

A DUAL-PATHWAY APPROACH FOR ECO-FRIENDLY RECOVERY OF SILVER FROM DDRM E-WASTE USING ORGANIC LEACHING AGENTS

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Abstract -

Electronic waste (e-waste) contains significant quantities of valuable metals that can be recovered through environmentally sustainable processes. This study investigates an eco-friendly dual-pathway approach for the recovery of silver from discarded Double Data Rate Random Access Memory (DDRM) modules using organic acid leaching followed by electrolysis. Waste DDRM samples were collected, shredded and subjected to alkaline pretreatment using different concentrations of potassium hydroxide (KOH) to remove the epoxy coating. Sonication was subsequently employed to enhance the removal of the protective polymer layer. The pretreated DDRM was then subjected to leaching using citric acid and formic acid in the presence of hydrogen peroxide as an oxidizing agent. The leachates were analyzed using UV–VIS spectroscopy to confirm the presence of silver ions, while electrolysis was employed to recover the dissolved metal. FTIR analysis confirmed the breakdown of epoxy functional groups after alkaline pretreatment. Among the organic acids investigated, citric acid exhibited better silver leaching performance than formic acid. The study demonstrates that organic acid leaching combined with electrolysis provides a simple, economical and environmentally safer alternative for silver recovery from DDRM e-waste.

Key Words: DDRM e-waste, silver recovery, organic acid leaching, citric acid, formic acid, electrolysis.

1. INTRODUCTION

1.1 Electronic Waste

Electronic waste is one of the rapidly increasing waste streams resulting from technological development. E-waste consists of discarded electronic devices and components that have reached the end of their useful life. Improper disposal can cause environmental pollution and health hazards because e-waste contains hazardous substances as well as valuable metals such as gold, silver, copper, iron and aluminium. [3]

1.2 DDRM E-Waste

Double Data Rate Random Access Memory (DDRM) modules are widely used computer memory components. Older generations such as DDR, DDR1, DDR2 and DDR3 have increasingly been replaced by newer DDR4 and DDR5 technologies. Consequently, discarded RAM modules represent a potential secondary source of valuable metals. DDRM contains metals including gold, silver and copper, making it suitable for metal recovery through recycling processes. [3]

1.3 Metal Recovery from E-Waste

Metal recovery from e-waste can be performed through pyrometallurgical, hydrometallurgical, biometallurgical and pyrolysis-based approaches. Among these, hydrometallurgy provides greater process control and can employ leaching followed by metal recovery through cementation, solvent extraction or electrolysis. [1,10,17]

1.4 Research Gap

Conventional mineral acid-based extraction processes can involve environmental and operational concerns. Therefore, the present work investigates citric acid and formic acid as organic leaching agents for silver recovery from DDRM e-waste, coupled with alkaline pretreatment and electrolysis. [1,10]

1.5 Objectives

- To collect and pre-treat DDRM e-waste for silver extraction.
- To investigate the removal efficiency of epoxy coating using KOH.
- To determine the leaching efficiency of silver using organic acids.
- To compare citric acid and formic acid for metal extraction.
- To recover silver from the leachate through electrolysis.

2. MATERIALS AND METHODOLOGY

2.1 Materials

The major materials used in the study were waste DDRM modules, sodium hydroxide (NaOH), potassium hydroxide (KOH), citric acid, formic acid, hydrogen peroxide (H_2O_2), ultrapure water, copper electrode and mild steel electrode.

2.2 Experimental Methodology

The experimental methodology followed the sequence: Collection of DDRM → Washing → Shredding → KOH Pretreatment → Sonication → Organic Acid Leaching → Filtration → UV–VIS Analysis → Electrolysis → Silver Recovery.

2.3 Collection and Shredding of DDRM

The DDRM samples were collected from computer service centres. The modules were washed using ultrapure water, dried and shredded into approximately 20 mm pieces.



Fig.1. DDRM E-waste

2.4 Alkaline Pretreatment

NaOH and KOH solutions with 2N, 4N and 6N concentrations were prepared. The shredded DDRM samples were immersed overnight. Following immersion, the samples were subjected to bath sonication for different durations of 5, 10, 15 and 20 min. The maximum epoxy removal efficiency was observed at 20 min sonication.



Fig.2. Sonication

2.5 Organic Acid Leaching

For the leaching experiment, 20 g of pretreated DDRM was treated separately with (1) Citric acid + 10 mL H₂O₂ and (2) Formic acid + 10 mL H₂O₂. Each solution was made up to 200 mL. The samples were maintained for 24 h and analyzed using UV–VIS spectroscopy.

2.6 Electrolysis

The leachates were filtered and diluted to 400 mL before electrolysis. Copper and mild-steel plates were used as electrodes, and the voltage was maintained between 8–12 V. The electrolysis process was carried out for 3 h, with observations recorded every 15 min.

3. RESULTS AND DISCUSSION

3.1 Pretreatment and FTIR Analysis

The alkaline pretreatment effectively removed the epoxy coating from the DDRM surface. FTIR analysis showed changes in characteristic functional groups and reduction of epoxy-related peaks.

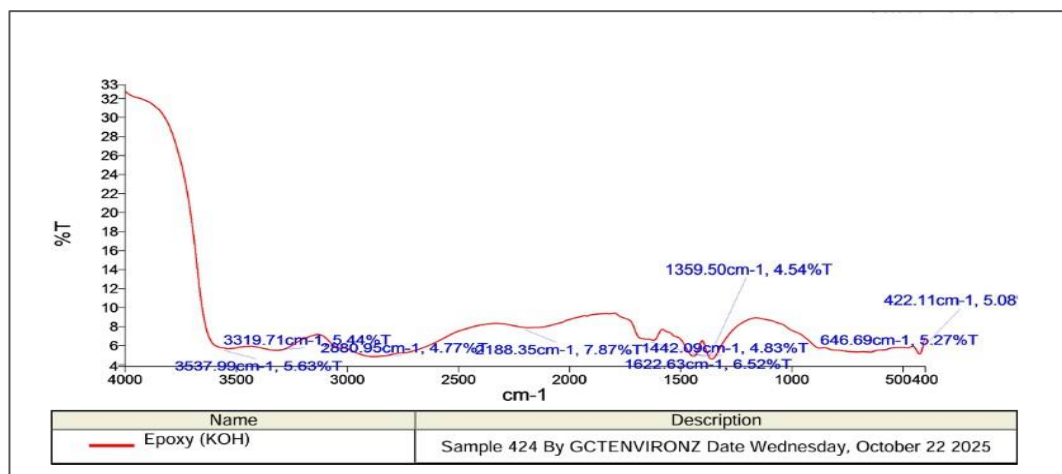


Fig.3. FTIR Spectra of epoxy resin for 4N (Potassium hydroxide)

Fig.3 depicts the Fourier Transform Infrared Spectroscopy (FTIR) analysis of epoxy resin treated with 6N KOH to examine the degradation and removal of epoxy functional groups.

A broad absorption peak observed at around 3420 cm^{-1} corresponds to O–H stretching vibrations, indicating the formation of hydroxyl groups due to the epoxy ring-opening reaction under alkaline conditions. The peaks appearing near 2920 cm^{-1} are attributed to C–H stretching vibrations of aliphatic groups present in the resin backbone.

A distinct absorption band at approximately 1720 cm^{-1} represents the C=O stretching vibration, which suggests the formation of carbonyl or ester groups after alkaline hydrolysis. The reduction in the characteristic epoxy peak around 910 cm^{-1} (C–O–C asymmetric stretching) and 1240 cm^{-1} (epoxy ether linkage) confirms the decomposition of the epoxy ring structure by KOH.

The slight shifts and variations in the intensity of these peaks, compared to the untreated epoxy resin, indicate significant chemical interaction and breakdown of the epoxy network, resulting in the formation of hydroxylated degradation products.

3.2 UV-VIS Analysis

UV-VIS analysis confirmed the presence of silver in the leachate. The silver absorption peak was observed at approximately 320 nm. Copper, lead and zinc were also detected in the leachate. The formic acid leachate also showed evidence of precious-metal leaching, although comparatively little silver absorbance was observed.

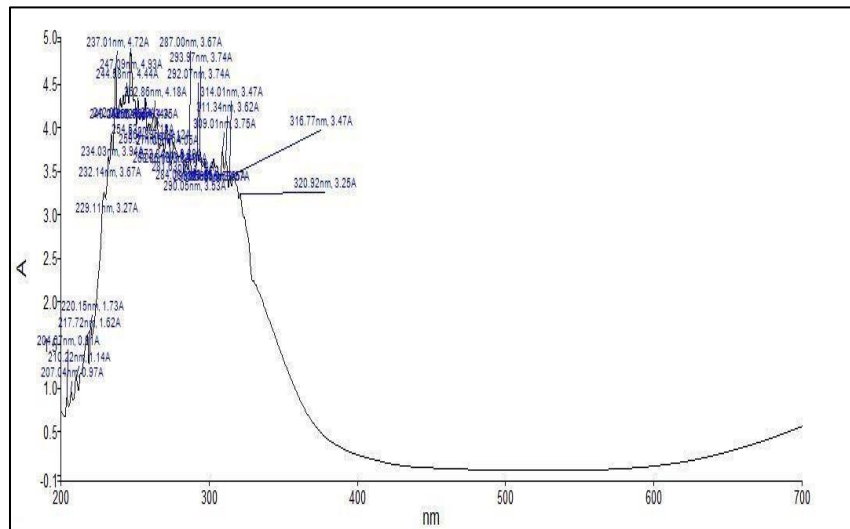


Fig.4. Absorbance of metal in Citric acid

From Fig.4, Each metal has a specific wavelength and their types are identified and the absorbance of silver is confirmed,

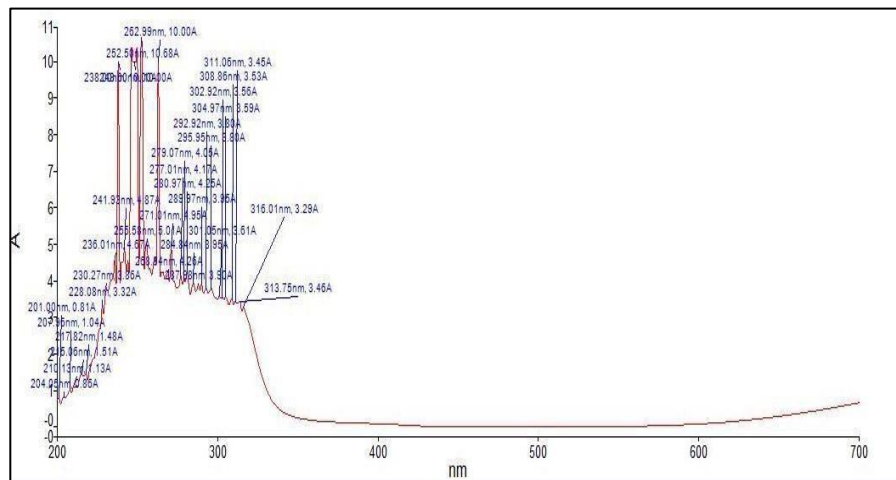


Fig.5. Absorbance of metal in Formic acid

The result shows that the absorbance level of various metals leached by formic acid. From observation (Fig.5), it is evident that formic acid is effective in leaching of precious metals (Au, Ag) as that of citric acid. Very little absorbance of silver was observed.

3.3 Electrochemical Recovery of Silver

Electrolysis was performed using the organic-acid leachates as electrolytes. Visible deposition of metal occurred on the cathode, with differences in surface colour and texture between citric-acid and formic-acid systems. [20]

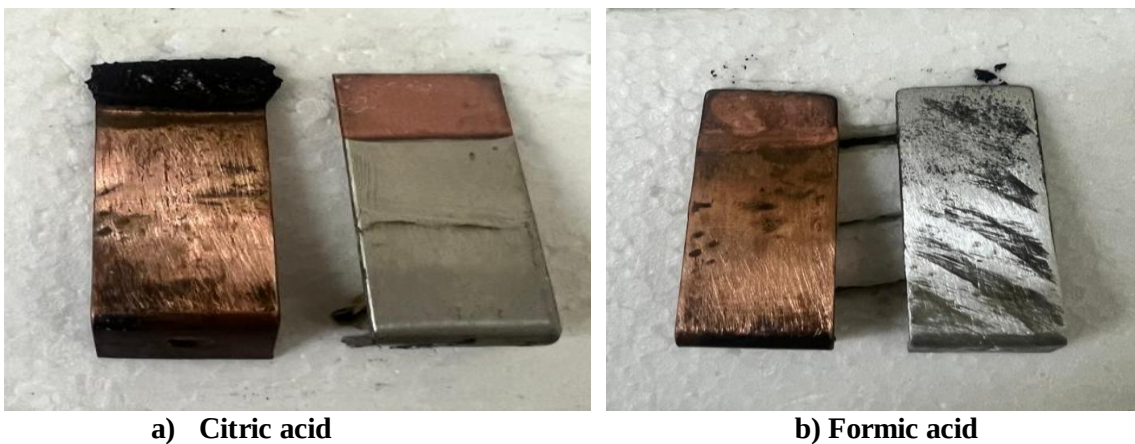


Fig.6 Deposition of metals on electrodes.

3.4 Comparison of Organic Acids

Citric acid showed higher silver leaching and recovery performance than formic acid. The reported recovery range was 65–90% for citric acid compared with 45–80% for formic acid.

4. CONCLUSION

The present study demonstrated the feasibility of recovering silver from DDRM e-waste through an eco-friendly dual-pathway process involving alkaline pretreatment, organic acid leaching and electrolysis. KOH pretreatment showed better epoxy removal. FTIR confirmed the chemical breakdown of the epoxy layer, while UV–VIS analysis verified the presence of silver ions in the leachate. Among the two organic acids, citric acid demonstrated better leaching and recovery performance than formic acid, with the reported recovery range of 65–90% compared with 45–80% for formic acid. The proposed process provides a simple and comparatively environmentally safer route for recovering valuable metals from DDRM e-waste.

REFERENCES

- [1] Gautam Mishra, Rohit Jha, Mudila Dhanunjaya Rao, Arunabh Meshram (2021). Recovery of silver from waste printed circuit boards (WPCBs) through hydrometallurgical route: A review. *Environmental Challenges*, 2021 – Elsevier.
- [2] Abdel Mohsen Onsy Mohamed (2024). Sustainable recovery of silver nanoparticles from electronic waste: applications and safety concerns. *Academia Engineering*, 2024.
- [3] J. Cui, H.J. Roven (2011). Electronic Waste. *Waste: A Handbook for Management*, Chapter 20, pp. 281–296.
- [4] A. Chauhan, R. Bal, R. Srivastava (2025). Upcycling Waste Electronic Chips into Metallic Catalysts for Sustainable Biomass Valorization into Fuel Additives and Fine Chemicals. *Industrial & Engineering Chemistry Research*.
- [5] Massimiliana Pietrantonio, Stefano Pucciarmati, Federica Forte (2025). Recovery of metallic gold, silver and copper from end-of-life mobile phones by hydrometallurgy. *Journal of Materials*.
- [6] DS Ferreira, ER Pereira-Filho (2025). A preliminary study of a sequential leaching process to recover Ag, Au, Cu, and Sn from E-waste. *Hydrometallurgy*.
- [7] S. Diallo, LH Tran, D. Larivière, JF Blais (2025). Leaching and recovery of rare earth elements, copper, nickel, silver and gold from used smartphone circuit boards. *Minerals Engineering*.
- [8] A. Trivedi, M. Khetri, A. Surampudi, MC Gupta (2025). Gold Metal Recovery from Electronic Waste through Laser Generation of Micro and Nanoparticles. *ACS Omega*.

- [9] O. Gajare, NB Jadhav, S. Zele, N. Lucas (2025). Sustainable silver recovery by chemical treatment of metal rich fines from solar panel waste. *Solar Energy Materials*.
- [10] DA Ferreira-Filipe, AC Duarte, AS Hursthouse (2025). Biobased Strategies for E-Waste Metal Recovery: A Critical Overview of Recent Advances. *Environments*.
- [11] R. Khiari, N. Marlin, D. Curtil, M. Aurousseau (2025). Separation of Silver and Cellulosic Fibers for Recycling and Reuse of Printed Electronic Devices Components. *Recycling*.
- [12] XQ Jin, JL Li, CY Li, LL Chen, XT Wang (2025). Efficient and selective gold recovery from practical e-waste and electroplating wastewater using protein crystals. *Volume 222*, August 2025, 108450.
- [13] E.A. Abdel-Aal, F.E. Farghaly (2007). Preparation of silver powders in micron size from used photographic films via leaching–cementation technique. *Powder Technology*, 178, pp. 51–55.
- [14] S.H. Ahmed, O.S. Helaly, M.S. Abd El-Ghany (2015). Evaluation of rare earth double sulphate precipitation from monazite leach solutions. *International Journal of Inorganic and Bioinorganic Chemistry*, 5.
- [15] H. Arima, T. Fujita, W.T. Yen (2002). Gold cementation from ammonium thiosulfate solution by zinc, copper and aluminium powders. *Materials Transactions*, 43(3), pp. 485–493.
- [16] S. Hasnain (2025). Modelling of a Continuous Stirred Tank Reactor (CSTR) System and its Applications in Silver Recovery in Solar Panel Recycling.
- [17] P. Phogat, S. Kumar, M. Wan (2025). A scientometrics study of advancing sustainable metal recovery from e-waste: processes, challenges, and future directions. *RSC Sustainability*.
- [18] Advancing sustainable metal recovery from e-waste: processes, challenges, and future directions. *RSC Sustainability*.
- [19] MG Genduso, S. Farokhmehr, A. Dotti (2025). Reduced graphene oxide supported on polyurethane foams for metal recovery from e-waste. *Book of Abstracts*.
- [20] S. Cho, J. Kim, SY Park, HS Lee, S. Kim (2024). High-Efficiency Silver Recovery from End-of-Life Photovoltaic Modules via Hydrodynamically Optimized Electrowinning. *ACS Omega*.

