



Quantitative Determination and Characterization of Metallic Constituents in Waste Printed Circuit Boards

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Abstract

The rapid global expansion of the electronics industry has led to a corresponding surge in electronic waste (e-waste), posing both environmental and economic challenges. Among the numerous e-waste components, waste printed circuit boards (WPCBs) are particularly significant due to their complex composition and high concentration of valuable metals such as copper (Cu), nickel (Ni), gold (Au), and iron (Fe), alongside hazardous substances that require careful management. This study aims to determine and characterize the metallic composition of WPCBs sourced from a local Malaysian e-waste recycling facility, with the goal of evaluating their potential for resource recovery and sustainable waste management. The metallic fraction of the boards was manually separated and subjected to acid digestion using concentrated hydrochloric acid (HCl) in a controlled microwave oven digester to ensure efficient dissolution of metal constituents. The resulting solutions were analyzed using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES), a technique renowned for its precision and sensitivity in multielemental quantification. Analytical results revealed that copper constituted the dominant metal (43.60%), followed by nickel (2.56%), while trace concentrations of gold (0.001%) and iron (0.001%) were also detected. Although these metal concentrations were slightly lower than those reported in some comparable studies, they confirm that WPCBs remain an economically attractive secondary source of strategic and precious metals. The observed discrepancies in metal yield are attributed to factors such as incomplete digestion, residual adhesive materials, and the encapsulation of metallic particles within non-metallic polymer matrices. These findings highlight the critical need to optimize pre-treatment and leaching conditions to enhance metal recovery efficiency. Beyond their economic relevance, improved processing of WPCBs could significantly reduce the environmental footprint associated with e-waste disposal, supporting circular-economy principles and sustainable materials management. This research therefore reinforces the role of advanced analytical techniques such as ICP-OES in guiding the development of efficient, environmentally sound recovery strategies for valuable metals from electronic waste streams.

Keywords

Waste Printed Circuit Boards (WPCBs)
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Metal recovery
ICP-OES analysis
Sustainable resource management

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Introduction

The exponential growth in the use of electronic devices across both developed and developing nations has become a global environmental concern due to the rapid increase in electronic waste (e-waste) generation (Rajesh et al., 2022). The proliferation of consumer electronics, coupled with shorter product life cycles and technological obsolescence, has led to the accumulation of vast quantities of discarded electrical and electronic equipment (EEE). Managing this growing waste stream presents major environmental, economic, and public health challenges worldwide.

Recycling and disposal of e-waste remain problematic, particularly in developing countries where informal recycling practices are widespread and often unregulated (Okeke et al., 2022). Inadequate handling, dismantling, and disposal methods can result in the release of a wide range of toxic pollutants into the surrounding environment. These include heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), as well as persistent organic pollutants like polybrominated diphenyl ethers (PBDEs) and phthalate esters (PAEs), all of which are known to pose severe risks to human health and ecosystems. Studies have consistently reported elevated levels of such contaminants in soil, air, water, and biota near e-waste recycling and disposal facilities (Bao et al., 2020).

Among the various components of electronic systems, printed circuit boards (PCBs) constitute a critical and ubiquitous part of nearly all modern electronic devices—from household appliances to telecommunications

and computing systems (Charles et al., 2020). Structurally, PCBs are composed of epoxy resin reinforced with glass fibers and laminated with thin copper films. They also contain connectors and contact points often coated with precious metals such as gold and silver to enhance conductivity and resistance to corrosion (Rajesh et al., 2022). Consequently, waste printed circuit boards (WPCBs) are both an environmental burden and a valuable secondary resource due to their high metal content and complex material composition.

Recycling of WPCBs offers significant environmental and economic benefits. It enables the recovery of valuable and scarce metals such as copper, nickel, silver, and gold, thereby conserving natural resources and reducing dependence on primary mining operations. Furthermore, efficient e-waste recycling contributes to pollution reduction, energy conservation, and resource circularity—key pillars of sustainable development. It also stimulates economic activity by supporting material recovery industries and creating employment opportunities in the recycling and manufacturing sectors (Charles et al., 2020).

However, the same components that make PCBs valuable also render them hazardous. Heavy metals and toxic substances—including lead, mercury, cadmium, and brominated flame retardants—are integral to their design and function (Liaquat et al., 2022). Improper handling, open burning, or crude acid leaching during recycling can release these hazardous materials into the environment, contaminating soil and water and posing chronic health risks to humans. Therefore, the sustainable

management of WPCBs requires a comprehensive understanding of their metal composition, recovery potential, and associated environmental risks.

Problem Statement

The continuous increase in global e-waste generation has emerged as one of the most pressing environmental and sustainability challenges of the 21st century. Waste printed circuit boards (WPCBs), a major component of e-waste, contain a complex mixture of precious and base metals that hold substantial economic value. However, their recovery remains inefficient and often environmentally hazardous, particularly in developing countries where informal recycling dominates. Current practices—such as open burning, crude acid leaching, and mechanical dismantling—release toxic substances including heavy metals, brominated flame retardants, and persistent organic pollutants into the environment, contaminating air, soil, and water resources. Despite their potential as a secondary source of valuable metals, comprehensive studies on the precise metal composition of WPCBs from locally generated e-waste are limited, especially in Southeast Asia. This knowledge gap hampers the optimization of recovery processes and the design of environmentally sound recycling technologies. Furthermore, variations in composition due to differences in device type, manufacturing technology, and lifespan complicate the development of standardized treatment methods.

Therefore, there is a critical need to systematically determine and characterize the metallic content of WPCBs using advanced analytical methods. Understanding the concentration and distribution of metals such

as copper, nickel, gold, and iron will not only aid in developing efficient recovery strategies but also help minimize environmental contamination associated with improper e-waste management.

Objectives of the Study

The main objective of this study is to determine the metal composition of waste printed circuit boards (WPCBs) obtained from a local Malaysian e-waste recycling facility, with a view to assessing their recovery potential and environmental implications.

The specific objectives are to:

1. Separate and prepare the metallic fraction of WPCBs for analytical determination.
2. Digest the metallic components using concentrated hydrochloric acid in a microwave oven digester to ensure efficient dissolution.
3. Quantify the concentrations of key metals (Cu, Ni, Au, Fe) using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES).
4. Compare the obtained metal concentrations with values reported in previous studies to evaluate compositional differences and potential causes.
5. Assess the implications of the results for metal recovery, sustainable e-waste management, and environmental protection.

Figure 1 illustrates the major categories of e-waste based on end-user applications as defined by the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive, a framework widely adopted by policymakers and researchers globally. Among these categories, PCBs and mobile phone components represent some of the most common micro-waste items, characterized by a high concentration of precious and base metals (Udayakumar et al., 2022).

Understanding their compositional diversity is essential for developing efficient recycling technologies and advancing the goals of

circular economy and sustainable material management.

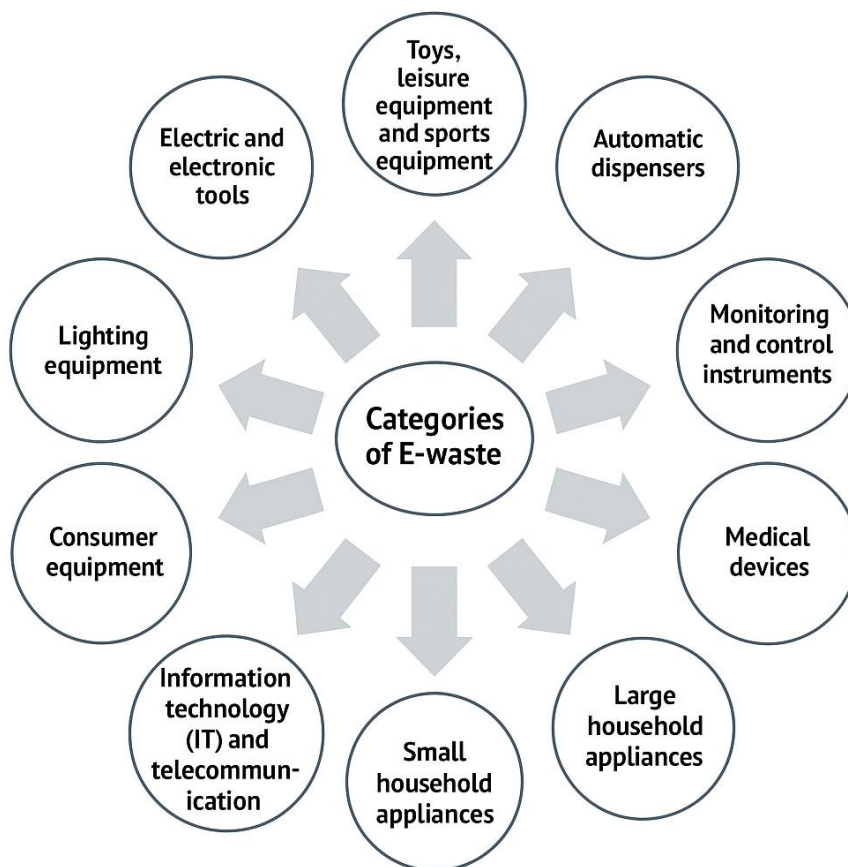


Figure 1. Categories of e-waste based on applications adopted from (Udayakumar et al., 2022)

The generation of e-waste is directly proportional to the consumption rate of electronic devices. The waste printed circuit boards (WPCBs) must be processed in an effective and environmentally friendly manner (Trivedi et al., 2022). Furthermore, recycling PCBs supports the economic development of underdeveloped nations in their quest for self-sufficiency, going beyond simple resource recovery. Recycling in terms of recovery of metallic and non-metallic materials seems to be a realistic solution for the valorisation of WPCBs (Jadhao et al., 2020).

The recovery of constituent metals from WPCBs can be achieved using pyrometallurgical, hydrometallurgical, electrometallurgical, and bioleaching processes (Cocchiara et al., 2019).

The standard method of pyrometallurgy does not allow for the selective recovery of metals for WPCBs (Shu et al., 2022). Pyrometallurgy is a method for recovering metals from primary and secondary sources. Unfortunately, the technique has energy-intensive procedures that may recycle a wide range of

e-waste and are harmful to the environment as they produce a lot of soot, emit polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs), and emit other harmful gases (reference). PCBs can be processed using hydrometallurgical processes, which are a promising option because they are selective, relatively inexpensive, don't emit fumes or dust, and are appropriate for conventional applications. When compared to other PCB recycling technologies, they are also believed to be more environmentally friendly and energy efficient (Wu et al., 2022). Although, a lot of study have been carried out on the determination and recovery of heavy metals from different types of e-waste, yet there appears to be paucity of report on the determination of metal composition present in WPCBs. As such, this work aims to bridge the gap.

Materials and Method

In this study, PCBs were obtained from Hokuden (M) Sdn. Bhd., Bandar Tenggara, Kulai, Malaysia. First, the metal part of the PCB was removed from the plastic and weighed with an analytical balance. Subsequently, the metal part of the PCB was crushed into smaller pieces and thereafter, 0.30 g of the crushed sample was added to about 10 mL of concentrated HCl in a pressurized container. Then, the container was placed into a Milestones microwave oven digester (Model number of this microwave) for digestion. The sample was analyzed with Agilent ICP-OES for quantifying the concentrations of Cu, Ni, Au and Fe.

Results and Discussion

The quantitative results obtained from Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) were used to determine the percentage composition of metals present in the metallic fraction of the waste printed circuit boards (WPCBs). As summarized in Table 4.1, the analysis revealed that copper (Cu) constituted the dominant metallic element, accounting for 43.60%, followed by nickel (Ni) at 2.56%, while gold (Au) and iron (Fe) were each

detected at trace levels of 0.001%. These results are consistent with the general composition trend of PCBs reported in the literature, where copper typically dominates due to its extensive use as conductive tracks, while nickel, gold, and iron occur in smaller proportions as coating and structural materials (Cui and Forssberg, 2003; Li et al., 2019).

However, the metal concentrations recorded in this study are comparatively lower than those reported by Sahni et al. (2016), who documented 75.84% Cu, 3.17% Ni, 0.42% Au, and 1.28% Fe in similar WPCB samples. Several factors may account for this discrepancy. Firstly, sample contamination by non-metallic residues, such as adhesive layers, epoxy resins, and glass fibers, could have contributed to an apparent reduction in the measured metal percentages. During the manual separation of metallic parts, traces of adhesive or resinous components may have adhered to the metallic fraction, thereby increasing the total sample mass without contributing to the metal yield. This dilution effect would consequently lower the calculated metal concentrations.

Secondly, incomplete digestion during microwave-assisted acid treatment may have reduced the total quantity of metals available in the analyte solution. The efficiency of acid digestion depends on several factors, including acid concentration, reaction temperature, exposure time, and particle size of the sample. If digestion was incomplete, certain metals encapsulated within polymer matrices or solder compounds might not have been fully dissolved, leading to an underestimation of their true concentrations. Similar observations have been made by Veit et al. (2006) and Zhang et al. (2018), who emphasized the importance of optimizing digestion parameters to ensure complete dissolution of metallic constituents from complex e-waste matrices.

Another possible explanation for the observed variation lies in differences in PCB origin, design, and manufacturing technology. The metal composition of printed circuit boards varies widely depending on the type of electronic equipment, its function, and the year of production. For instance, boards from older computers and telecommunications devices typically contain higher proportions of copper and gold compared to modern boards, which tend to use thinner metallic layers for cost and weight reduction (Iji and Yokoyama, 2014). Therefore, the lower metal content in this study may reflect the changing material composition of more recent electronic devices commonly recycled in Malaysia.

Despite the relatively low concentrations, the detected metal fractions confirm that WPCBs remain a valuable secondary resource for metal recovery. The high proportion of copper, in particular, reinforces its

potential as an economically viable target for recycling operations. Moreover, the trace presence of gold and nickel, though small, is still of commercial and technological interest given their high market value and industrial demand.

Overall, the findings highlight the necessity of refining sample preparation and digestion methodologies to enhance analytical accuracy and recovery efficiency. Future studies should explore the use of multi-acid digestion systems (e.g., aqua regia or HNO₃-HCl mixtures), prolonged heating cycles, and mechanical pre-treatment to ensure complete dissolution of metals. Standardizing such procedures will allow for more accurate inter-study comparisons and provide a stronger basis for designing efficient and environmentally responsible recovery technologies for e-waste-derived metals.

Table 1.1 Metal Content Analysis of PCB

Element	Concentration (x10 ppm)	Concentration per 100 g	Percentage (% W/W)
Cu	440.400	44.040	43.600
Ni	24.080	2.408	2.560
Au	0.283	0.028	0.001
Fe	0.243	0.024	0.001

This present study is significant for several interrelated environmental, economic, and scientific reasons. As the world transitions toward a circular economy, the recovery and reuse of valuable resources from waste streams have become an essential strategy for sustainable development. Waste printed circuit boards (WPCBs) represent one of the richest secondary sources of metals, yet their potential remains underutilized, particularly in developing countries where improper recycling and disposal practices prevail. By investigating the metal composition of WPCBs using reliable and precise analytical methods, this research contributes to

bridging the knowledge gap on the quality and quantity of recoverable metals from locally sourced e-waste.

From an environmental perspective, the study provides essential baseline data on the metallic content of WPCBs, which can guide policymakers, waste managers, and recyclers in developing eco-friendly treatment and recovery technologies. Understanding the concentration of metals such as copper, nickel, gold, and iron helps in formulating strategies to minimize environmental pollution arising from informal recycling operations. Efficient recycling processes, informed by compositional data, can significantly reduce the

release of hazardous substances into soil and water, thereby protecting ecosystems and human health.

From an economic standpoint, the research underscores the potential of WPCBs as an alternative source of strategic and precious metals. Copper and gold, for instance, are increasingly scarce in natural ores, and their recovery from electronic waste presents a cost-effective means of supplementing global supply. The findings of this study can therefore support local recycling industries and entrepreneurs in identifying economically viable recovery routes, contributing to resource conservation, job creation, and industrial sustainability.

From a scientific and technological viewpoint, the study demonstrates the application of Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) as a powerful tool for multi-elemental analysis of e-waste materials. The methodology and results provide a foundation for future research in material characterization, waste valorization, and environmental monitoring. Moreover, the outcomes can inform the development of standardized analytical protocols and best practices for assessing the metal content of WPCBs across diverse e-waste categories.

Conclusion

This study demonstrates the potential of waste printed circuit boards (WPCBs) as a significant secondary source of valuable metals, particularly copper (Cu) and nickel (Ni), which are essential to modern industrial applications. The results obtained from Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) revealed that while the concentrations of these metals were relatively lower than those reported in previous studies, WPCBs nonetheless contain recoverable quantities of economically important elements. The reduced metal percentages observed can be attributed to several

factors, including incomplete sample digestion during microwave-assisted acid treatment, and the inadvertent inclusion of adhesive and non-metallic residues during the sample preparation and weighing stages.

Despite these limitations, the findings reaffirm that WPCBs remain a viable raw material for metal recovery and recycling. The predominance of copper highlights its continued economic importance, while the presence of nickel, iron, and trace gold supports the feasibility of multi-metal extraction from e-waste. These outcomes further emphasize the critical role of optimized pre-treatment, digestion, and analytical procedures in improving recovery efficiency and ensuring more accurate quantification of metallic content.

Future research should therefore focus on refining digestion parameters—such as acid composition, reaction temperature, and exposure duration—to achieve complete dissolution of metal-bearing phases. Moreover, integrating mechanical pre-treatment and advanced hydrometallurgical or bioleaching processes could enhance overall recovery efficiency and sustainability.

Beyond the analytical findings, this study contributes to the broader agenda of sustainable e-waste management. By promoting the recovery and reuse of valuable metals from discarded electronics, such research supports environmental protection, resource conservation, and the development of a circular economy—particularly in regions where formal recycling infrastructures are still emerging. Efficient metal recovery from WPCBs not only reduces the environmental hazards associated with improper e-waste disposal but also provides new economic opportunities through the establishment of resource recovery industries.

In conclusion, while further methodological improvements are needed to enhance recovery accuracy, this research underscores the dual importance of WPCB recycling—both as a pathway for sustainable resource utilization and as a vital component of global environmental stewardship.

References

- Bao, S., Pan, B., Wang, L., Cheng, Z., Liu, X., Zhou, Z., & Nie, X. (2020). Adverse effects in *Daphnia magna* exposed to e-waste leachate: Assessment based on life trait changes and responses of detoxification-related genes. *Environmental Research*, *188*, 109821.
- Charles, R. G., Douglas, P., Dowling, M., Liversage, G., & Davies, M. L. (2020). Towards Increased Recovery of Critical Raw Materials from WEEE—evaluation of CRMs at a component level and pre-processing methods for interface optimisation with recovery processes. *Resources, Conservation and Recycling*, *161*, 104923.
- Cocchiara, C., Dorneanu, S.-A., Inguanta, R., Sunseri, C., & Ilea, P. (2019). Dismantling and electrochemical copper recovery from Waste Printed Circuit Boards in H₂SO₄-CuSO₄-NaCl solutions. *Journal of Cleaner Production*, *230*, 170-179.
- Jadhao, P. R., Ahmad, E., Pant, K., & Nigam, K. (2020). Environmentally friendly approach for the recovery of metallic fraction from waste printed circuit boards using pyrolysis and ultrasonication. *Waste Management*, *118*, 150-160.
- Liaquat, H., Imran, M., Latif, S., Hussain, N., & Bilal, M. (2022). Multifunctional nanomaterials and nanocomposites for sensing and monitoring of environmentally hazardous heavy metal contaminants. *Environmental Research*, *214*, 113795.
- Okeke, E. S., Huang, B., Mao, G., Chen, Y., Zhengjia, Z., Qian, X., Wu, X., & Feng, W. (2022). Review of the environmental occurrence, analytical techniques, degradation and toxicity of TBBPA and its derivatives. *Environmental Research*, *206*, 112594.
- Rajesh, R., Kanakadhurga, D., & Prabakaran, N. (2022). Electronic waste: A critical assessment on the unimaginable growing pollutant, legislations and environmental impacts. *Environmental Challenges*, *7*, 100507.
- Shu, Q., Qiu, W., Luo, M., & Xiao, L. (2022). Copper selenides controlled hydrothermal synthesis of porous micro-networks with highly efficient photocatalysis. *Materials Today Sustainability*, *18*, 100135.
- Trivedi, A., Vishwakarma, A., Saawarn, B., Mahanty, B., & Hait, S. (2022). Fungal biotechnology for urban mining of metals from waste printed circuit boards: A review. *Journal of Environmental Management*, *323*, 116133.
- Udayakumar, S., Abd Razak, M. I. B., & Ismail, S. (2022). Recovering valuable metals from Waste Printed Circuit Boards (WPCB): A short review. *Materials Today: Proceedings*.
- Wu, C., Awasthi, A. K., Qin, W., Liu, W., & Yang, C. (2022). Recycling value materials from waste PCBs focus on electronic components: A review on technologies, obstruction and prospects. *Journal of Environmental Chemical Engineering*, 108516.