaye et al., 2017). The redundancy of older devices has been aided by the emergence of newer models that offer better value, miniaturisation and improved adaptability (Shittu et al., 2021). Hence, the growth of electronic usage. Another factor that led electronic procuring is the compatibility of the device to the upgrade version of software, where older electronic devices cannot support the upgraded hardware (Kumar & Rawat, 2018). This led to older devices being replaced although it's still working properly. As a consequence, the demands and the production of electronic and electrical equipment will continue to rise further in the future (Shittu et al., 2021) along with the advancement of technology.

One of the fastest growing waste streams globally has been identified as Waste Electrical and Electronic Equipment (WEEE) (Adeola, 2018; Pekarkova et al., 2021; Tesfaye et al., 2017) . According to (Adeola, 2018; Ilankoon et al., 2018), WEEE refers

to all discarded or end-of-life ICTs and other electronic/electrical equipment that requires an electrical current from an electromagnetic field (circuitry) in order to function. Pekarkova et al., (2021) stated approximately 54 million tonnes of global WEEE generation were recorded in 2019 which is a rise from 45 million tonnes reported in 2016. Therefore, it was estimated that e-waste production can reach up to 74.7 million tonnes in 2030 (Shittu et al., 2021; Yeoh, 2020; Ankit et al., 2021) as depict in Figure 2.1. Following Malaysia record to generation of 364 kilo tonnes of e-waste in 2019 (Yeoh, 2020) in contrast to 280 kilo tonnes waste generated in 2017 (Yong et al., 2019). Thereby, it was foreseeing that the total volume of e-waste in Malaysia is 1.1 million tonnes by 2020 with annual growth rates of 14 percent. Furthermore, this amount will continue to rise substantially due to emergence of new technologies and product compatibility. Additionally, the high volume of WEEE is due to rapid product obsolescence and device shelf life. Hence, the reduction on e-waste generated is unfeasible.

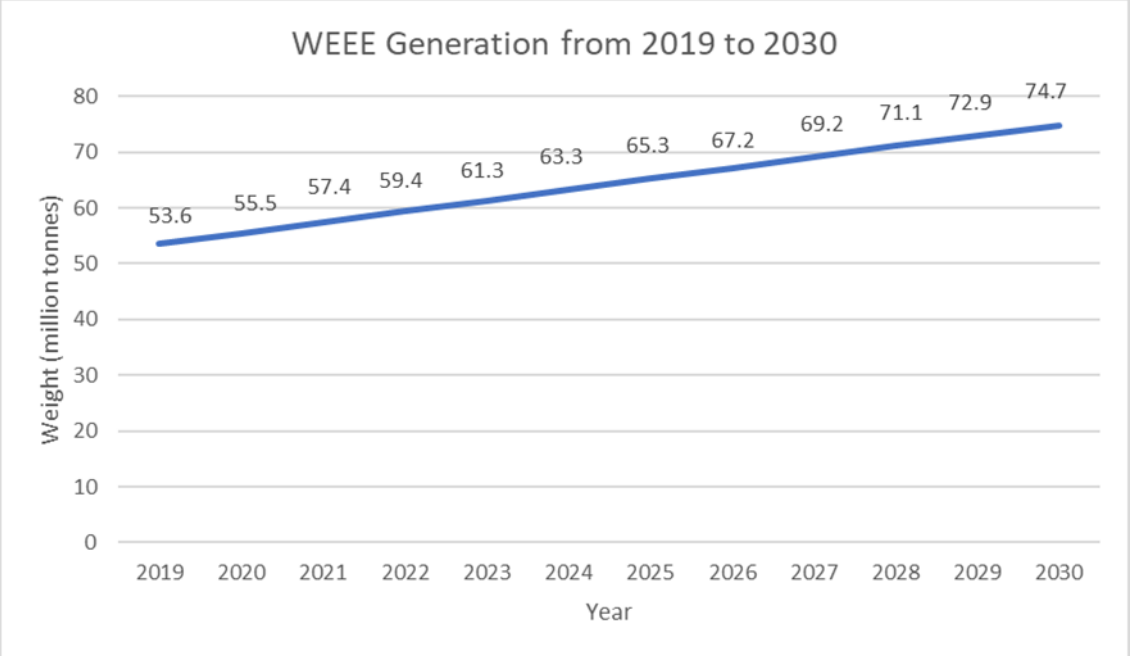


Figure 2. 1 WEEE generation between 2019 and 2030.
Source: Shittu et al. (2021)

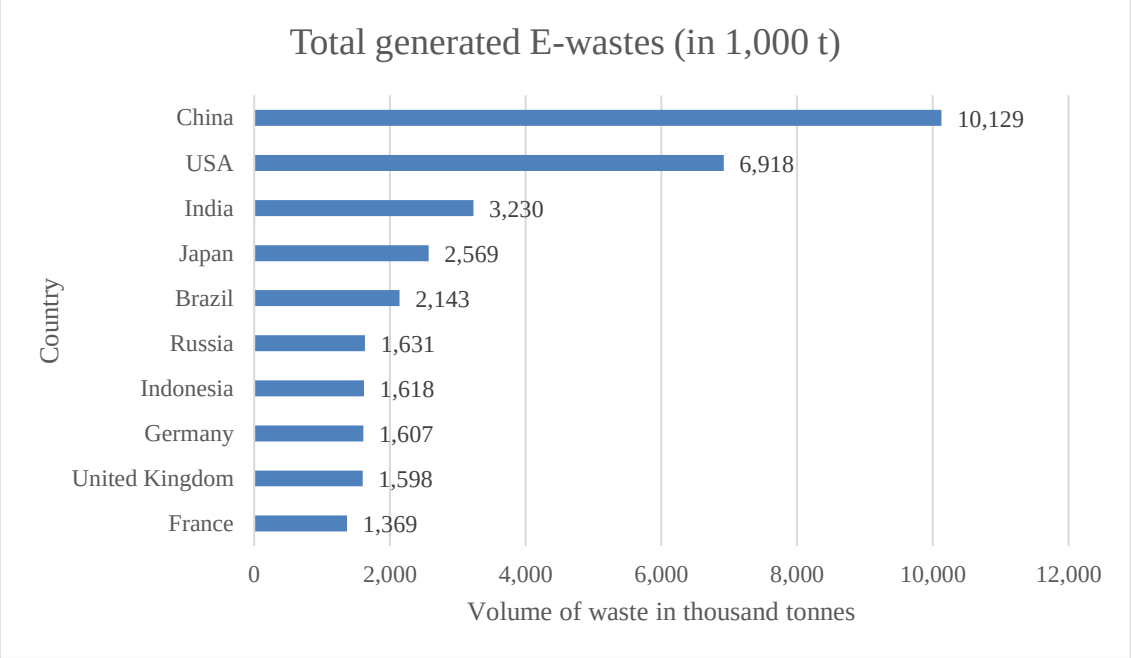


Figure 2. 2 Rank of countries based on e-waste generation worldwide in 2019. Source: Tabelin et al. (2021)

Nowadays, the accumulation of e-waste generated is a problem. This is due to the waste property which includes ferrous material, nonferrous material, plastics and ceramic materials (Ardelean et al., 2021). The complex mixture of valuable metal, hazardous metal, and other materials making the disposal become complicated and seen as arduous task due to strenuous effort taken to separate parts from WEEE. Moreover, Ardelean et al., (2021) also stated that the metal fraction in electronic waste made up more than 60% mixture of iron, copper, aluminium, gold and others. Meanwhile, 2.70% of the waste becomes polluting residues and the rest is plastics. Correspondingly, the significant number of valuable metals contains in e-waste is seen as economical and secondary resource. However, electronic waste also seen as environmentally problematic due notable number of hazardous substances (Tesfaye et al., 2017). In addition, the enormous volume of e-waste poses a significant hazard to the local community as e-waste has the potential to harm human health (Nithya et al., 2021). Furthermore, according to United States Environmental Protection Agency (2019), e-waste containing lead (Pb), mercury (Hg), cadmium (Cd) and arsenic (As) can lead to irreversible health effects, including

cancers, miscarriages, neurological damage and diminished IQs if has prolong exposure to these metals. Additionally, hazardous substances effect on the environment and it give impact to the soil fertility, pollutes the atmosphere, and affect the aquatic habitats. As an example, copper (Cu) metals is highly toxic and hazardous to the ecological system, as defined by RoHS (Restriction of certain Hazardous Substances) and recovering Cu using inefficient methods such as open burning will results in the release of hazardous substances into the environment (Nithya et al., 2021). Hence, viable and environmentally sound methods are needed to manage e-waste as it is crucial to safeguard human health and attain the ecosystem's survival.

2.2 Disposal of E-waste

In 2016, only 20% of global e-waste was properly recycled or disposed of. The remaining 80% of e-waste were undocumented which likely to be dumped, traded, or recycled under inferior conditions (Ilankoon et al., 2018). Furthermore, when it came to WEEE management, most people were perplexed, and they were unaware of the few targeted awareness programmes. The ability of people to distinguish between WEEE and non-WEEE in their homes is a critical issue that must be addressed. This is due to the widespread practice of disposing WEEE in residual waste bins. This e-waste will eventually send to municipal landfills which cause negative impact on the environment. In the United Kingdom, for example, around 1.5% of WEEE enter the residual waste stream annually. Hence, raising awareness about the importance and benefits of reuse and recycling is beneficial for all (Pekarkova et al., 2021). Apart from that, despite the high annual e-waste generated in different countries and regions, the quantities are not necessarily processed or recycled in the same country. Traditionally, transboundary e-waste movements are typically occurred when developed countries exported their e-waste to underdeveloped countries. The reason for this movement is because Asian regions provide cheaper disposal facilities, has poor environmental standards and laws management and enforcement on e-waste disposal (Ilankoon et al., 2018). Consequently, this method caused environmental pollution due to malpractice and the 75% of the exported items end up in landfills, causing impacts to both on the local environment and

humans. As a result, Basel Convention entered into force to control this problem. Thus, the e-waste disposal managements were reviewed and e-waste can only be treated by permitted disposal facilities and its movement is controlled by Basel Convention members.

Like other types of waste, disposing electronic waste has its own way and method. Additionally, e-waste is chemically and physically distinct from other types of waste and thus requires suitable disposal method (Ismail & Hanafiah, 2019). The conventional and primary methods for e-waste disposal are incineration and landfills. However, due to the complex structure of e-waste, which contains numerous valuable elements and toxic compounds both methods were the least preferred option for e-waste final disposal. Moreover, the traditional e-waste management option is no longer an option for e-waste disposal because of the increasing volume of e-waste generated at alarming rate and strict environmental regulations. Furthermore, earlier research on the consequences of e-waste disposal though incineration and landfill revealed that there are significant adverse impacts on human health and on the environment (Tesfaye et al., 2017). Moreover, the management of e-waste in developed countries is more advanced and supported by the policies and legislations in the country. On the other hand, developing countries e-waste management is more backward and improper with manual dismantling and open burning. As a consequences, these premature techniques showed poor efficiency in recovering the metals and also polluting the ecosystem to a greater extent (Nithya et al., 2021).

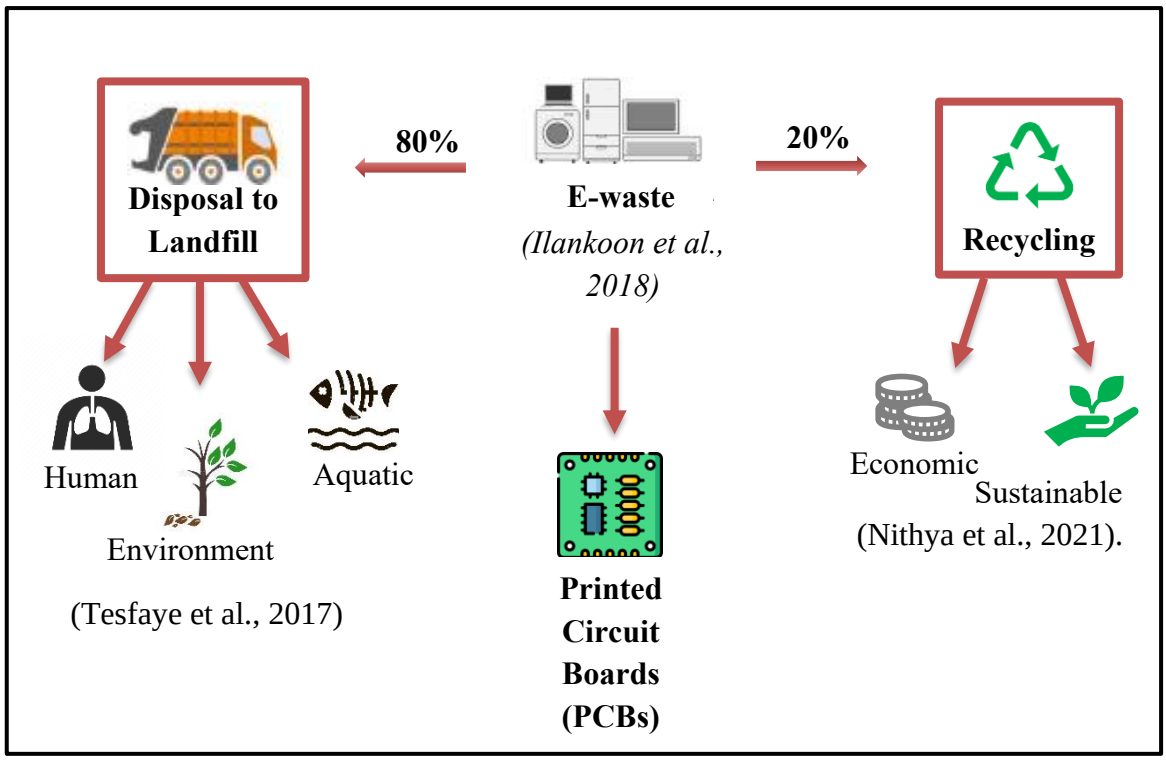


Figure 2. 3 E-waste disposal and its effect

The majority of developed and developing countries are establishing policies and stringent laws to support a sustainable approach of managing the e-waste from the collection to the recycling stages. In certain regions of the world, however, these rules were entirely ineffective (Nithya et al., 2021). In developing countries, the recycling rate are typically about 20%, with the remaining 80% of the e-waste are being improperly managed. Figure 2.4 depicts a systematic and formal recycling procedure. It includes e-waste collection, pre-treatment, and the metal recovery. E-waste was dismantled physically as part of the pre-treatment process, which included de-soldering, size reduction and fractionation processes (metallic and non-metallic). The e-metallic waste's fractions were then subjected to the recovery process that included pyro-metallurgical, hydro-metallurgical, and bio-metallurgical processes (Correa et al., 2018; Tesfaye et al., 2017). The incorrect method of e-waste recycling is characterised by the recovery of metals using non-scientific and unethical methods with low or no safety measures (Shittu et al., 2021). This practice pollutes natural resources and puts human health at risks. For example, extracting valuable metals through a combustion approach releases

hydrocarbons into the air, polluting it. Furthermore, the extraction efficiency is less than 80%, but it can reach more than 95% in formal processing of e-waste.

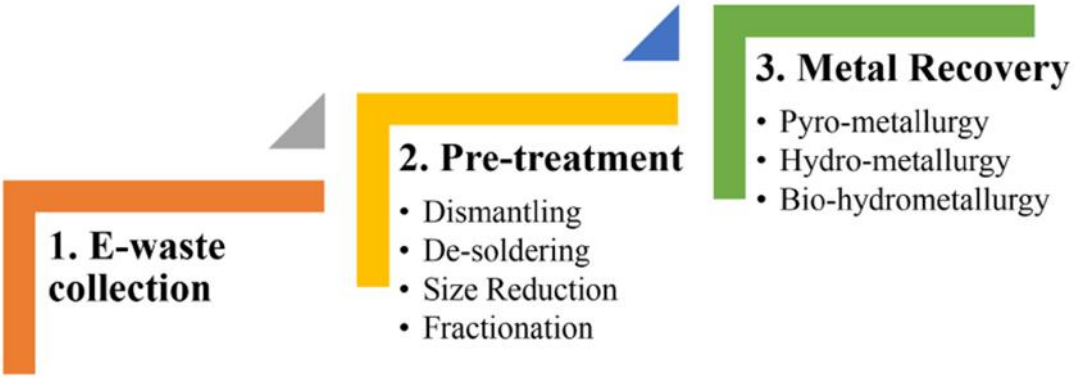


Figure 2. 4 Formal e-waste recycling stages.
Source: Correa et al. (2018) and Tesfaye et al. (2017)

2.3 Conventional Mining and Urban Mining

Today's valuable metals manufacturing system faces challenges from increasing metal demand, scarcity of primary resources and earth's inherent constraints. Urban mining, such as the recovery of critical metals from WEEE through sustainable recycling procedures, is evolving to augment scarce natural resources. As worldwide demand for these important metals continues to rise, the United Nation Environment Program (UNEP) is asking for an urgent re-think of metals recycling processes. Sustainable recycling strategies can improve vital metals production while also addressing environmental concerns such as hazardous waste and pollution (Tesfaye et al. 2017).

As a matter of fact, the amount of gold (Au), copper (Cu), silver (Ag), palladium (Pd) found in e-waste is exceeds the amount found in the natural reserves. Furthermore, the existing ore is deteriorating, and the ore's supplies are insufficient to meet the total demand (Shittu et al., 2021). Moreover, according to Tesfaye et al. (2017), materials recovered from e-waste is more profitable than processing primary raw materials largely. This is because e-waste recycling is associated with energy efficiency. Besides, the cost of processing natural ore is typically 10-160 times higher than the cost of recycling (Nithya et al. 2021). According to American Chemical Society, conventional mining

costs 13 times more to obtain compared to urban mining. Fortunately, the presence of critical metals in e-waste, as well as the difficulties of currently accessible primary resources make e-wase recycling an appealing choice. Therefore, despite the problem due to large volume e-waste generated, an optimistic view of using e-waste as additional resources of metals or as non-natural ores was taken into consideration. Additionally, extracting metals from e-waste requires only from 10 to 15% of the total energy required in metals extraction from ore concentrations (Tesfaye et al., 2017). Thus, recovering metals from e-waste has direct impact in reducing the greenhouse gas emissions by minimising the consumption of energy sources such as coal combustion. Given a fact, Japan launched the Tokyo 2020 medal project, which gathered 78,985 tonnes of e-waste collected across the country. This initiative retrieved approximately 32 kg of gold, 3500 kg of silver and 2200 kg of bronze for the Olympic and Paralympic medals. (Nithya et al., 2021). Thus, urban mining of e-waste can be a feasible alternative for metals source.

2.4 Copper

The value of the metallic components is a primary economic driver for WEEE recycling. Because of their high grade and economic value, the general goal of e-waste recycling has been to separate and recover particular valuable metals (Ilankoon et al., 2018). It is noteworthy to cite that the quantity of copper (Cu) in e-waste was found to be 40 times greater than the amount present in their natural ores (Nithya et al., 2021). Copper is valuable due to its characteristic which is durable and has a very high thermal and electrical conductivity. Hence, this metal is the most suitable to be drawn as wire. Apart from the characteristic, copper demand has been increasing as of late. The high demand is because of the unprecedented development of technology (Harmsen et al., 2013). On top of that, copper was the most used metal for every electronic product. Thus, copper is economically essential on electric energy as this sector depend heavily on copper metal. Furthermore, copper is used for the electric car. For instance, the electric Tesla Model S requires three times more copper wiring than an internal combustion engine (Andrew, 2017). In addition, wind technology relies heavily on copper for generator and electrical

transmission grid. Therefore, copper metal was sought by many apart from other valuable metals such as titanium, gold, and silver.

Copper is supply from two different sources which is conventional mining and urban mining (recycling). Mining copper ore from conventional mining has a few drawbacks such as the copper is not easily accessible, and the ore volumes is finite and might depleted in the future (Sverdrup et al., 2019). As a matter of fact, copper has been classified as scarce mineral material with only 60 years of expected availability (Harmsen et al., 2013) Furthermore, the mining process itself cause adverse impact to the environment because of the lands exploration and disturbance. Meanwhile, copper extracted from urban mining is more environmentally friendly than conventional mining. In addition, the averages metals grades found in the e-waste are significantly higher than mined ores (Tesfaye et al. 2017). Moreover, copper supplied from the urban mining provided security to the country. By means, the largest copper exporter in the world is Chile, Peru, China, and other developed countries. In occasion if wars break out in this country, copper export will stop. Thus, extracting copper from e-waste is a feasible solution for copper source as a security for copper supply.

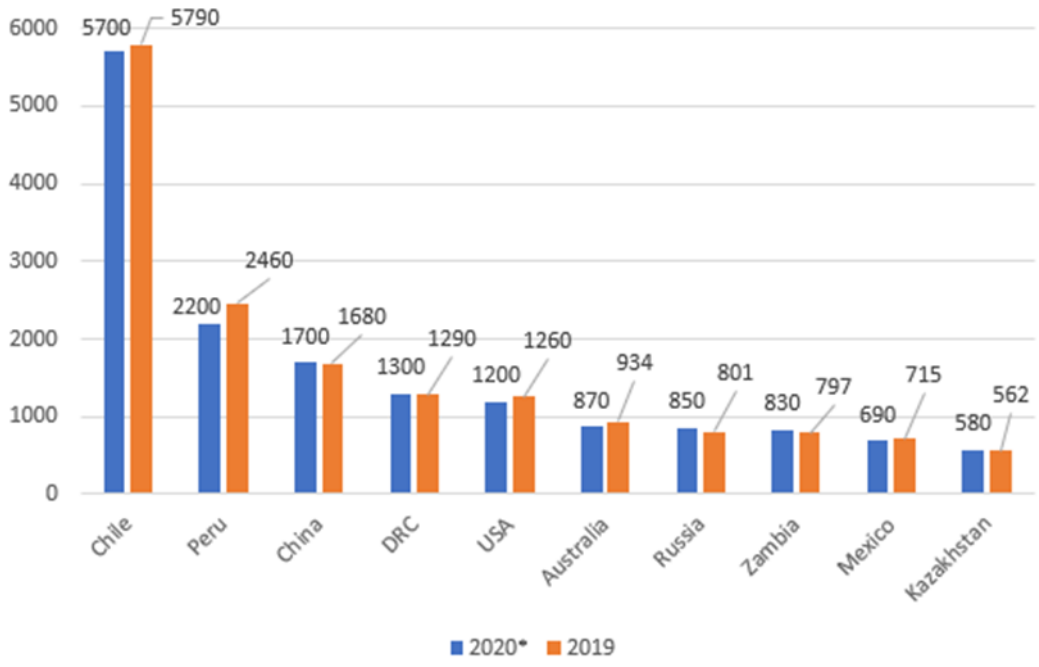


Figure 2. 5 Rank of countries for the biggest worldwide copper exporter through mining.

Source: Basov (2021)

2.5 Printed Circuit Boards (PCBs)

Printed circuit boards are an essential part for almost all electronic equipments (Wang et al., 2021). The most valuable fraction of WEEE is Printed Circuit Boards (PCBs). PCBs composed of non-metals, metals, and tin. Waste PCBs contain large amount of metals fraction. As an example, copper, iron, nickel, tin, lead, gold, and other metals. In addition, a large number of harmful substances were embodied in PCBs. Therefore, direct disposal of PCBs is a serious problem due to risk on human health and on the environment (Zhang et al., 2018). Moreover, there are many valuable metals imbedded to PCBs. As an example, precious metal such as gold, silver, titanium, and scarce metal such as copper. Moreover, the concentration of copper and precious metals contains in the PCBs are higher than the concentration of these metals from their natural primary ores. Additionally, approximately 1.5 million tonnes of PCBs were reported have been discarded every year (Sethurajan & van Hullebusch, 2019). Besides, the metals contain in PCBs can be recycled and extracted to be reuse. As an example, extracting copper. Based on previous studies, the highest percentage of metals in PCBs remains to be copper despite the different in age, origin and manufacturer of PCBs (Mokhlis et al., 2021). Meanwhile, typical PCBs has high concentrations of copper that can reach up to 27 wt% (Rajahalme et al., 2021). In addition, metals recovery process are economically practical due to high concentrations of precious metals such as silver, gold and palladium.(Correa et al., 2018). Thereby, it is worth the process to extract these valuable metals from PCBs.

Table 2. 1 Printed Circuit Board (PCB) metal composition according to ACS-MS analysis. Source: Liu et al. (2022)

Metallic Content (wt.%)														
Cu	Fe	Al	Zn	Sn	Mg	Ba	Cr	Ti	Ag	Mn	Mo	Pb	Ni	Sum
13.20	7.62	1.75	2.48	3.14	0.95	1.01	0.51	0.34	0.12	0.05	0.01	0.09	1.29	32.56

Standard Deviation														
±1.04	±1.23	±0.66	±0.22	±0.21	±0.05	±0.10	±0.02	±0.03	±0.02	±0.01	±0.01	±0.02	±0.25	± 3.66

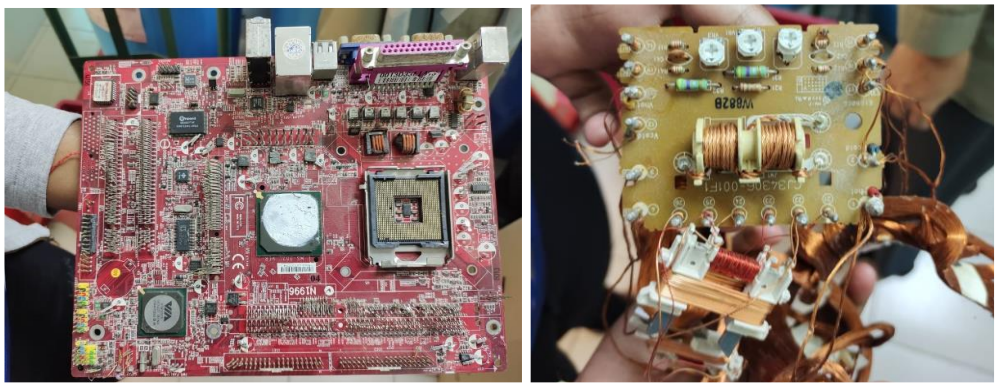


Figure 2. 6 Printed Circuit Board (PCBs)

2.6 Leaching Process

Inorganic acids such as hydrochloric acid, sulfuric acid and nitric acid are the most used leaching solutions (Mokhlis et al., 2021). As an example, the usual solution combination for copper leaching in PCBs is sulfuric acid and hydrogen peroxide (Correa et al., 2018). According to previous study, copper extraction can be up to 90 wt% when using sulfuric acid, hydrogen peroxide and a solid: liquid ration of 1:10 (g/mL) for 3h at 23°C. Meanwhile, another study stated that 100% of copper can be leached when using sulfuric acid, hydrogen peroxide and 1:10 solid/liquid ratio for 4h over 75°C and repeated for two times. But according to Liu et al., (2022), ethylene glycol was the most effective solvent to induce the electrochemical leaching and copper recovery. Leaching under this solvent takes only 60 to 120 minutes to make the copper ion into steady-state condition. Figure below depict the reaction time of leaching process using ethylene glycol as the leaching solutions and copper powder as its leaching materials. The table shown the highest metals leach to the ethylene glycol solutions is copper with 31.72 g/L concentration at 60 minutes. Thus, showing the possibility to leach a high amount of copper for the electrolysis process with low amount of time.

Table 2. 2 Metal concentration in solution after acid leaching in an oxidizing medium (pH=0.5; ORP=673mV). Source: Correa et al. (2018)

Metal	Concentration (g/L)
Al	1.20
Cu	31.72
Fe	0.003
Ni	0.11
Zn	2.91

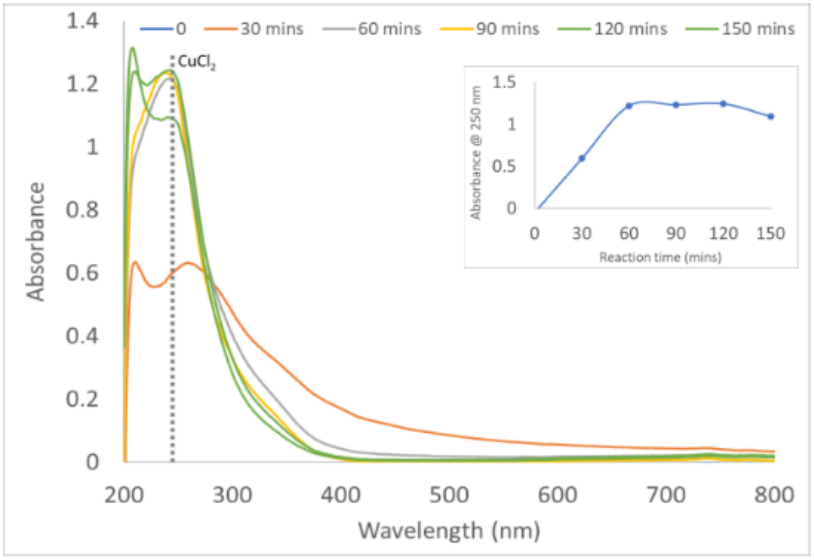


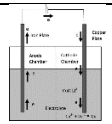
Figure 2. 7 Spectroscopic change of the leaching reaction from T_0 to T_{150}. Source: Liu et al. (2022)

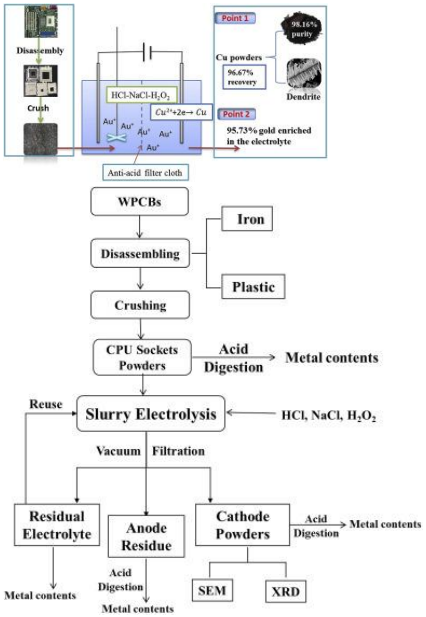
2.7 Electrolysis Process

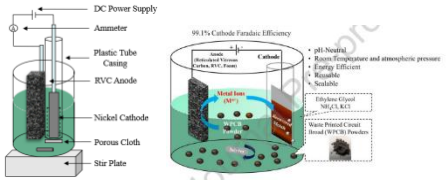
Electrolysis is a process in which current passes through electrolyte solution or molten electrolyte (also known as electrolyte) to generate redox reaction on cathode and anode (He et al., 2020). This process has a short process and is environmentally friendly. According to a previous study, recovery of copper with purity higher than 99.0% with an efficiency higher than 97% can be achieved by using metal from waste PCBs , metal concentrated waste PCBs and CPU slots (Wang et al., 2021). Thus, the recovery of copper metal from waste PCBs for this study is using electrolysis process. Not only this process

can recover desired metal but also the recovered metals is high in purity. The chosen method for the experiment is based on study from (Liu et al., 2022). This is because Liu study used environmentally friendly electrolyte and Reticulated Vitreous Carbon (RVC) material as the anode and nickel strip as the cathode. Although the anode for Liu study is RVC which highly expensive and not available in the market, the anode used for this study is switch to a regular carbon strip as a replacement. The regular carbon strip is low cost compared to RVC and easy to find in the market. Furthermore, there are no other constrains as electrode used is common and easily accessible unlike other studies electrode is high in cost and not easy to find. Thus, the main reference for electrolysis is A Green Slurry Electrolysis to Recover Valuable metals from Waste Printed Circuit Board (WPCB) in Recyclable pH-Neutral Ethylene Glycol.

Table 2. 3 Literature review table

Author & year	Title	Objectives	Methodology	Findings	Recommendation	Limitation
(Choubey, Goswami, and Gautam 2021)	Recovery of copper from Waste PCB boards using electrolysis	To recover cooper from waste PCB boards (non-ferrous metal powder) using electrolysis.	 1. 8 gm of nonferrous metal was dissolved into H_2SO_4 and stirred at 80 °C temperature for 4 h. 2. Solution was filtered and 40 ml of aquaregia (30 ml HCl and 10 ml HNO_3) was added and stirred for 60 min at a temperature of 80 °C 3. Iron Anode and Copper cathode were used for electrolysis and the chambers were separated by an anti-acid filter cloth 4. Analysis sample using AAS 5. The Extraction rate of metals calculated using formula	- Cu recovery in this case is 98%. The extracted copper is collected from the cathode chamber.	- pH for the electrolyte should be between 2 and 3 (control with NaOH) - The preparation of electrolyte is important	Not mentioned by author
(Li et al. 2019)	Copper and gold recovery from CPU sockets by one-step slurry electrolysis	To recover of copper and gold from Waste Printed Circuit Boards (WPCBs) using slurry electrolysis	1. metal powder were digested by the HCl-HNO_3-HF_$HClO_4$ system and tested by Inductively Coupled Plasma Optical Emission Spectrometer (to know the exact compound and quantity in the powder) 2. slurry electrolysis is conduct in a cubic electrolysis cell (10cmx6cmx7cm) made from polytetraflouroethylene 3. anode and cathode separated by anti-acidic filter cloth 4. Anode= ruthenium-plated titaniumm cathode= titanium 5. Insert powder into anode chamber	-copper and gold recovery rate increase significantly with the increase of HCl concentration. When concentration change from 2 to 4 mol/L, the recovery rate	-optimum condition of copper recovery is pulp density 75g/L, current density 80mA/cm2, HCl concentration 4mol/L And reaction time 4h.	-finding anode and cathode for this experiment

			6. Add 200ml electrolyte, a mixture of HCL, NaCl and H_2O_2 (30wt.%)…where NaCl (60g/L) and H_2O_2 (10mL) 7. Analysis sample using AAS 8. Metal recovery rate is calculated using formula 	increases from 83% to 91%. But if concentration increase to 5 mol/L, the recovery rate will decline	Recovery rate 97%	

Author & year	Title	Objectives	Methodology	Findings	Recommendation	Limitation
(Liu et al. 2022)	A green slurry electrolysis to recover valuable metals from waste printed circuit board (WPCB) in recyclable pH-neutral ethylene glycol	Copper recovery using electrolyte that can be recycled, and can overcome solvent acidity and toxicity drawbacks	1. Electrolysis under ambient temperature and pressure 2. Electrolysis does not require any separator 3. The cathode compartment was constructed with a plastic capsule with an open end covered by a porous cloth to induce Cu oxidation 4. After experiment, the cell was dismantled and cleaned with distilled water 	-this is the greener method for slurry electrolysis -the process does not need separator between cathode and anode -FEc =99.1%	-ambient temperature - Anode= RVC (reticulated vitreous carbon) Cathode=nickel strip - Electrolyte: 40 mL ethylene glycol, 0.23g NH_4Cl, 0.20g KCl	-to many processes and chemical needed after electrolysis
(Yang et al. 2018)	Completely separating metals and nonmetals from waste printed circuit boards by slurry electrolysis	To separate metals and nonmetals from WPCBs	1. Slurry electrolyser was separated to anode and cathode zone by porous ceramic (50um) 2. Anode= graphite stick, cathode= titanium mesh 3. At the bottom of anode, an inlet pipe was linked to an ozonizer (1.5L/min) to provide an oxidation environment 4. Metal powder in cathode collected with ultrasound washed with absolute ethanol, then dried vacuum. 5. Analysis sample with AAS	Copper recovery rate is 99%	-3g of WPCBs in 100 mL electrolyte. Electrolyte= 30g/L $CUSO_4 + 5H_2O$ + 40g/L NaCl + 150g/L H_2SO_4 -@ 0.5A for 9h -ambient temperature	

Author & year	Title	Objectives	Methodology	Findings	Recommendation	Limitation
(Sarwar et al. 2021)	Copper recovery by slurry electrolysis using ionic liquids from waste printed circuit boards	To evaluate the appropriate ionic liquid for extracting copper along with various types of ionic liquid, leaching time (reaction time) and temperature	1. 5ml of ion liquid of [Bmim][PF6] was put in 5 beakers 2. Then the 5 beakers were out in the water bath and feed materials with weight of 1g, 2g, 3g, 4g, and 5g were feed into the beakers with a 25 degree celsius temperature and 60 min of heating time. 3. The plate was washed for 3 min with 13% concentration of hydrochloric acid (diluted) and was continually cleaned for further 10 min with alcohol (absolute) 4. Plate was eventually rinsed and further used oven dried it	-Optimum time for copper recover is 3h (productivity rise from 47% to 87%) -if 5g of WPCB = copper recovery rate is 45%, but if WPCB is 2g to 3g = copper recovery is 94%- the best current for electrolysis is 0.5A (85% efficiency)		Not mentioned by author

2.8 Reaction Time

Copper recovery rates increase with reaction time, based to previous study, and there is no intervention point for copper recovery. As a result, the graph below depicts the influence of time on copper recovery and current efficiency. When the time changed from 1 hour to 5 hours, the copper recovery rate jumps roughly 50% to 73%. The current efficiency, on the other hand, indicated an inflection point during the entire reaction period. Current productivity increased from roughly 47% to 87% when the time was changed from 1 hours to 3 hours. As the reaction progressed, the current efficiency decreased to roughly 56%. As a result, the current efficiency achieved the optimum volume when the reaction was conducted over 3 hours (Sarwar et al., 2021; Yang et al., 2018). Thus, this study is to investigate the effect of reaction time on the copper concentration extracted from the electrolyte. The variable for reaction time for this study is 1 hour, 3 hours and 5hours.

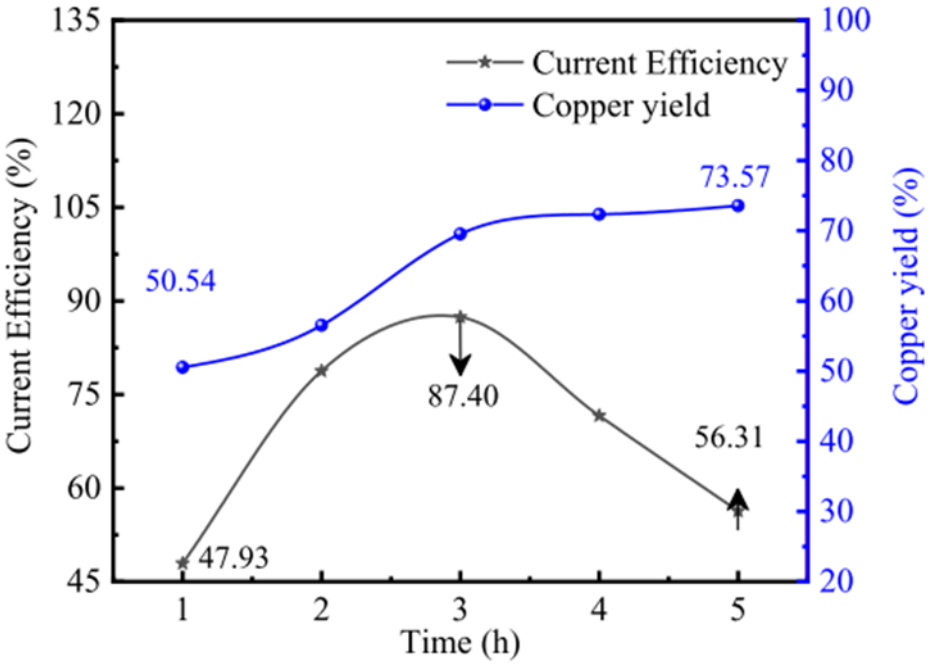


Figure 2. 8 Influence of time on copper recovery and current efficiency.
Source: Sarwar et al. (2021)

2.9 Current

The inflection points the copper recovery rate occurs during the entire reaction period, as seen in the graph in figure 2.9. At first, the amount of electricity used is raised, and the copper recovery effect is seen. The copper recovery rose by roughly 25% to 71% when the current was increased from 0.4A to 0.5A. The amount of electricity consumed rose over time, and the copper recovery rate dropped to 50.01% at 1.0A. In this time range, the copper recovery rate was still higher than it had been previously. On the other hand, while the current is 0.5A, current efficiency reached roughly 85% at a maximum point of inflection. Continue to raise the current level to 1.0A, resulting in a 35% drop for the performance (Yang et al., 2018). The current efficiency of the low current power 0.4A was 46%, and the current efficiency was not improved by the high electricity (Sarwar et al., 2021).

A huge number of useable electrons are raised at the reduced current value, according to the low electricity calculation. At a lower current value, the current increased. the reaction is added by the higher current, which enhances the pace of metal copper recovery and the overall process. The current is prolonged if the amount of electricity continues to climb. The voltage corresponding to the entire electrolytic cell is likewise increased, allowing for faster electrolytic copper recovery and easier deposition. Because of the hydrogen evolution reaction, the solutions are much reduced, and the cations are essentially filled in the cathode chamber throughout the electrolyte, resulting in more failed side reactions. Other metals will deposit in the electrolyte alongside metallic copper, affecting the rate of metallic copper recovery. It also reduced the amount of electricity used in the electrolysis reaction (Sarwar et al., 2021).

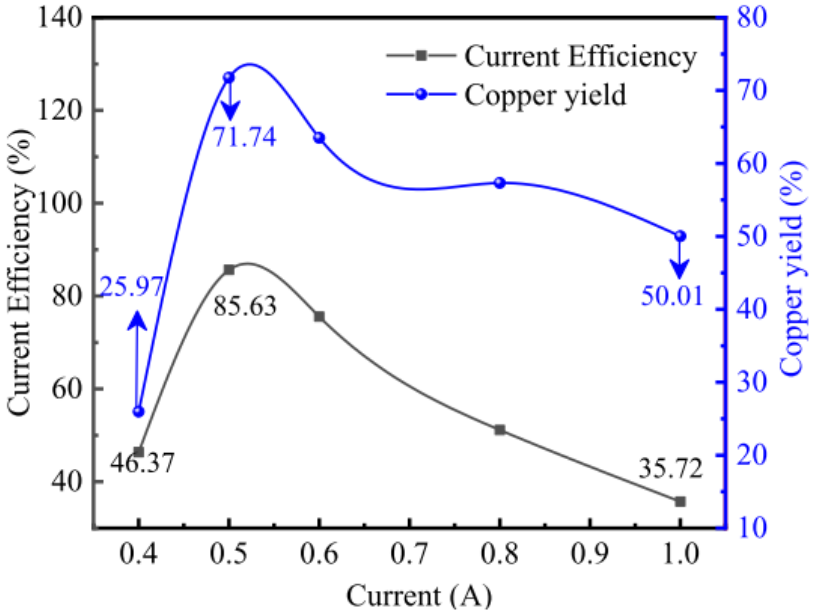


Figure 2. 9 Influence on current magnitude on copper recover and current efficiency. Source: Sarwar et al. (2021)

CHAPTER 3

METHODOLOGY

3.1 Introduction

The chapter discussed the procedure for experimental design of the electrolysis process in extracting copper from e-waste. The methods described in this chapter are intended to accomplished the project objectives.

3.2 Design and Materials

The experiment setup will be conducted as shown in the Figure 3.1. The most important material in the process is the electrodes and the electrolyte. The electrode is made up of anode and cathode where anode used is carbon strip while the cathode used is nickel strip. Each electrode is connected to a simple electrical circuit with a battery and ammeter. The solutions or electrolyte for the electrolysis process is the mixture of 40 ml Ethylene Glycol, 0.24 g of Ammonium Chloride and 0.20 g of Potassium Chloride for each experiment. The e-waste leachate from the leaching process will be the electrolyte for the electrolysis process. Electrolysis process occur with the additional help from the slow-moving magnet stirrer. The main material for this experiment is waste PCBs. The PCBs is supply from Pusat Kelestarian Ekosistem dan Sumber Alam, Universiti Malaysia Pahang. The waste PCBs chosen is from the same types of e-waste with a similar weight.

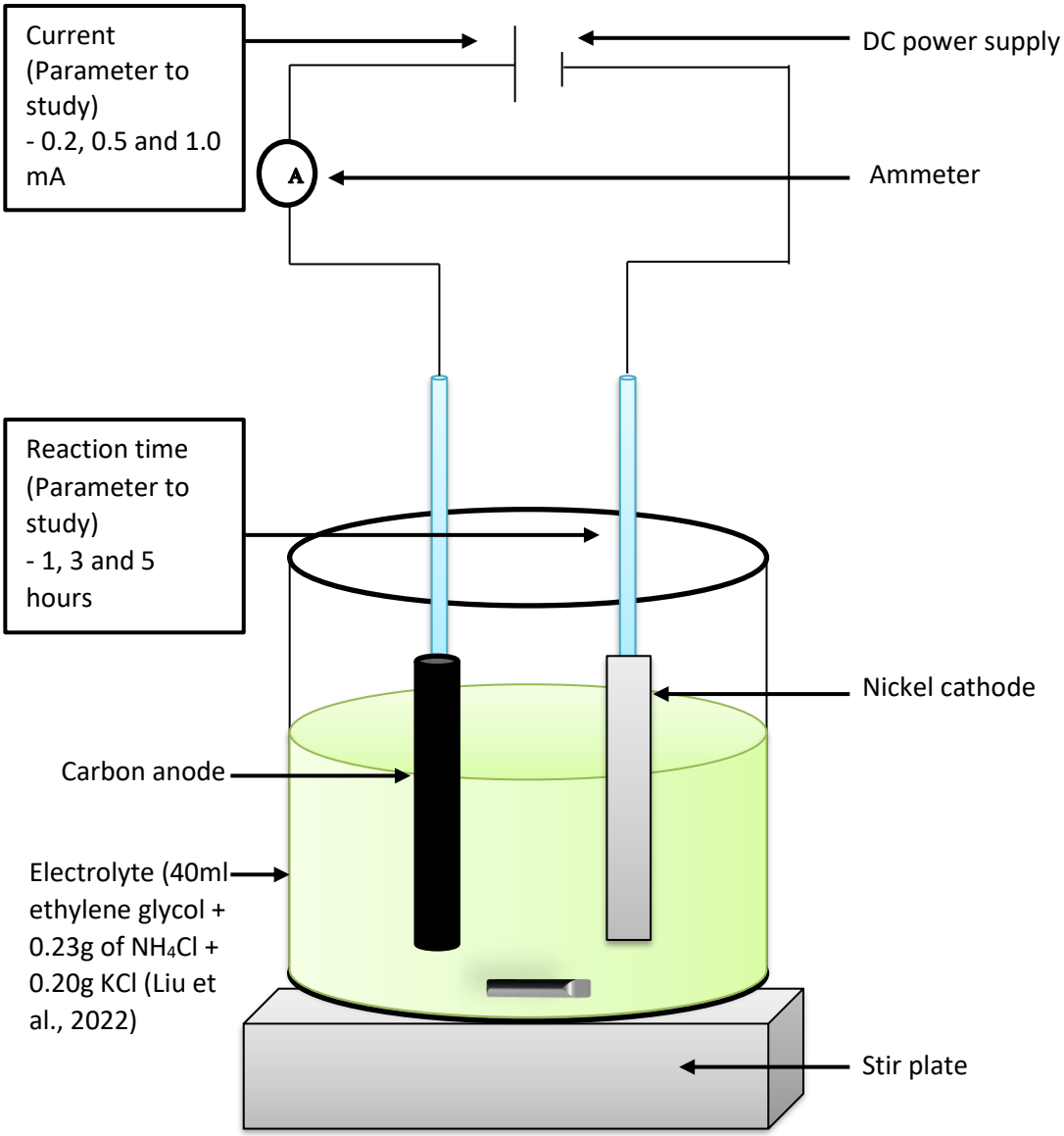


Figure 3. 10 Electrolysis process

3.3 Methods

The experiment method involved the raw material which is the e-waste from PCBs. The PCBs were taken from Pusat Kelestarian Ekosistem dan Sumber Alam, Universiti Malaysia Pahang. First, the PCBs is manually dissembled and selective copper metal is taken for the experiment. Next, the selective copper was cut into smaller pieces before the leaching process can happen to increase the surface area of the reaction. Then, the metals will be put inside a 500 ml beaker for the leaching process. The leaching

solutions is done in batch with 400 ml of Ethylene Glycol, 2.3 g of Ammonium Chloride and 2.0 g of Potassium Chloride. At first, the chemical solution was mixed and then pour into the beaker containing e-waste for the leaching process. Then, the e-waste and the solutions will be left to react for 24 hours. Once, 24 hours is up, the e-waste were taken out from the beaker while the leachate were placed aside to be used for the next process. The subsequent process is electrolysis process. The experiment design consists of a 50 ml beaker for reaction cell, carbon anode and nickel cathode for electrode, previous leachate as electrolyte and electrical circuit with battery and ammeter. Once the experiment setup is complete, 40 ml of leachate solutions is measured and use for one experiment. Meanwhile the remaining will be stored and used for different reaction time (1 hour, 3 hours and 5 hours) and current (0.2 mA, 0.5 mA and 1.0 mA) parameters. The first experiment is under electrolysis with parameter reaction time at 1h with 0.8A current. Once the experiment has been setup, the solutions is poured into the electrolysis container. After the allocated time is complete, the electrolyte will be taken for analysis using UV-Vis's spectrophotometer to check copper concentration before and after the electrolysis.

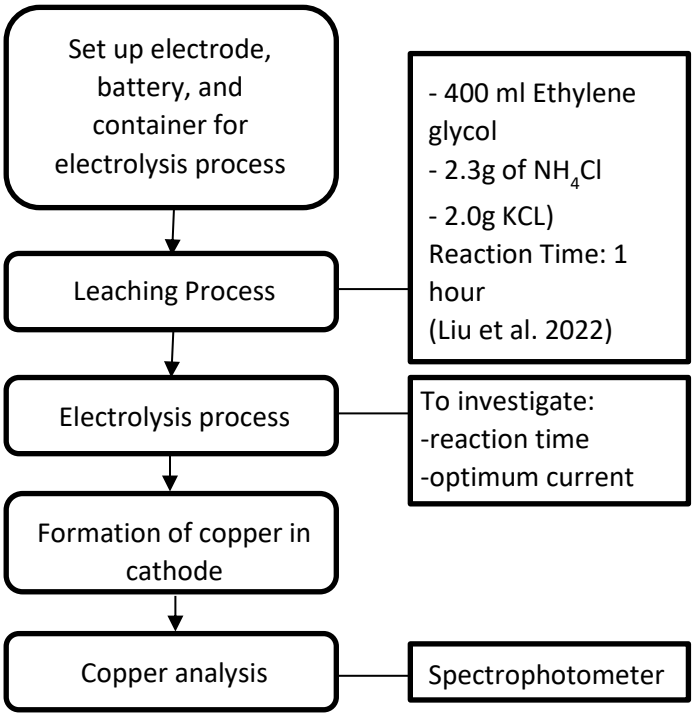


Figure 3. 11 Flow chart of experiment method

3.4 Analysis

Figure 3. 12 HACH DR 5000 UV-Vis Spectrophotometer

The analysis for this experiment is conducted by using DR 5000 UV-Vis Spectrophotometer. This equipment measured copper volume contains in the electrolyte before and after the electrolysis process. In a dual 25 ml analysing tube, 10 ml of electrolyte sample is measured for each analysing tube as blank sample and sample with reagent. This sample is used to measure the copper concentration in the electrolyte solution. Blank sample is without added a sachet of CuVer 1 Copper Reagent Powder Pillow. Meanwhile, the measured sample is added with a sachet of CuVer 1 Copper Reagent Powder Pillow. After the reagent is added to one of the samples, the analysing tube were manually shake until the reagent powder dissolved to the sample. Once the sample turned into purple colour, the point-blank sample which is the sample without the reagent were put inside the spectrophotometer for calibrating the reading before analysing tube with sample and reagent powder can be put inside Hach DR 5000 UV-Vis Spectrophotometer to be read. Finally, the data were recorded (Kharade et al., 2022).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter focuses on the results obtained from the experimental work. Detailed information regarding the extraction of copper through leaching and electrolysis process were further discussed. The samples underwent UV-Vis Spectrophotometer analysis. In addition, detailed explanation of extraction of copper ions by using different reaction time and current were clarified.

4.2 Leaching Process

In this study, the waste Printed Circuit Boards (PCBs) were dismantled and selective copper coils were taken from the waste PCBs. The copper coil was then cut into smaller pieces to ensure a high surface contact area while leaching. Leaching is the initial process before the electrolysis process can take place, this is where the copper metal transforms into copper ions (Cu^{2+}). The leaching process is conducted by adding chemicals and waste copper coil to a solution and letting it leach for 24 hours at room temperature. Afterwards, the chemical solution will contain copper ions. Following that, the solution and the copper coil were separated, and the solution, or leachate, was taken for the electrolysis process. Figure 4.1 illustrates the difference in leachate colour with different leaching durations from the PCBs. According to the observation, 24 hours copper leaching is colourless. While 96 hours of copper leaching showed the solution colour is blue, indicating the presence of copper ions. This blue colour was due to the large amount of Cu^{2+} ions that leached into the solution. Based on the analysis of (b) 24 hours leachate, there is 45.6 mg/L of copper leached to the solution. Meanwhile, (c) 96 hours leachate has 72.8 mg/L of copper leached the solution. In summary, the longer the duration of the leaching process, the greater amount of copper can be extracted for copper

recovery through the electrolysis process. But in this study, 24 hours leachate is used for the electrolysis process due to following the guidelines from the previous study who use the same chemicals for the electrolyte solution. As for 96 hours leachate, it can be used for the future study.

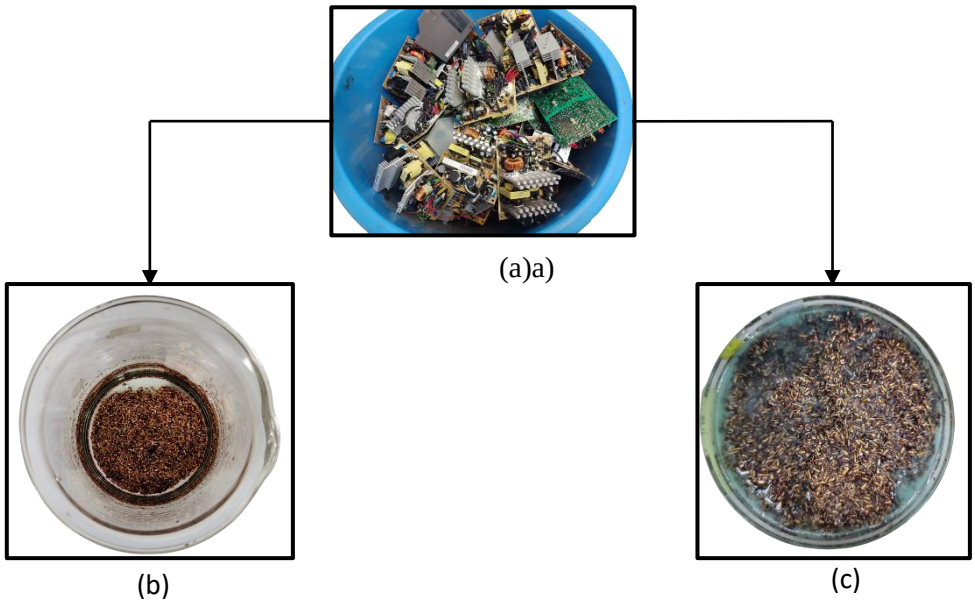
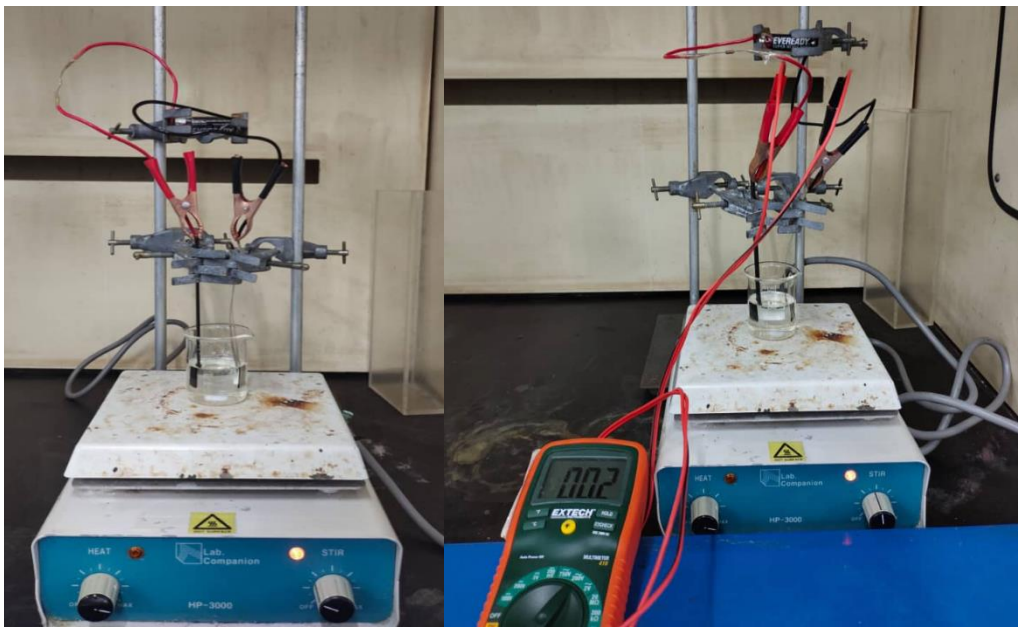


Figure 4. 13 (a) Waste Printed Circuit Boards (PCBs) (b) Leaching ar 24 hours, (c) Leaching at 96 hours

4.3 Electrolysis Process

Electrolysis is a process in which current is passed through an electrolyte solution to produce a redox reaction on the cathode and anode (He et al., 2020). The main purpose of this study is to recover copper from e-waste using the electrolysis process. Leaching, solution purification, and electrodeposition are all completed in a single step with slurry electrolysis (Wang et al., 2021). Thus, making it an attractive process due to its short process and environmentally friendly method. Additionally, this process is chosen because the electrolysis process can extract metallic copper from waste printed circuit boards (PCBs) with a purity higher than 99.0 percent. In this study, the electrolysis process is done twice to ensure similar data extracted from the process.



(a) (b)

Figure 4. 14 Electrolysis process (a) without multimeter, (b) with multimeter

4.4 UV-Vis Spectrophotometer Analysis

A UV-Vis spectrophotometer analysis described the concentration in mg/L Cu of the electrolyte. This technique uses UV light to measure the absorption or transmission of light through the sample in comparison to a reference or blank. This way, the concentration of the sample was determined. In the experiment, a UV-Vis spectrophotometer was used to perform the analysis on the leachate after the electrolysis process. The sample solution performed in the range of 560 nm. The sample with the highest concentration of copper ions indicates the lowest concentration of copper ions extracted from the electrolyte. Table 4.1 depicted the copper concentration detected from the analysis process using spectrophotometer with the lowest copper concentration is found out in the sample is in reaction time of 3 hours. Meanwhile, the figure 4.3 shows the different in colour for all the samples. This colour indicates the present of copper ions in the solutions, and thus showing in the first run at 3 hours, the copper ions present in the sample is the lowest compared to all other samples.

Table 4. 4 Copper concentration on reaction time of electrolysis process

Electrolysis	1 hour (mg/L Cu)	3 hours (mg/L Cu)	5 hours (mg/L Cu)
1st run	11.87	2.51	10.83
2nd run	11.07	11.57	9.33

Figure 4. 15 Copper concentration (a1) Sample 1st run at 1 hour (a2) Sample 2nd run at 1 hour (b1) Sample 1st run at 3 hours (a2) Sample 2nd run at 3 hours (c1) Sample 1st run at 5 hours (a2) Sample 2nd run at 5 hours

4.4.1 Effect of Reaction Time

The first set of analyses examined the impact of reaction time on the extraction of copper through the electrolysis process. The experimental study was done twice. Based on Figure 4.4 below, the highest copper yield extracted from the electrolysis process is from a 3 hours reaction time. This is because the reaction of metal cations is continuously provided throughout the anodizing phase. Furthermore, large amounts of metal are deposited electrolytically, and the cathode reducing reaction is fast. As a result, the speed of copper recovery increases. Meanwhile, the copper yield extracted from the electrolyte

solution in 1 hour and 5 hours of reaction time shown no significant differences. According to the study on 3 hours reaction time, the reaction just starts to progress. Meanwhile, 5 hours reaction time, as the reaction continues, the cathode reaction promotes metal laxation at a much faster pace than the anodyne reaction due to the apparent process of hydrogen transformation. Thus, low amount of copper yield. Additionally, other metals are deposited together in the anode, which reduce the copper recovery and effect metallics copper recovery. This theory is supported by (Sarwar et al., 2021) in his study, which show the effect of time on copper recovery rate. The results suggest that the optimum reaction time for the process reaction is 3 hours.

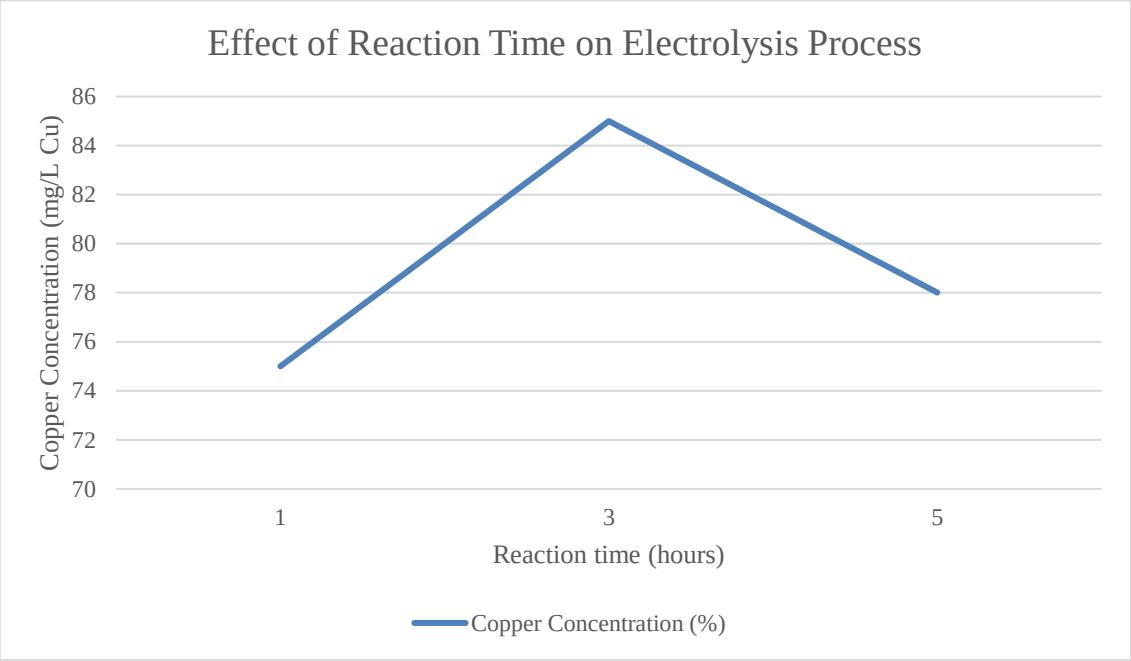


Figure 4. 16 Graph of effect on reaction time towards copper extraction

4.4.2 Effect of Current

The table below illustrates the influence of current on the electrolysis process. It can be seen from the data in Table 4.2 that the highest copper yield extracted is after 3 hours at 1.0 mA, which results in an 81% copper yield. Meanwhile, the lowest copper yield is when the current is 0.2 mA. In summary, the optimum current for the electrolysis

process is 1.0 mA. The findings from this experimental study are without the variable on the current, the copper yield is still higher than the investigate current. Thus, using 1.5V battery is enough to recover 85 percent of copper from the waste PCBs.

Table 4. 5 Effect of current towards copper extraction

Reaction Time (hours)	Current (mA)	Resistance (kΩ)	Copper Concentration (%)
3	1.0	1.5	81
3	0.5	3	77
3	0.2	7.5	75

(a) (b) (c)

Figure 4. 17 Electrode after electrolysis (a) 3 hours, 1.0 mA (b) 3 hours, 0.5 mA (c) 3 hours, 0.2 mA

(a) (b) (c)

Figure 4. 18 Resistor (a) 1.5kΩ (b) 3kΩ (c) 7.5kΩ

4.4.3 Effect of Electrolyte on pH

Table 4.4 presents the pH measures for each condition (i.e., manipulate variable is hours and current). Following the electrolysis process, there is a clear trend of decreasing pH value over hours and varying current value compared to the initial pH of electrolyte, which is pH 6.05. The results in this study are contradictory to other studies where the pH value increases and the formation of OH from the electrochemical CO_2 reduction process is primarily responsible for raising the pH near the cathode surface and narrowing the pH gradient layer when a reduction current is applied (Lu et al. 2020). Although the pH value is contradictory, the pH is still in a pH-neutral state. This might be due to the chemicals used in this study, namely, ethylene glycol which is pH-neutral solvent compared to the conventional usage of acidic solvent in the electrolysis process. Furthermore, according to Environmental Quality (Scheduled Waste) Regulations 2005 the range of pH between more than 2.5 and less than 11.5 is not considered as hazardous as long as it doesn't have another attribute that can be considered as hazardous. Thus, this waste can be disposed without the proper treatment.

Table 4. 6 Electrolyte pH

Sample	pH
1 hour	5.99
3 hours	5.92
5 hours	5.11
3 hours, 1.0 mA	5.09
3 hours, 0.5 mA	5.39
3 hours, 0.2 mA	5.45

CHAPTER 5

CONCLUSION

5.1 Conclusion

In brief, the rapid advancement of electric and electronic devices has caused the generation of e-waste to skyrocket in recent years. The main concern is the disposal process and its detrimental effects on the environment. Components inside these devices and instruments contain both toxic and valuable metals that must be treated and recovered before they can be discarded. Therefore, the purpose of the current study was to recover copper from waste printed circuit boards (PCBs) using electrolysis and to determine the optimum reaction time and current needed for the process. This study has demonstrated that the electrolysis process can effectively recover copper from waste PCBs. Additionally, 3 hours was determined to be the optimum reaction time for the extraction of copper metal, which is in line with other studies. One of the more significant findings to emerge from this study is that the optimum current is 1.0 mA at 3 hours, which is contrary to other studies that suggest a 0.5 A current is the most suitable for the e-waste electrolysis process. Furthermore, this is the first study to report the recovery of high copper yields up to 85 percent of initial leaching despite using a carbon strip anode. By changing the anode from a reticulated vitreous carbon (RVC) anode to a carbon strip anode, the experimental study is more cost-effective compared to using an expensive RVC. Finally, several important limitations need to be considered. Firstly, the PCBs need to be fully utilised for future studies as in this study, the researchers faced the challenge of handling toxic components in the PCBs due to safety reasons and the lack of machinations needed to dissemble the boards. Secondly, the cost limitation for further analysis on the electrolyte and lastly the current investigation was limited to reaction time and current only. There are more factors effecting the rate of copper recovery and it is suggested that these factors are investigated in future studies to gain a more comprehensive understanding of the process.

5.2 Recommendation

Finding from this research study, several recommendations can be proposed to overcome the process limitations and enhance the project performance of recovering copper from e-waste. To improve this study, the following suggestions for further research work are proposed:

I. To make use every component in waste PCBs to recover valuable metals.

II. To improve the methodology on the electrolysis and its parameter without the cost limitation.

III. To carry out further analysis on the electrolyte after electrolysis process such as Response Surface Methodology (RSM) analysis to determine the most suitable parameter for the experiment.

REFERENCES

Adeola, Francis O. 2018. *WEEE Generation and the Consequences of Its Improper Disposal*. Elsevier Ltd.

Andrew, Sickle Van. 2017. "Copper: Now a Precious Metal." *Money Week*. Retrieved April 23, 2022 (https://moneyweek.com/475695/copper-now-a-precious-metal).

Ankit, Lala Saha, Virendra Kumar, Jaya Tiwari, Sweta, Shalu Rawat, Jiwan Singh, and Kuldeep Bauddh. 2021. "Electronic Waste and Their Leachates Impact on Human Health and Environment: Global Ecological Threat and Management." *Environmental Technology and Innovation* 24:102049.

Ardelean, M., E. Ardelean, G. Mihut, and O. Găianu. 2021. "The Importance of Recovering Precious Metals from Waste Electrical and Electronic Equipment." *Journal of Physics: Conference Series* 1781(1).

Basov, Vladimir. 2021. "Mining News Chile Was the Largest Copper Producer in 2020; Top Copper Countries Felt Impact of the Pandemic - Report."

Borthakur, Anwesha. 2022. "Design, Adoption and Implementation of Electronic Waste Policies in India." *Environmental Science and Pollution Research* (0123456789).

Choubey, Sourav, Prerna Goswami, and Shina Gautam. 2021. "Recovery of Copper from Waste PCB Boards Using Electrolysis." Pp. 2656–59 in *Materials Today: Proceedings*. Vol. 42. Elsevier.

Correa, Mónica Maria Jiménez, Flávia Paulucci Cianga Silvas, Paula Aliprandini, Viviane Tavares de Moraes, David Dreisinger, and Denise Crocce Romano Espinosa. 2018. "Separation of Copper from a Leaching Solution of Printed Circuit Boards by Using Solvent Extraction with D2EHPA." *Brazilian Journal of Chemical Engineering* 35(3):919–30.

Environment, Department of. n.d. "E-Waste Infographic." Retrieved April 10, 2022 (https://ewaste.doe.gov.my/index.php/infographic/).

Harmsen, J. H. M., A. L. Roes, and M. K. Patel. 2013. "The Impact of Copper Scarcity on the Efficiency of 2050 Global Renewable Energy Scenarios." *Energy* 50(1):62–73.

He, Jingfeng, Jiaxin Yang, Sarwar Muhammad Tariq, Chenlong Duan, and Yuemin Zhao. 2020. "Comparative Investigation on Copper Leaching Efficiency from Waste Mobile Phones Using Various Types of Ionic Liquids." *Journal of Cleaner Production* 256:120368.

Ilankoon, I. M. S. K., Yousef Ghorbani, Meng Nan Chong, Gamini Herath, Thandazile Moyo, and Jochen Petersen. 2018. "E-Waste in the International Context – A Review of Trade Flows, Regulations, Hazards, Waste Management Strategies and Technologies for Value Recovery." *Waste Management* 82:258–75.

Ismail, Haikal, and Marlia M. Hanafiah. 2019. "Discovering Opportunities to Meet the Challenges of an Effective Waste Electrical and Electronic Equipment Recycling System in Malaysia." *Journal of Cleaner Production* 238.

Kharade, Sangram B., Rajvardhan K. Chougale, Umesh B. Barache, Kallappa R. Sanadi, Kishan C. Rathod, Shashikant H. Gaikwad, Yong Chein Ling, Mansing A. Anuse, and Ganesh S. Kamble. 2022. "Design and Optimization of Sensitive Analytical Spectrophotometric Method for Micro Determination of Copper(II) from e-Waste by Using of Novel Chromogenic Extractant." *Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy* 267:120502.

Kumar, Sashi, and Shatrunjay Rawat. 2018. "Future E-Waste: Standardisation for Reliable Assessment." *Government Information Quarterly* 35(4):S33–42.

Li, Feifan, Mengjun Chen, Jianchen Shu, Mehran Shirvani, Yungui Li, Zhi Sun, Shuhui Sun, Zhong Hui Xu, Kaibin Fu, and Shu Chen. 2019. "Copper and Gold Recovery from CPU Sockets by One-Step Slurry Electrolysis." *Journal of Cleaner Production* 213:673–79.

Liu, Kaixin, Shuquan Huang, Yangxin Jin, Lan Ma, Wen-Xiong Wang, and Chun Ho Lam. 2022. "A Green Slurry Electrolysis to Recover Valuable Metals from Waste Printed Circuit Board (WPCB) in Recyclable PH-Neutral Ethylene Glycol." *Journal of Hazardous Materials* 128702.

Lu, Xu, Chongqin Zhu, Zishan Wu, Jin Xuan, Joseph S. Francisco, and Hailiang Wang. 2020. "In Situ Observation of the PH Gradient near the Gas Diffusion Electrode of CO2Reduction in Alkaline Electrolyte." *Journal of the American Chemical Society* 142(36):15438–44.

Mokhlis, H., R. D. Daoudi, and M. Azzi. 2021. "Selective Leaching of Copper from Waste Printed Circuit Boards (Pcbs) Using Glycine as a Complexing Agent." *Global Nest Journal* 23(1):90–96.

Morris Tom. 2022. "Sustainability in 2022: The e-Waste Problem." *GWI*. Retrieved April 23, 2022 (https://blog.gwi.com/chart-of-the-week/sustainability-2022-e-waste/).

Nithya, Rajarathinam, Chandrasekaran Sivasankari, and Arunachalam Thirunavukkarasu. 2021. "Electronic Waste Generation, Regulation and Metal Recovery: A Review." *Environmental Chemistry Letters* 19(2):1347–68.

Pekarkova, Zora, Ian D. Williams, Loretta Emery, and Rachel Bone. 2021. "Economic and Climate Impacts from the Incorrect Disposal of WEEE." *Resources, Conservation and Recycling* 168(January).

Rajahalme, Joona, Siiri Perämäki, Roshan Budhathoki, and Ari Väisänen. 2021. "Effective Recovery Process of Copper from Waste Printed Circuit Boards Utilizing Recycling of Leachate." *Jom* 73(4):980–87.

Reyna, Ana, Cristian Martín, Jaime Chen, Enrique Soler, and Manuel Díaz. 2018. "On Blockchain and Its Integration with IoT. Challenges and Opportunities." *Future Generation Computer Systems* 88(2018):173–90.

Sarwar, M. T., Z. Hanhui, J. Yang, A. Maqbool, R. K. M. Khan, and B. Ullah. 2021. "Copper Recovery by Slurry Electrolysis Using Ionic Liquids from Waste Printed Circuit Boards." *Global Nest Journal* 23(2):226–31.

Sethurajan, Manivannan, and Eric D. van Hullebusch. 2019. "Leaching and Selective Recovery of Cu from Printed Circuit Boards." *Metals* 9(10):1–12.

Shittu, Olanrewaju S., Ian D. Williams, and Peter J. Shaw. 2021. “Global E-Waste Management: Can WEEE Make a Difference? A Review of e-Waste Trends, Legislation, Contemporary Issues and Future Challenges.” *Waste Management* 120:549–63.

Sverdrup, Harald Ulrik, Anna Hulda Olafsdottir, and Kristin Vala Ragnarsdottir. 2019. “On the Long-Term Sustainability of Copper, Zinc and Lead Supply, Using a System Dynamics Model.” *Resources, Conservation and Recycling: X* 4(December 2018):100007.

Tabelin, Carlito Baltazar, Ilhwan Park, Theerayut Phengsaart, Sanghee Jeon, Mylah Villacorte-Tabelin, Dennis Alonzo, Kyoungkeun Yoo, Mayumi Ito, and Naoki Hiroyoshi. 2021. “Copper and Critical Metals Production from Porphyry Ores and E-Wastes: A Review of Resource Availability, Processing/Recycling Challenges, Socio-Environmental Aspects, and Sustainability Issues.” *Resources, Conservation and Recycling* 170(April):105610.

Tesfaye, Fiseha, Daniel Lindberg, Joseph Hamuyuni, Pekka Taskinen, and Leena Hupa. 2017. “Improving Urban Mining Practices for Optimal Recovery of Resources from E-Waste.” *Minerals Engineering* 111(June):209–21.

United States Environmental Protection Agency, EPA. 2019. “Cleaning Up Electronic Waste (E-Waste).” Retrieved (https://www.epa.gov/international-cooperation/cleaning-electronic-waste-e-waste#:~:text=What is E-Waste%3F,or given to a recycler.).

Wang, Jiqin, Zhouman Huang, Deze Yang, Xiangfei Zeng, Mengjun Chen, Jiancheng Shu, Zhi Sun, Shuhui Sun, and Zhengxue Xiao. 2021. “A Semi-Scaled Experiment for Metals Separating and Recovering from Waste Printed Circuit Boards by Slurry Electrolysis.” *Process Safety and Environmental Protection* 147:37–44.

Yang, Deze, Yingying Chu, Jianbo Wang, Mengjun Chen, Jiancheng Shu, Furong Xiu, Zhonghui Xu, Shuhui Sun, and Shu Chen. 2018. “Completely Separating Metals and Nonmetals from Waste Printed Circuit Boards by Slurry Electrolysis.” *Separation and Purification Technology* 205(January):302–7.

Yeoh, Angeli. 2020. “The UN Says Humanity Recorded the Highest Amount of E-Waste in 2019. Here’s How to Discard Unwanted Electronics Reponsibly.” *The Star*.

Yong, Yun Siew, Yi An Lim, and I. M. S. K. Ilankoon. 2019. “An Analysis of Electronic Waste Management Strategies and Recycling Operations in Malaysia: Challenges and Future Prospects.” *Journal of Cleaner Production* 224:151–66.

Zhang, Ding jun, Li Dong, Yong tong Li, Yanfei Wu, Ying xia Ma, and Bin Yang. 2018. “Copper Leaching from Waste Printed Circuit Boards Using Typical Acidic Ionic Liquids Recovery of E-Wastes’ Surplus Value.” *Waste Management* 78:191–97.

Adeola, Francis O. 2018. *WEEE Generation and the Consequences of Its Improper Disposal*. Elsevier Ltd.

Andrew, Sickle Van. 2017. “Copper: Now a Precious Metal.” *Money Week*. Retrieved April 23, 2022 (https://moneyweek.com/475695/copper-now-a-precious-metal).

Ankit, Lala Saha, Virendra Kumar, Jaya Tiwari, Sweta, Shalu Rawat, Jiwan Singh, and Kuldeep Bauddh. 2021. “Electronic Waste and Their Leachates Impact on Human Health and Environment: Global Ecological Threat and Management.” *Environmental Technology and Innovation* 24:102049.

Ardelean, M., E. Ardelean, G. Mihut, and O. Găianu. 2021. “The Importance of Recovering Precious Metals from Waste Electrical and Electronic Equipment.” *Journal of Physics: Conference Series* 1781(1).

Basov, Vladimir. 2021. “Mining News Chile Was the Largest Copper Producer in 2020; Top Copper Countries Felt Impact of the Pandemic - Report.”

Borthakur, Anwesha. 2022. “Design, Adoption and Implementation of Electronic Waste Policies in India.” *Environmental Science and Pollution Research* (0123456789).

Choubey, Sourav, Prerna Goswami, and Shina Gautam. 2021. “Recovery of Copper from Waste PCB Boards Using Electrolysis.” Pp. 2656–59 in *Materials Today: Proceedings*. Vol. 42. Elsevier.

Correa, Mónica Maria Jiménez, Flávia Paulucci Cianga Silvas, Paula Aliprandini, Viviane Tavares de Moraes, David Dreisinger, and Denise Crocce Romano Espinosa. 2018. “Separation of Copper from a Leaching Solution of Printed Circuit Boards by Using Solvent Extraction with D2EHPA.” *Brazilian Journal of Chemical Engineering* 35(3):919–30.

Environment, Department of. n.d. “E-Waste Infographic.” Retrieved April 10, 2022 (https://ewaste.doe.gov.my/index.php/infographic/).

Harmsen, J. H. M., A. L. Roes, and M. K. Patel. 2013. “The Impact of Copper Scarcity on the Efficiency of 2050 Global Renewable Energy Scenarios.” *Energy* 50(1):62–73.

He, Jingfeng, Jiaxin Yang, Sarwar Muhammad Tariq, Chenlong Duan, and Yuemin Zhao. 2020. “Comparative Investigation on Copper Leaching Efficiency from Waste Mobile Phones Using Various Types of Ionic Liquids.” *Journal of Cleaner Production* 256:120368.

Ilankoon, I. M. S. K., Yousef Ghorbani, Meng Nan Chong, Gamini Herath, Thandazile Moyo, and Jochen Petersen. 2018. “E-Waste in the International Context – A Review of Trade Flows, Regulations, Hazards, Waste Management Strategies and Technologies for Value Recovery.” *Waste Management* 82:258–75.

Ismail, Haikal, and Marlia M. Hanafiah. 2019. “Discovering Opportunities to Meet the Challenges of an Effective Waste Electrical and Electronic Equipment Recycling System in Malaysia.” *Journal of Cleaner Production* 238.

Kharade, Sangram B., Rajvardhan K. Chougale, Umesh B. Barache, Kallappa R. Sanadi, Kishan C. Rathod, Shashikant H. Gaikwad, Yong Chein Ling, Mansing A. Anuse, and Ganesh S. Kamble. 2022. “Design and Optimization of Sensitive Analytical Spectrophotometric Method for Micro Determination of Copper(II) from e-Waste by Using of Novel Chromogenic Extractant.” *Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy* 267:120502.

Kumar, Sashi, and Shatrunjay Rawat. 2018. “Future E-Waste: Standardisation for Reliable Assessment.” *Government Information Quarterly* 35(4):S33–42.

Li, Feifan, Mengjun Chen, Jianchen Shu, Mehran Shirvani, Yungui Li, Zhi Sun, Shuhui Sun, Zhong Hui Xu, Kaibin Fu, and Shu Chen. 2019. “Copper and Gold Recovery from CPU Sockets by One-Step Slurry Electrolysis.” *Journal of Cleaner Production* 213:673–79.

Liu, Kaixin, Shuquan Huang, Yangxin Jin, Lan Ma, Wen-Xiong Wang, and Chun Ho Lam. 2022. “A Green Slurry Electrolysis to Recover Valuable Metals from Waste Printed Circuit Board (WPCB) in Recyclable PH-Neutral Ethylene Glycol.” *Journal of Hazardous Materials* 128702.

Lu, Xu, Chongqin Zhu, Zishan Wu, Jin Xuan, Joseph S. Francisco, and Hailiang Wang. 2020. “In Situ Observation of the PH Gradient near the Gas Diffusion Electrode of CO2Reduction in Alkaline Electrolyte.” *Journal of the American Chemical Society* 142(36):15438–44.

Mokhlis, H., R. D. Daoudi, and M. Azzi. 2021. “Selective Leaching of Copper from Waste Printed Circuit Boards (Pcbs) Using Glycine as a Complexing Agent.” *Global Nest Journal* 23(1):90–96.

Morris Tom. 2022. “Sustainability in 2022: The e-Waste Problem.” *GWI*. Retrieved April 23, 2022 (https://blog.gwi.com/chart-of-the-week/sustainability-2022-e-waste/).

Nithya, Rajarathinam, Chandrasekaran Sivasankari, and Arunachalam Thirunavukkarasu. 2021. “Electronic Waste Generation, Regulation and Metal Recovery: A Review.” *Environmental Chemistry Letters* 19(2):1347–68.

Pekarkova, Zora, Ian D. Williams, Loretta Emery, and Rachel Bone. 2021. “Economic and Climate Impacts from the Incorrect Disposal of WEEE.” *Resources, Conservation and Recycling* 168(January).

Rajahalme, Joona, Siiri Perämäki, Roshan Budhathoki, and Ari Väisänen. 2021. “Effective Recovery Process of Copper from Waste Printed Circuit Boards Utilizing Recycling of Leachate.” *Jom* 73(4):980–87.

Reyna, Ana, Cristian Martín, Jaime Chen, Enrique Soler, and Manuel Díaz. 2018. “On Blockchain and Its Integration with IoT. Challenges and Opportunities.” *Future Generation Computer Systems* 88(2018):173–90.

Sarwar, M. T., Z. Hanhui, J. Yang, A. Maqbool, R. K. M. Khan, and B. Ullah. 2021. “Copper Recovery by Slurry Electrolysis Using Ionic Liquids from Waste Printed Circuit Boards.” *Global Nest Journal* 23(2):226–31.

Sethurajan, Manivannan, and Eric D. van Hullebusch. 2019. “Leaching and Selective Recovery of Cu from Printed Circuit Boards.” *Metals* 9(10):1–12.

Shittu, Olanrewaju S., Ian D. Williams, and Peter J. Shaw. 2021. “Global E-Waste Management: Can WEEE Make a Difference? A Review of e-Waste Trends, Legislation, Contemporary Issues and Future Challenges.” *Waste Management* 120:549–63.

Sverdrup, Harald Ulrik, Anna Hulda Olafsdottir, and Kristin Vala Ragnarsdottir. 2019. “On the Long-Term Sustainability of Copper, Zinc and Lead Supply, Using a System Dynamics Model.” *Resources, Conservation and Recycling: X* 4(December 2018):100007.

Tabelin, Carlito Baltazar, Ilhwan Park, Theerayut Phengsaart, Sanghee Jeon, Mylah Villacorte-Tabelin, Dennis Alonzo, Kyoungkeun Yoo, Mayumi Ito, and Naoki Hiroyoshi. 2021. “Copper and Critical Metals Production from Porphyry Ores and E-Wastes: A Review of Resource Availability, Processing/Recycling Challenges, Socio-Environmental Aspects, and Sustainability Issues.” *Resources, Conservation and Recycling* 170(April):105610.

Tesfaye, Fiseha, Daniel Lindberg, Joseph Hamuyuni, Pekka Taskinen, and Leena Hupa. 2017. "Improving Urban Mining Practices for Optimal Recovery of Resources from E-Waste." *Minerals Engineering* 111(June):209–21.

United States Environmental Protection Agency, EPA. 2019. "Cleaning Up Electronic Waste (E-Waste)." Retrieved (https://www.epa.gov/international-cooperation/cleaning-electronic-waste-e-waste#:~:text=What is E-Waste%3F,or given to a recycler.).

Wang, Jiqin, Zhouman Huang, Deze Yang, Xiangfei Zeng, Mengjun Chen, Jiancheng Shu, Zhi Sun, Shuhui Sun, and Zhengxue Xiao. 2021. "A Semi-Scaled Experiment for Metals Separating and Recovering from Waste Printed Circuit Boards by Slurry Electrolysis." *Process Safety and Environmental Protection* 147:37–44.

Yang, Deze, Yingying Chu, Jianbo Wang, Mengjun Chen, Jiancheng Shu, Furong Xiu, Zhonghui Xu, Shuhui Sun, and Shu Chen. 2018. "Completely Separating Metals and Nonmetals from Waste Printed Circuit Boards by Slurry Electrolysis." *Separation and Purification Technology* 205(January):302–7.

Yeoh, Angeli. 2020. "The UN Says Humanity Recorded the Highest Amount of E-Waste in 2019. Here's How to Discard Unwanted Electronics Reponsibly." *The Star*.

Yong, Yun Siew, Yi An Lim, and I. M. S. K. Ilankoon. 2019. "An Analysis of Electronic Waste Management Strategies and Recycling Operations in Malaysia: Challenges and Future Prospects." *Journal of Cleaner Production* 224:151–66.

Zhang, Ding jun, Li Dong, Yong tong Li, Yanfei Wu, Ying xia Ma, and Bin Yang. 2018. "Copper Leaching from Waste Printed Circuit Boards Using Typical Acidic Ionic Liquids Recovery of E-Wastes' Surplus Value." *Waste Management* 78:191–97.

Adeola, Francis O. 2018. *WEEE Generation and the Consequences of Its Improper Disposal*. Elsevier Ltd.

Andrew, Sickle Van. 2017. "Copper: Now a Precious Metal." *Money Week*. Retrieved April 23, 2022 (https://moneyweek.com/475695/copper-now-a-precious-metal).

Ankit, Lala Saha, Virendra Kumar, Jaya Tiwari, Sweta, Shalu Rawat, Jiwan Singh, and Kuldeep Bauddh. 2021. "Electronic Waste and Their Leachates Impact on Human Health and Environment: Global Ecological Threat and Management." *Environmental Technology and Innovation* 24:102049.

Ardelean, M., E. Ardelean, G. Mihut, and O. Găianu. 2021. "The Importance of Recovering Precious Metals from Waste Electrical and Electronic Equipment." *Journal of Physics: Conference Series* 1781(1).

Basov, Vladimir. 2021. "Mining News Chile Was the Largest Copper Producer in 2020; Top Copper Countries Felt Impact of the Pandemic - Report."

Borthakur, Anwesha. 2022. "Design, Adoption and Implementation of Electronic Waste Policies in India." *Environmental Science and Pollution Research* (0123456789).

Choubey, Sourav, Prerna Goswami, and Shina Gautam. 2021. "Recovery of Copper from Waste PCB Boards Using Electrolysis." Pp. 2656–59 in *Materials Today: Proceedings*. Vol. 42. Elsevier.

Correa, Mónica Maria Jiménez, Flávia Paulucci Cianga Silvas, Paula Aliprandini, Viviane Tavares de Moraes, David Dreisinger, and Denise Crocce Romano Espinosa. 2018. "Separation of Copper from a Leaching Solution of Printed Circuit Boards by Using Solvent Extraction with D2EHPA." *Brazilian Journal of Chemical Engineering* 35(3):919–30.

Environment, Department of. n.d. "E-Waste Infographic." Retrieved April 10, 2022 (https://ewaste.doe.gov.my/index.php/infographic/).

Harmsen, J. H. M., A. L. Roes, and M. K. Patel. 2013. "The Impact of Copper Scarcity on the Efficiency of 2050 Global Renewable Energy Scenarios." *Energy* 50(1):62–73.

He, Jingfeng, Jiaxin Yang, Sarwar Muhammad Tariq, Chenlong Duan, and Yuemin Zhao. 2020. "Comparative Investigation on Copper Leaching Efficiency from Waste Mobile Phones Using Various Types of Ionic Liquids." *Journal of Cleaner Production* 256:120368.

Ilankoon, I. M. S. K., Yousef Ghorbani, Meng Nan Chong, Gamini Herath, Thandazile Moyo, and Jochen Petersen. 2018. "E-Waste in the International Context – A Review of Trade Flows, Regulations, Hazards, Waste Management Strategies and Technologies for Value Recovery." *Waste Management* 82:258–75.

Ismail, Haikal, and Marlia M. Hanafiah. 2019. "Discovering Opportunities to Meet the Challenges of an Effective Waste Electrical and Electronic Equipment Recycling System in Malaysia." *Journal of Cleaner Production* 238.

Kharade, Sangram B., Rajvardhan K. Chougale, Umesh B. Barache, Kallappa R. Sanadi, Kishan C. Rathod, Shashikant H. Gaikwad, Yong Chein Ling, Mansing A. Anuse, and Ganesh S. Kamble. 2022. "Design and Optimization of Sensitive Analytical Spectrophotometric Method for Micro Determination of Copper(II) from e-Waste by Using of Novel Chromogenic Extractant." *Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy* 267:120502.

Kumar, Sashi, and Shatrunjay Rawat. 2018. "Future E-Waste: Standardisation for Reliable Assessment." *Government Information Quarterly* 35(4):S33–42.

Li, Feifan, Mengjun Chen, Jianchen Shu, Mehran Shirvani, Yungui Li, Zhi Sun, Shuhui Sun, Zhong Hui Xu, Kaibin Fu, and Shu Chen. 2019. "Copper and Gold Recovery from CPU Sockets by One-Step Slurry Electrolysis." *Journal of Cleaner Production* 213:673–79.

Liu, Kaixin, Shuquan Huang, Yangxin Jin, Lan Ma, Wen-Xiong Wang, and Chun Ho Lam. 2022. "A Green Slurry Electrolysis to Recover Valuable Metals from Waste Printed Circuit Board (WPCB) in Recyclable PH-Neutral Ethylene Glycol." *Journal of Hazardous Materials* 128702.

Lu, Xu, Chongqin Zhu, Zishan Wu, Jin Xuan, Joseph S. Francisco, and Hailiang Wang. 2020. "In Situ Observation of the PH Gradient near the Gas Diffusion Electrode of CO2Reduction in Alkaline Electrolyte." *Journal of the American Chemical Society* 142(36):15438–44.

Mokhlis, H., R. D. Daoudi, and M. Azzi. 2021. "Selective Leaching of Copper from Waste Printed Circuit Boards (Pcbs) Using Glycine as a Complexing Agent." *Global Nest Journal* 23(1):90–96.

Morris Tom. 2022. “Sustainability in 2022: The e-Waste Problem.” *GWI*. Retrieved April 23, 2022 (https://blog.gwi.com/chart-of-the-week/sustainability-2022-e-waste/).

Nithya, Rajarathinam, Chandrasekaran Sivasankari, and Arunachalam Thirunavukkarasu. 2021. “Electronic Waste Generation, Regulation and Metal Recovery: A Review.” *Environmental Chemistry Letters* 19(2):1347–68.

Pekarkova, Zora, Ian D. Williams, Loretta Emery, and Rachel Bone. 2021. “Economic and Climate Impacts from the Incorrect Disposal of WEEE.” *Resources, Conservation and Recycling* 168(January).

Rajahalme, Joona, Siiri Perämäki, Roshan Budhathoki, and Ari Väisänen. 2021. “Effective Recovery Process of Copper from Waste Printed Circuit Boards Utilizing Recycling of Leachate.” *Jom* 73(4):980–87.

Reyna, Ana, Cristian Martín, Jaime Chen, Enrique Soler, and Manuel Díaz. 2018. “On Blockchain and Its Integration with IoT. Challenges and Opportunities.” *Future Generation Computer Systems* 88(2018):173–90.

Sarwar, M. T., Z. Hanhui, J. Yang, A. Maqbool, R. K. M. Khan, and B. Ullah. 2021. “Copper Recovery by Slurry Electrolysis Using Ionic Liquids from Waste Printed Circuit Boards.” *Global Nest Journal* 23(2):226–31.

Sethurajan, Manivannan, and Eric D. van Hullebusch. 2019. “Leaching and Selective Recovery of Cu from Printed Circuit Boards.” *Metals* 9(10):1–12.

Shittu, Olanrewaju S., Ian D. Williams, and Peter J. Shaw. 2021. “Global E-Waste Management: Can WEEE Make a Difference? A Review of e-Waste Trends, Legislation, Contemporary Issues and Future Challenges.” *Waste Management* 120:549–63.

Sverdrup, Harald Ulrik, Anna Hulda Olafsdottir, and Kristin Vala Ragnarsdottir. 2019. “On the Long-Term Sustainability of Copper, Zinc and Lead Supply, Using a System Dynamics Model.” *Resources, Conservation and Recycling: X* 4(December 2018):100007.

Tabelin, Carlito Baltazar, Ilhwan Park, Theerayut Phengsaart, Sanghee Jeon, Mylah Villacorte-Tabelin, Dennis Alonzo, Kyoungkeun Yoo, Mayumi Ito, and Naoki Hiroyoshi. 2021. “Copper and Critical Metals Production from Porphyry Ores and E-Wastes: A Review of Resource Availability, Processing/Recycling Challenges, Socio-Environmental Aspects, and Sustainability Issues.” *Resources, Conservation and Recycling* 170(April):105610.

Tesfaye, Fiseha, Daniel Lindberg, Joseph Hamuyuni, Pekka Taskinen, and Leena Hupa. 2017. “Improving Urban Mining Practices for Optimal Recovery of Resources from E-Waste.” *Minerals Engineering* 111(June):209–21.

United States Environmental Protection Agency, EPA. 2019. “Cleaning Up Electronic Waste (E-Waste).” Retrieved (https://www.epa.gov/international-cooperation/cleaning-electronic-waste-e-waste#:~:text=What is E-Waste%3F,or given to a recycler.).

Wang, Jiqin, Zhouman Huang, Deze Yang, Xiangfei Zeng, Mengjun Chen, Jiancheng Shu, Zhi Sun, Shuhui Sun, and Zhengxue Xiao. 2021. “A Semi-Scaled Experiment for Metals Separating and Recovering from Waste Printed Circuit Boards by Slurry Electrolysis.” *Process Safety and Environmental Protection* 147:37–44.

Yang, Deze, Yingying Chu, Jianbo Wang, Mengjun Chen, Jiancheng Shu, Furong Xiu, Zhonghui Xu, Shuhui Sun, and Shu Chen. 2018. “Completely Separating Metals and Nonmetals from Waste Printed Circuit Boards by Slurry Electrolysis.” *Separation and Purification Technology* 205(January):302–7.

Yeoh, Angeli. 2020. “The UN Says Humanity Recorded the Highest Amount of E-Waste in 2019. Here’s How to Discard Unwanted Electronics Reponsibly.” *The Star*.

Yong, Yun Siew, Yi An Lim, and I. M. S. K. Ilankoon. 2019. “An Analysis of Electronic Waste Management Strategies and Recycling Operations in Malaysia: Challenges and Future Prospects.” *Journal of Cleaner Production* 224:151–66.

Zhang, Ding jun, Li Dong, Yong tong Li, Yanfei Wu, Ying xia Ma, and Bin Yang. 2018. “Copper Leaching from Waste Printed Circuit Boards Using Typical Acidic Ionic Liquids Recovery of E-Wastes’ Surplus Value.” *Waste Management* 78:191–97.