International Journal of Membrane Science and Technology, 2023, Vol. 10, No. 5, pp 196-208

An Electrochemical Approach to Recycle and Extraction of Metals from Electronic Waste

Sourav Choubey[1*], Prerna Goswami[2], Shina Gautam[3]

[1,2]*Institute of Chemical Technology, Matunga, Mumbai, Maharashtra,India, 400019*

[1,3]*Shroff S.R.Rotary Institute of Chemical Technology, UPL University of Sustainable Technology, Ankleshwar, Gujarat, India, 393135; E-mail: souravchoubey1@gmail.com*

Abstracts: Scraped e-waste is a result of increased production and demand for Electrical and Electronic Appliances (EEA). Because the discarded EEA contains heavy metals, it must be carefully disposed of in order to prevent any environmental harm. Researchers and pollution control boards in the relevant nations are taking notice of this rapid increase in e-waste in order to properly dispose of and recycle the garbage. A variety of materials, including gold, silver, copper, iron, etc., are included in e-waste. For research, it is crucial to safely and sustainably remove all of those metals from old electrical and electronic products. Electrochemical, pyrometallurgical, hydrometallurgical, and bioleaching methods for extracting metals from waste scrap have all evolved in the development of environmentally friendly and sustainable technologies. Among all the methods for extracting metals that are accessible, electrochemical extraction is one of the most admired. One of the reported most effective techniques among all of these is electrochemical. (80-95%) of the metal is reported to have been extracted using the previously stated procedure and various electrolytes. Additionally, after processing and chemical leaching of the Waste, various combinations of electrodes are employed to independently recover the metals from E-Waste is presented in the paper. The study presents an electrolysis method for copper extraction. In order to achieve the highest Cu extraction efficiency, a variety of electrode and electrolyte combinations are used in this study work, along with an energy model for the process. adjusting the electrolyte content to examine the Cu extraction rate for improved extraction efficiency. It is possible to extract copper with 99% efficiency using this electrolysis method.

Keywords: Electrochemical, E-Waste, Extraction, Recycling.

1. INTRODUCTION

Due to the associated complexity in the E-Waste, researchers are extremely concerned about the rate of growth of EEA. [1][2][3] As a result of wasteful trash disposal contaminating the land and soil, the rise in e-waste volume raises serious concerns about its effects on society and the environment. The Waste contains more than 30 different types of metal, including valuable metals like Gold, Platinum, Silver, and others. If recycled properly, these precious metals can be a lucrative business opportunity. In the developing countries like India, whose GDP (Gross Domestic Product) is growing at the fastest rate in the world, e-waste output is rapidly increasing. Although the CPCB (Central Pollution Control Board), India has established some guidelines for the collection and recycling of electronic waste, India is still unable to keep up with the production of E-Waste since the capability for recycling is only 20% of the garbage being produced, as detailed in Chapter 1. [4]

Electrical and electronic waste has grown quickly as a result of technological development and national economic expansion, raising serious environmental and health concerns [5][6]. There is a potential that the waste may be illegally burned and dumped because 83% of the total waste produced worldwide was not documented [7][8]. Only 22% of the e-waste that was collected in India was recycled [4]. Asia generates 46.4% of the world's waste, which is a serious worry, but the fundamental issue is that only 11% of the rubbish is documented.

Despite the relatively restricted and primitive recycling practises for outdated personal computers, the burden of disposal and associated costs are significantly reduced by the metal value recovered from computer waste. Even though a sizeable amount of computer waste is recycled during the process, the unscientific methodology used for material salvaging comes with a very high risk to the environment and human health as a logical consequence of the implementation of rudimentary recycling and recovery processes and their detrimental effects on both life and the environment. In addition to the difficulties already mentioned, this recycling method has inherent limitations on the recovery of both metals and non-metals. This processing procedure does not actually contribute value despite the partial recovery of materials like copper, gold, silver, aluminium, iron, tin, lead, and plastics, for example, because so many important metallic elements like germanium, barium, platinum, antimony, cobalt, and nickel are still lost.

According to a study, developing nations like India, China, and Brazil are giving more weight to economic considerations than to environmental laws governing the recycling of e-waste [9]. The huge increase in e-waste globally has made its management a primary priority for science and business. Numerous research on the various aspects of managing e-waste have been undertaken and published globally. The complexity of treating trash on a state and national level was first the main focus [10][11]. For the extraction and reuse of metals, a number of recycling procedures using chemical, mechanical, and thermal methods have been developed [12][13][14]. Despite the fact that there aren't many research articles on the subject that give a thorough overview of the procedure. Manually choosing, categorising, and analysing published works might be time-consuming and biassed due to the exponential growth of publications [15]. E-waste requires substantial recycling because it is made up of such a diverse range of materials. Various precious metals and dangerous materials can be found in e-waste. Therefore, strict and proper recycling practises are required to reduce threats to the environment and human health. Landfills, incinerators, and open flames should not be used to dispose of electronic waste [16]. With the development of technology, various novel recycling techniques with lower environmental effect and higher metal recovery rates have arisen. The three main stages of the e-waste recycling process are e-waste collection, e-waste pretreatment shown in Figure. 1, and e-waste final treatment. E-waste pretreatment is a crucial step in the recycling process [17].

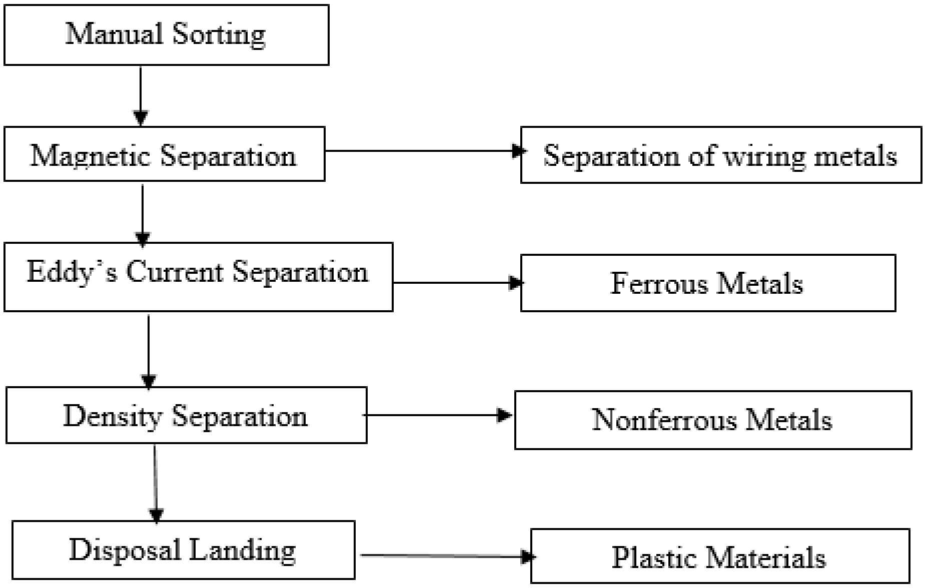

Figure 1. E-Waste pre-treatment steps.

The use and recycling of the non-metallic parts present in e-waste PCBs, which contain at least 70% non-metallic parts, has been the subject of numerous research [18][19]. Glass fibre and thermosetting resin are the main components of printed circuit boards' non-metallic parts. Additionally, these resins cannot be remoulded due to their chain structure [20]. To further purify metals recovered from e-waste and retrieve trace metals/elements, various metallurgical techniques can be applied [20]. Pretreatment of e-waste is typically not necessary for pyrometallurgical processes, but it is for hydrometallurgical and biometallurgical processes in order to separate metals and non-metals.

The PCB that resulted from the amalgamation has a about 40% metal, 30% ceramic, and 30% plastic composition [21][22]. On the other hand, waste PCBs have a higher concentration of valuable metals than natural ore, such as gold and palladium. Because recycling PCBs has positive economic and environmental effects [23], it is more important to extract precious metals and other non-ferrous metals from PCB Boards. Non-ferrous metals are recovered from used PCB boards using a variety of techniques, including electrochemical [24], pyro-metallurgical [25], hydrometallurgical [26], and bioleaching [25][26][27]. Due to their environmental friendliness, extreme efficacy, and excellent extraction purity, electrochemical techniques have generated the most interest of any technology for the extraction of metal [28]. According to research [29], extracting copper at a concentration of 30 g/L $CuSO_4.5H_2O$, 60 g/L NaCl, and 150 g/L H_2SO_4 with an 80 mA/cm^2 current density can yield a purity of up to 99.3% for the copper. Another study found that the electro kinetic approach [30] for extracting copper resulted in copper with a purity of 97.6%.

In this study, copper is removed from the scraped Intel dual-core motherboard using an electrochemical approach. Different combinations of anode and cathode are utilised in an electrochemical process with varying concentrations of H_2SO_4, HCl, and H_2O_2. For the environmentally friendly electrochemical extraction of copper, an energy model is described. The PCB first underwent pre-treatment, as depicted in Figure. 2, which entails disassembling, shredding, and crushing the components to (1-2)mm in size[31][32]. Eddy current technique, electrostatic separator, or density separator are used to separate nonferrous metals from the pre-treated PCB powders for the electrochemical process of extracting metals from PCB boards [33]. When compared to other metals, the nonferrous metals thus discovered possess the highest proportion of copper [34].

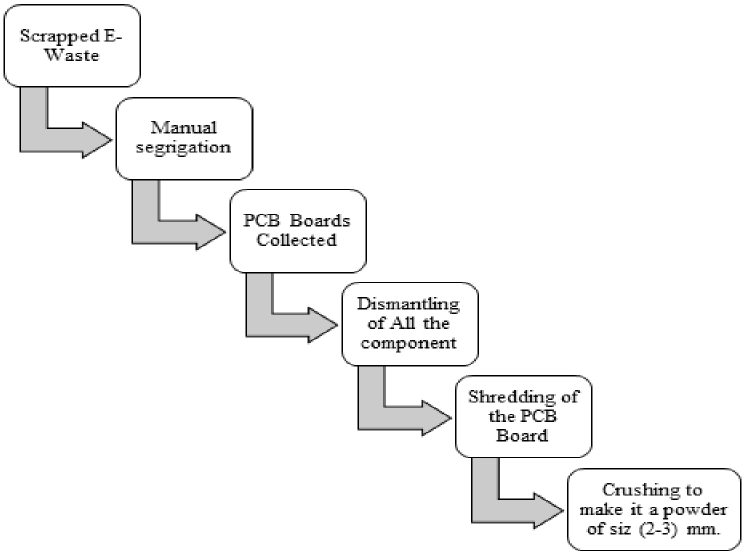

Figure 2. Pretreatment process of PCB Recycling.

2. MATERIEL AND METHODS

For the investigation, abandoned computers, laptops, printers, and refrigerators were removed. The Figure shows that each E-Waste is carefully segregated, and PCB boards were eliminated while taking the environment's consequences into account. The built replicas of an old monitor screen, mouse, keyboard, and CPU were methodically weighed and dismantled as indicated in Figure 3. These tools included a screwdriver, hammer, deshouldering rod, plier, mortar and pestle, and tin scissors. Pliers, hammers, and a de-shouldering rod were used to etch the WPCBs that were placed over the non-metallic parts. In order to ensure everyone's safety, personal protective equipment (PPE) was worn while carefully removing each PCB board in a well-ventilated room.

Figure 3. Removed PCB Boards from Various E-Waste

2.1. Characteristics of the Metal Powder

The electrolyte was developed taking into account the non-ferrous metals that will be eliminated. A 10 gm sample of waste PCB powder was ground up for the extraction experiment, and it was dissolved in several solvents that also served as the electrolytes for the electrolysis tests. As can be shown in Figure. 4, metal detection in the metal powder was found utilising X-ray spectroscopy (EDS).

As seen in Figure, the surface topology and morphology of the support and several catalysts synthesised using the co-precipitation approach are examined using SEM. As shown in Figure. 4 (A), the mesoporous support SBA-15 has a curved cylindrical configuration. The addition of Cu (II) and Mn (II) metals didn't change this morphology, as seen in Figure. 4 (B) , which attests to the preservation of the mesoporous support's physical structure and texture.

Energy Dispersive X-Ray Analysis (EDX) was used to do a compositional analysis of the synthesised SBA-15 support and catalysts. The synthesised material's presence in silica was successfully demonstrated by the SBA-15 EDX data (Figure. 4 (A)). The presence of copper and manganese metals was confirmed by the EDX spectra of the catalyst materials Cu/SBA-15 (Figure. 4 (B)), supporting the metal impregnation. The copper% from the EDX investigation was calculated using a small sample size and the assumption that the sample's composition was constant.

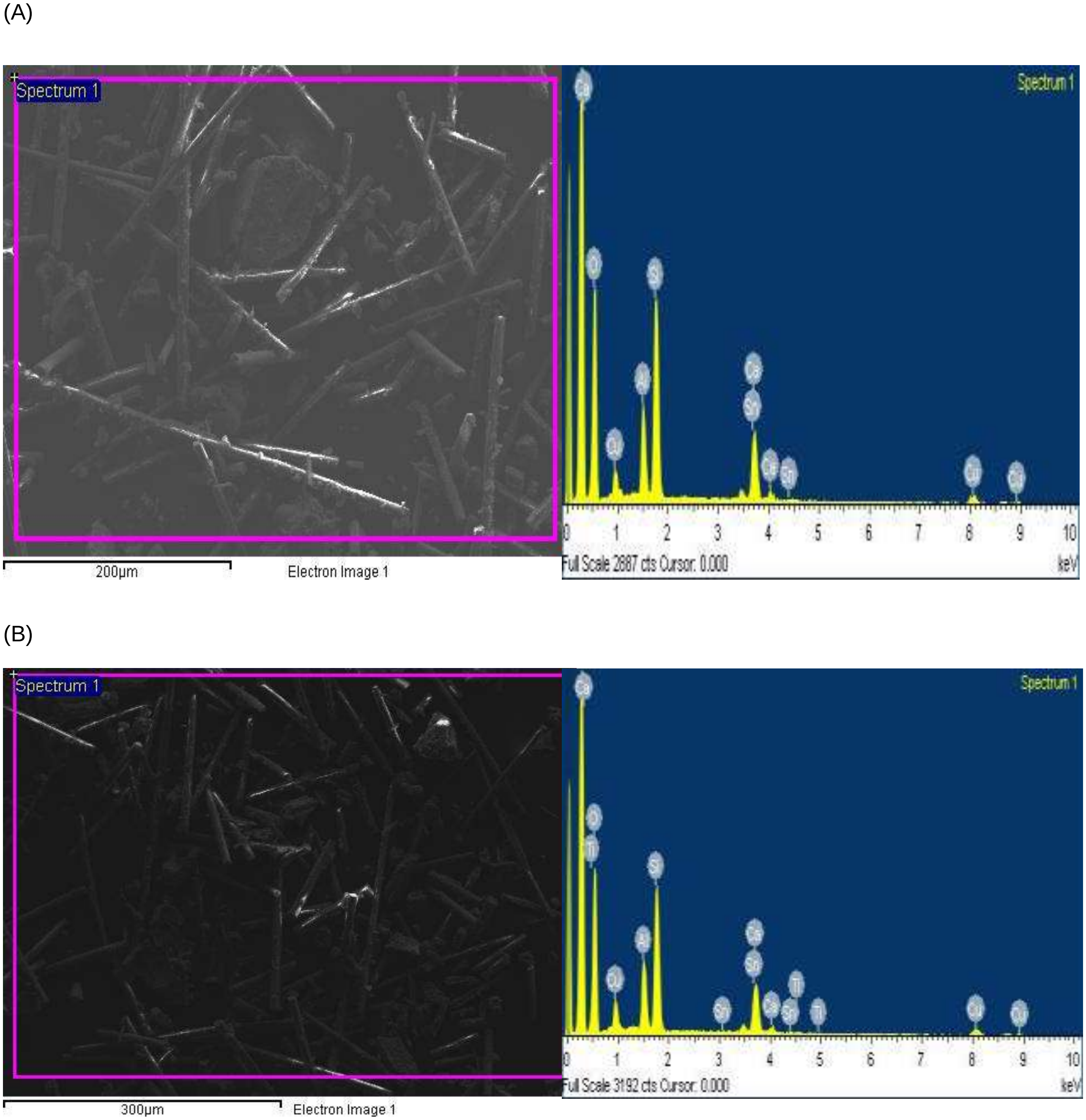

Figure 4: Analysis of (A) SBA-15, (B) Cu/SBA-15 using SEM and EDX.

2.2 : Presence of Metal in E-Waste:

The powdered E-Waste underwent initial chemical processing in order to test for the presence of metals. To determine whether metal was present in the solution, component-by-component analysis was performed. The hydrochloric acid and nitric acid solution Aquaregia (3:1) was used to leach the metal particles. For four hours, the trials were conducted at a temperature of 60^0C and a stirring speed of 300 rpm. For experimental purposes, each metal powder that was obtained from various PCB Boards and components was taken independently. Using a Shimadzu AA-7000 piece of equipment, an AAS (Atomic Absorption Spectrophotometer) study is performed to determine the amount of metals contained in the leached solution. The analysis was performed using an air coal gas flame at a temperature of 1800^{0}C.

Table 1: AAS Analysis result of Metal composition in different PCB Boards and components

Sample NO	ITEM	METALS (mg/L)							
		COPPER	ZINC	NICKEL	CHROMIUM	MANGANESE	LEAD	CADMIUM	IRON
1	printed circuit board of Xerox machine	10882.32	278.97	172.94	6.58	8.35	237.80	0.4481	238.34
2	Pentium 4 motherboard	11955.23	564.01	200.05	7.59	6.25	133.91	0.6406	251.91

The presence of metal in all the various PCB Boards and components was evaluated, as indicated in table 1, and it was discovered that copper was more prevalent in the tested components. Figure 4 illustrates the presence of metals by component. To extract copper from the metal powders, the components were removed one at a time.

2.3 Sample Preparation

For use in the investigations, WPCB samples, primarily from computer motherboards, were purchased at a waste appliance recycling facility. The HNO_3-H_2O_2-HF system was utilised to digest concentrated metal particles that had been mechanically and physically removed from WPCBs after being dried at 105^{0}C for 24 hours. To make the electrolyte, various electrolyte mixtures that enhanced copper leaching in the electrolyte medium were investigated.

Following the grinding operation, 20 gm of the powdered PCB Boards were first dissolved in 1 mole of H_2SO_4 and stirred for three hours at a speed of 300 rpm and a temperature of 60^{0}C. Following stirring, 1M of HCl was added to the mixture. The mixture was then stirred once more for 4 hours at the same speed and temperature specified in equations (1) through (3). By having two amine groups and two carboxylic acid groups with lone-pair electrons, the polyprotic acid EDTA chelates calcium and a number of other metal ions. In order to ensure that the waste powder was properly leached into the solution, 1M of EDTA was added to the mixture. The mixture was then stirred once more for 2 hours at a temperature of 60^{0}C and a stirring speed of 300 rpm. Leaching was followed by a further extraction of the EDTA using 10ml of H_2SO_4. Following the filtering procedure, the residues were once more collected for the experiments depicted in Figure 5. The remaining electrolytes also underwent the experiments.

Figure 5. Experimental set up for preparing Electrolyte

$$H_2SO_4 + HCl \rightarrow H_2O + Cl_2 + SO_2 \quad (1)$$

$$Cu + Cl_2 \rightarrow CuCl_2 \quad (2)$$

$$CuCl_2 + H_2SO_4 \rightarrow CuSO_4 + HCl \quad (3)$$

2.4: Electrolysis

A wide range of diverse electrolysis cells have been constructed for the extraction of metals from electrolytes in various research. The reactor cell was made of glass with dimensions of 12 by 8 by 7 cm and a volume of 672 cm^3 . The cathode and anode chambers were separated using an anti-acid filter cloth. The rector can hold up to one litre of electrolyte solutions. Which electrodes to employ depends on the metals that need to be recovered. Numerous investigations were conducted to determine the best set of electrodes for extracting copper from the electrolyte solution. Using a DC (0-30)V DC source, the potential between the electrodes was applied.

The potential of the cell, which is the difference between the oxidation (E^0_{Anode}) and reduction ($E^0_{Cathode}$) voltages, is given by equation number (4). In order to remove copper from the electrolyte solution, the equation (4) was solved, and the rectifier was set to the calculated voltage as shown in Figure 6.

$$E^0_{Cell} = E^0_{Cathode} - E^0_{Anode} \quad (4)$$

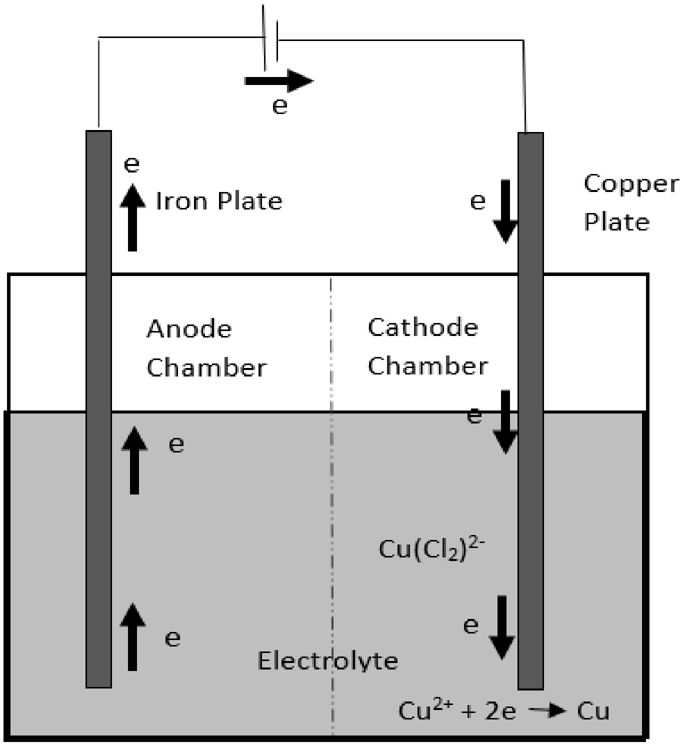

Figure 6. Electrolysis cell and Experiments carried out using Nernst equation.

3. RESULTS AND DISCUSSIONS

3.1. Effect of Parameters on Leaching

Numerous parameters were optimised in order to appropriately leach the e-waste in the electrolyte, and it was found that multiple metals were leaching in the solutions. To determine whether any metals had leached into the solution, the obtained solutions were sent for AAS analysis.

Solid to liquid mass, stirring temperature, and stirring speed were the variables that were optimised.

3.1.1 Mass of solids to liquids

E-waste particles in various proportions were added to 1 molar of solution, and the best leached solution was checked by observation. At a stirring temperature of 600C and a stirring speed of 300 rpm, the procedure was resumed for all the samples collected as listed in the table.

3.1.1.1 Sample 1: A Xerox machine's printed circuit board

In the 1M electrolyte solutions, the processed powder from the printed circuit board of the xerox machine was taken in 1gm, 2gm, 5gm, and 10gm portions, respectively. The AAS analysis report is provided in table 4.2.

Table 2: AAS Analysis report for a Xerox machine's printed circuit board.

METALS (mg/L)						
Sample 1						
PCB powder (g)	**COPPER**	**ZINC**	**NICKEL**	**CHROMIUM**	**LEAD**	**IRON**
1	1624	36.57	24.04	2.489	72.365	26.35
2	3876	74.28	39.11	3.368	106.367	41.09
5	6788	176.24	98.47	5.289	147.741	1149.25
10	**10882.322**	**278.9742**	**172.9434**	**6.5826**	**237.8011**	**2386.3379**

As we add more solids to the 1 m of the electrolyte solutions, the leaching is improving. The graph in Figureure 7 almost lines up with copper. Iron was the next prominent metal, whereas other metals barely leached compared to copper.

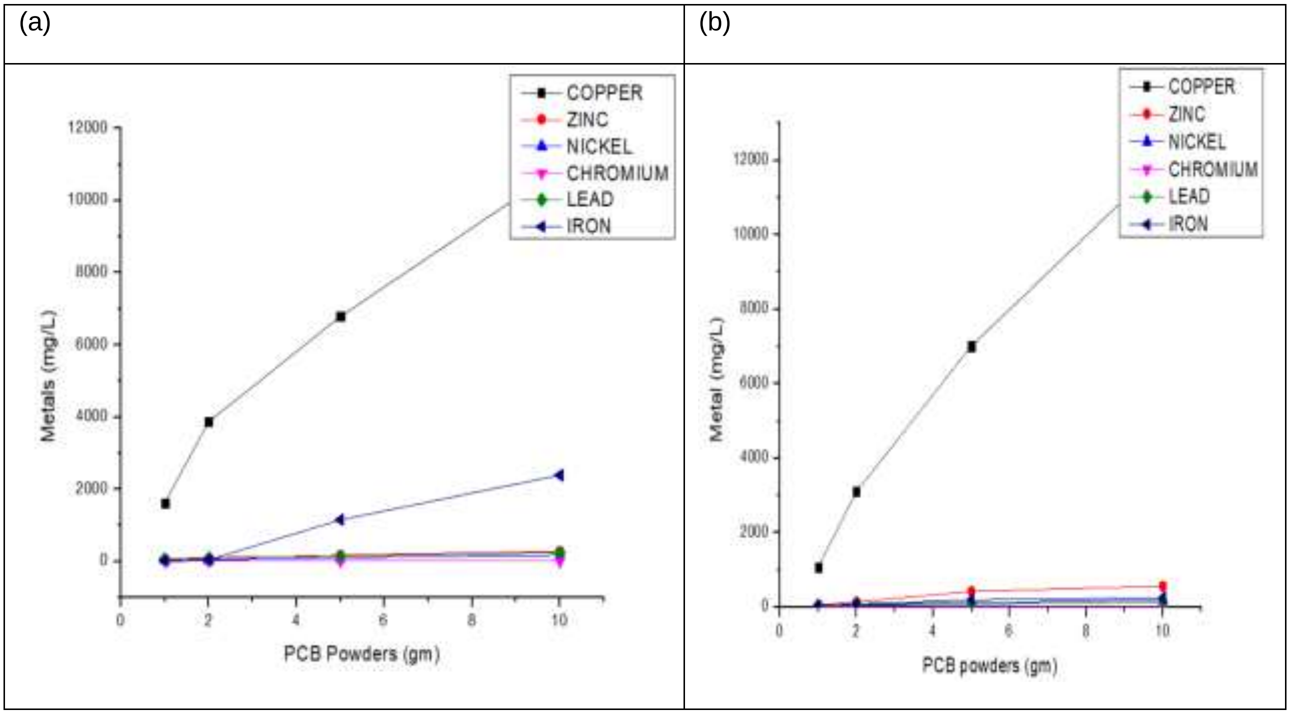

Figure 7. Different metals for (a) sample 1 and (b) sample 2 leached with different amounts of PCB powder.

3.1.1.2 Pentium 4 motherboard, Sample 2

The processed Pentium 4 motherboard powder was weighed out at 1gm, 2gm, 5gm, and 10gm in 1M electrolyte solutions, respectively. The AAS analysis data is provided in table 3.

Table 3: Pentium 4 motherboard AAS Analysis report.

METALS (mg/L)						
Sample 2						
pcb powder (g)	**COPPER**	**ZINC**	**NICKEL**	**CHROMIUM**	**LEAD**	**IRON**
1	1077	61.235	40.02	4.22	10.281	41.214
2	3104	139.77	71.17	6.74	36.241	82.141
5	7009	421.66	121.96	7.41	82.334	197.232
10	**11955.227**	**564.0118**	**200.0534**	**7.5964**	**133.9137**	**251.9072**

As we add more solids to the 1 m of the electrolyte solutions, the leaching is improving. The graph in the illustration almost perfectly lines up with copper. In comparison to Cu, other metals are almost insignificant.

3.2.1.3 Sample 3: a motherboard with an Intel duel core

The processed powder from an Intel dual core mother board was weighed out at 1gm, 2gm, 5gm, and 10gm in 1M electrolyte solutions, respectively. The AAS analysis report is provided in table 4.

Table 4. : AAS Analysis report for an Intel two core mother board

METALS (mg/L)						
Sample 3						
pcb powder (g)	**COPPER**	**ZINC**	**NICKEL**	**CHROMIUM**	**LEAD**	**IRON**
1	2866	76.34	9.06	0.432	17.31	14.04
2	6784	120.28	13.86	1.145	38.23	44.12
5	14698	397.63	57.64	1.588	82.04	89.24
10	**22193.806**	**1726.2589**	**393.563**	**5.5689**	**180.0859**	**169.1783**

3.1.2 : Stirring Speed and Temperature

The temperature and speed of stirring are two crucial factors in ensuring that the powdered waste is appropriately leached in the solution. For five hours in a 1M solution, 5gm of powdered waste was used for each experiment. Stirring speed was adjusted from 100 to 500 rpm with increments of 100, and temperature was adjusted from (40 to 120)^{0}C with increments of 20^{0}C. as depicted in the Figure 8, Cu leaching

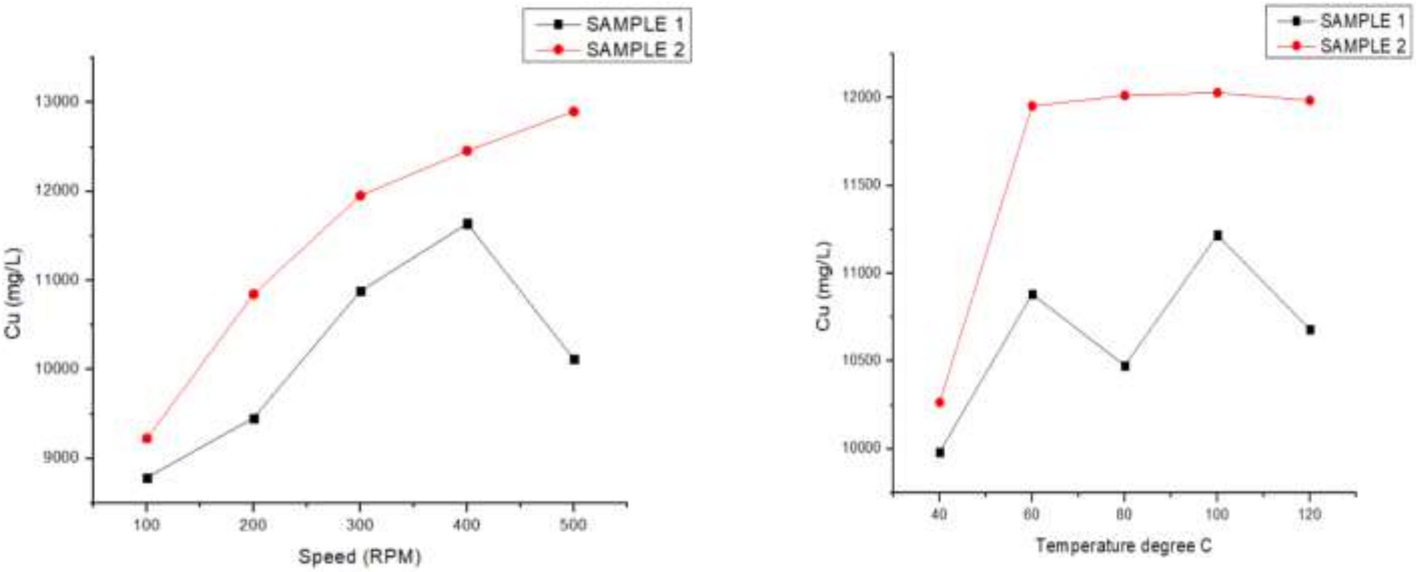

Figure 8. Cu leaching with varying rpm and temperature

According to Figure. 8, practically all samples leach copper more effectively when the stirring is done at a speed of 300 rpm and a temperature between (60 and 80)°C. Initial temperature increases cause a greater amount of leaching, and when the temperature approaches 100^0C, more samples experience less leaching. If the stirring speed were examined, Cu leaching first rose as the speed increased from 100 to 300 rpm, and for some samples, the leaching increased even more when the speed was increased to 500 rpm. However, after 300 rpm, it is seen that the leaching of Cu is virtually steady or decreasing in nature across all samples.

3.2 Effect of current density

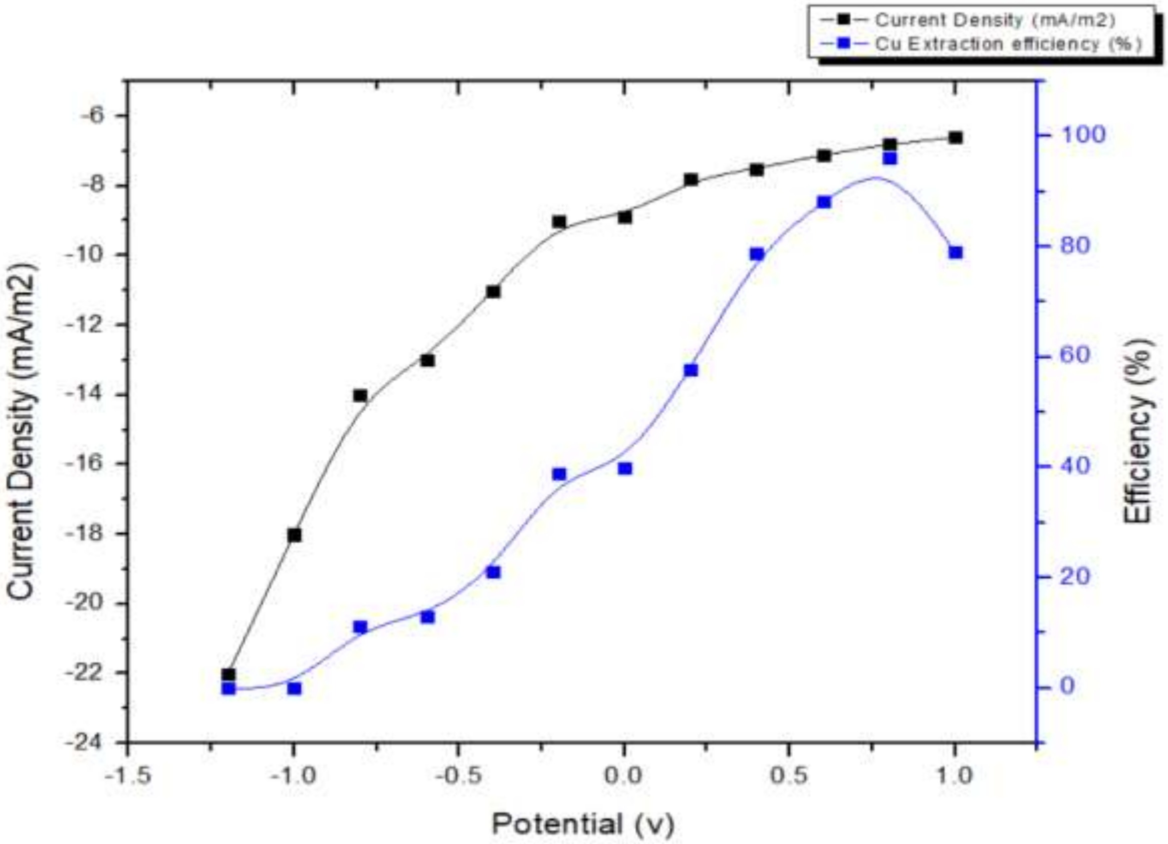

Figure 9. The effect of Nernst potential on Current density and extraction efficiency.

As seen in the Figure 9 the extraction efficiency of copper was increased with the increase of current density from -28mA/m^2 to -8mA. With the increase in current density the extraction efficiency also increases. Initially the current density was very low so the ions were not able to exchange through the membrane cell and there was no extraction initially. So at -2.0 V the extraction of the Cu was around (0-5) % and the current density was -24 mA/m^2.

3.3 Efficiency of Extraction

A graphite metal strip was used in the first step as both the cathode and the anode, and all of the samples had an extraction efficiency of 60%. The extraction efficiency was estimated using the following equation no. 5 and is given in table 5. Copper powder was recovered from the cathode chamber.

$$\eta_{Cu} = \frac{S_{Cu} - F_{Cu}}{S_{Cu}} \times 100\% \tag{5}$$

Where, S_{Cu} = Initial Metal Present in the Sample (gm) and

η_{Cu} =% Metal Extraction Efficiency

F_{Cu} = Metal present in the electrolyte (gm) after electrolysis.

Table 4 Cu extraction by varying different electrodes for all the samples.

Experiments for Cu Extraction	A	K	A	K	Sample No.
	Gr	**Gr**	**Zn**	**Fe**	
Before Electrolysis	12456.41		12456.41		1
After Electrolysis	4687.55		3047.23		
% Cu Recovery	62.37		75.54		
Before Electrolysis	13413.14		13413.14		2
After Electrolysis	5234.76		2971.34		
% Cu Recovery	60.97		77.85		

4. CHARACTERISTICS

For certain samples, the Cu obtained during electrolysis was in the form of CuO. At a temperature of 80^{0}C, the extracted CuO was dried, and the metal powder was gathered. The two samples' XRD analyses are displayed in Figure 10.

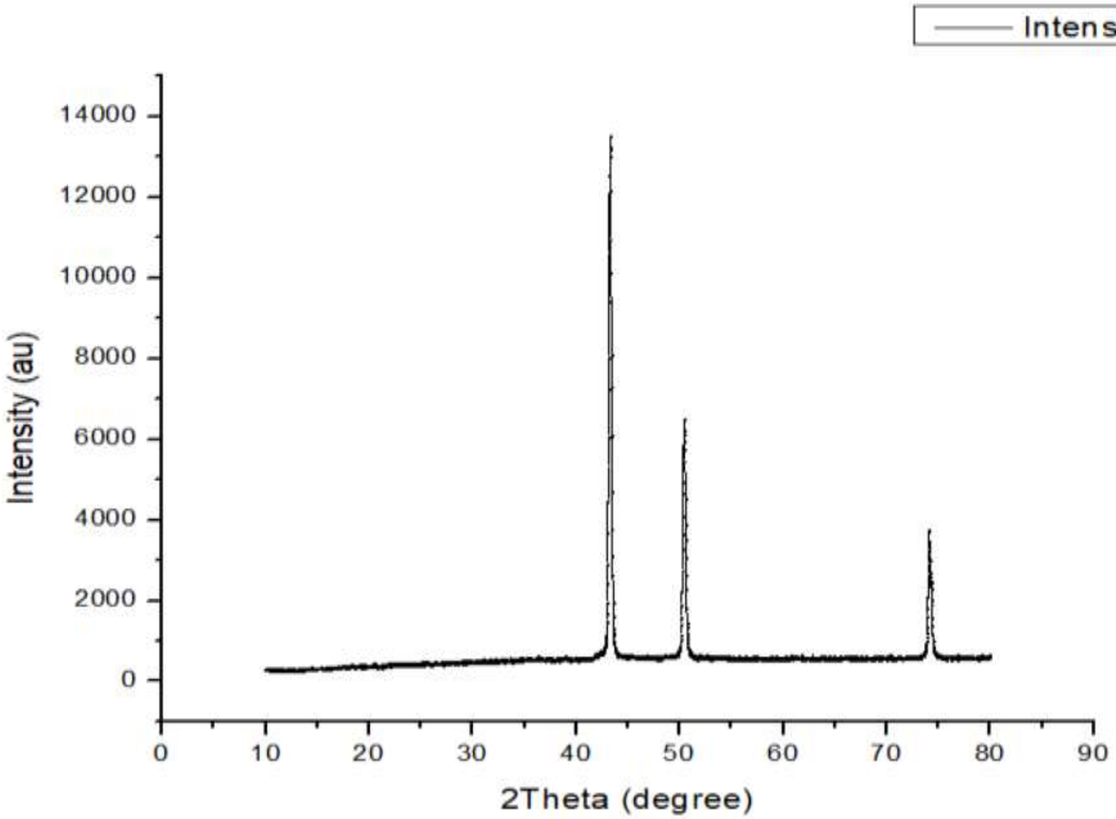

Figure 10: XRD Analysis of the sample

CONCLUSIONS

The Compared to the other elements, copper is present in PCB Board at a larger percentage. It is always suggested to take into account the selective components for selective separation of a particular metal in order to obtain a better extraction rate. The extraction requires careful electrolyte preparation.

REFERENCES

[1] Andersson, M, Söderman, ML & Sandén, BA 2019, 'Adoption of systemic and socio-technical perspectives in waste management, WEEE and ELV research', Sustainability (Switzerland), vol. 11, no. 6.

[2] Baldé, CP, Forti, V, Gray, V, Kuehr, R & Stegmann, P 2017, The global e-waste monitor 2017: quantities, flows, and resources, United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna.

[3] Xu, Y, Yeh, C-H, Liu, C, Ramzan, S & Zhang, L 2020, 'Evaluating and managing interactive barriers for sustainable e-waste management in China', Journal of the Operational Research Society, pp. 1-14.

[4] CPCB Annual Report 2020-2021.

[5] Matsakas L et al (2017) Green conversion of municipal solid wastes into fuels and chemicals. Electron J Biotechnol 26:69–83

[6] Bhuiya MMK et al (2020) Comparison of oil extraction between screw press and solvent (n-hexane) extraction technique from beauty leaf (Calophyllum inophyllum L.) feedstock. Ind Crops Prod 144:112024

[7] Statista (2020) Electronic waste generated worldwide from 2010 to 2019.

[8] Balde CP et al. (2017) The global e-waste monitor 2017. pp 1–116.

[9] Gupta, S., Modi, G., Saini, R., & Agarwala, V. (2014). A review on various electronic waste recycling techniques and hazards due to its improper handling. International Refereed Journal of Engineering and Science, 3(5), 5-17. ISSN: 2319-1821.

[10] Liu, F., Zheng, L. X., & Li, J. H. (2007). E-waste management in China, Japan and Korea: a comparative study. Environmental Pollution & Control, 39(1), 102e105 (in Chinese).

[11] Williams, I. D. (2016). Global metal reuse, and formal and informal recycling from electronic and other high-tech wastes. In R. M. Izatt (Ed.), Metal Sustainability: Global Challenges, Consequences, and Prospects (pp. 23e51). Oxford, UK: Wiley.

[12] S. Choubey , P. Goswami , S. Gautam, "An energy-efficient electrochemical process for the extraction of copper from scrap electrical and electronic circuit", Journal of Pharmaceutical Negative Results, 14(1),2023,pp 113–120. https://doi.org/10.47750/pnr.2023.14.01.018

[13] Li, J., Barwood, M., & Rahimifard, S. (2019). A multi-criteria assessment of robotic disassembly to support recycling and recovery. Resources, Conservation and Recycling, 140, 158-165.

[14] Van Schaik, A., & Reuter, M. A. (2012). 9 e shredding, sorting and recovery of metals from WEEE: linking design to resource efficiency. In V. Goodship, & Ab Stevels (Eds.), Waste Electrical and Electronic Equipment (WEEE) Handbook (pp. 163-211). Cambridge, UK: Woodhead Publishing.

[15] Jie Li, Shidi Zhang, Yanan Jiang, End-of-life management of electric and electronic equipment: A literature review based on mapping knowledge domains, Circular Economy, Volume 1, Issue 2, 2022, ISSN 2773-1677, https://doi.org/10.1016/j.cec.2022.100008.

[16] V Lakshmi, C H Satya and D Aravind, Electronic waste: overview, recycling and metal extraction methods, Conf. Series: Materials Science and Engineering, 1136 (2021) 012069, pp 1-13.

[17] S. Choubey , P. Goswami , S. Gautam, " Sustainable Approach for Metal Extraction from E-Waste: A Comprehensive literature review ", IEEE Sponsored third International Conference on Intelligent Sustainable Systems [ICISS 2020], (3-5) December, 2020, ISBN: 978- 1-7281-7088-6 ,Page No. 403-406. doi: 10.1109/ICISS49785.2020.9316121

[18] Guo J, Xu Z 2009 Recycling of non-metallic fractions from waste printed circuit boards: A review Journal of Hazardous Materials 168567–590 [18]

[19] Sohaili J, Muniyandi S.K, Mohamad S.S 2012 A review on printed circuit boards waste recycling technologies and reuse of recovered nonmetallic materials International Journal of Scientific & Engineering Research3 138–144.

[20] Ogunniyi IO, Vermaak MKG, Groot DR,. Chemical composition and liberation characterization of printed circuit board cumminution fines for beneficiation investigations. Waste Management 2009; 29: 2140-6.

[21] S. Choubey , P. Goswami , S. Gautam, “Recovery of Copper from Waste PCB Boards using Electrolysis”, Materials Today: Proceedings, Volume 42(5),2021,pp 2656-2659. https://doi.org/10.1016/j.matpr.2020.12.596

[23] Yuan CY, Zhang HC, McKenna G, Korzeniewski C, Li JZ. Experimental studies on cryogenic recycling of printed circuit board. Int J Adv Manuf Technol 2007; 34: 657-66.

[24] Q. Song, Y. Liu, L. Zhang, Z. Xu, Selective electrochemical extraction of copper from multi-metal e-waste leaching solution and its enhanced recovery mechanism, Journal of Hazardous Materials, Volume 407, 2021, 124799

[25] J. Willner, Extraction of metals from electric waste by bacterial leaching., Environment Protection Engineering .J. 2013,39.

[26] A. Khaliq, Metal Extraction process for electronic waste and existing industrial routes: A review and Australian Perspective, Resources 2014,3, 152-179.

[27] E. Ma, Recovery of Waste Printed Circuit Boards Through Pyrometallurgy, Electronic Waste Management and Treatment Technology, 2019, Pages 247-267

[28] W. Jin and Y. Zhang, Sustainable Electrochemical Extraction of Metal Resources from Waste Streams: From Removal to Recovery, ACS Sustainable Chemistry & Engineering 2020 8 (12), 4693-4707

[29] S. Zhang, Y. Li, R. Wang, Z. Xu, B. Wang, S. Chen, M. Chen,Superfine copper powders recycled from concentrated metal scraps of waste printed circuit boards by slurry electrolysis, Journal of Cleaner Production,Volume 152,2017,Pages 1-6.

[30] F. R. Xiu, F. S. Zhang, Recovery of copper and lead from waste printed circuit boards by supercritical water oxidation combined with electrokinetic process, Journal of Hazardous Materials, Volume 165, Issues 1–3, 2009,Pages 1002-1007.

[31] Sinha R.; Chauhan G.; A Novel eco-friendly hybrid approach for recovery and reuse of Copper from Electronic Waste, Journal of Environmental Chemical Engineering, 2018, 6, 1053-1061.

[32] Chu Y.; Mengjun Chen M.; Chen S.; Wang B.; Fu K.; Haiyan Chen H., Micro-copper powders recovered from waste printed circuit boards by electrolysis, Hydrometallurgy, 2015, 156, 52-157.

[33] L. Dascalescu, T. Zeghloul, A. Iuga, Electrostatic Separation of Metals and Plastics From Waste Electrical and Electronic Equipment, WEEE Recycling, 2016, 1-32.

[34] R. Jujuna, Q. Yiminga, X. Zhenming, Environment-friendly technology for recovering nonferrous metals from e-waste: Eddy current separation, Resources, Conservation and Recycling, 87 (2014), 109-116.

DOI: https://doi.org/10.15379/ijmst.v10i5.2458