Eco-Friendly Bioleaching: Innovative Technology for Extracting Critical Raw Materials From WEEE

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The rapid growth of the quantity of generated electronic waste (e-waste), driven by the increasing demand for electrical and electronic equipment (EEE), has raised urgent concerns regarding its environmental and health impacts. E-waste is the fastest-growing global waste stream, with only a small fraction recycled sustainably. Printed circuit boards (PCBs), a major component of e-waste, contain valuable metals and hazardous substances, complicating recycling efforts. This study explores bioleaching as an environmentally friendly alternative to traditional recycling methods. Bioleaching, utilising microorganisms such as *Acidithiobacillus ferrooxidans* and *A. thiooxidans*, which can effectively extracts metals like copper, nickel, and zinc from e-waste, reducing environmental contamination. Our research, conducted under the EIT RawMaterials WEEE-NET9 project, focuses on bioleaching's potential for sustainable recovery of critical raw materials (CRMs) from e-waste. Results demonstrate the effectiveness of bioleaching in metal extraction, supporting the EU's goals of increasing CRM recycling and reducing reliance on primary sources for critical materials, which we have to import into the EU.

Keywords:
WEEE,
E-waste,
circular economy,
critical raw materials,
bioleaching

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1 Introduction

The growing demand for innovative technologies and electrical and electronic equipment (EEE) has led to a rapid increase in waste electrical and electronic equipment (WEEE or e-waste). E-waste is the fastest-growing waste stream globally, expanding at an annual rate of 3–5% (Ji et al., 2022). According to the *Global E-waste Monitor 2024* (Baldé et al., 2024), e-waste production reached 62 million metric tons in 2022 (Figure 1), an 82% increase since 2010, with only a small fraction recycled in an environmentally sound manner. In 2022, just 22.3% of e-waste was formally collected and recycled (Figure 2). In Europe, 13.5 million tonnes of EEE are placed on the market annually, generating 4.9 million tonnes of e-waste, with less than 40% recycled and an average of 11 kg collected per person (EC ENV, 2024). E-waste contains hazardous and valuable materials, including critical raw materials (CRMs) and rare earth elements (REE), making recycling complex. The OECD projects global material demand will rise from 79 billion tonnes today to 167 billion tonnes by 2060 (Blengini et al., 2020).

It is estimated that 82 million metric tons of electronic waste will be generated in 2030, a significant increase from the 62 million tonnes generated in 2022 (Statista 2025). This situation underlines the urgent need for effective e-waste management strategies and the development of innovative technologies for extracting critical raw materials from e-waste. One of these technologies is also bioleaching, where we use microorganisms for CRM extraction from e-waste, for example PCBs.

The 2022 report on e-waste in the European Union (EU) and EFTA countries, based on data collected under Directive 2012/19/EU, outlines trends in the collection and processing of e-waste. In 2022, the collection rate in the EU reached 40.1%, measured as the weight of e-waste collected relative to the average weight of electronic equipment put on the market in 2019-2021. From 2012 to 2022, the amount of electrical and electronic equipment (EEE) on the EU market grew by 89.3%, from 7.6 million tonnes to 14.4 million tonnes. Over the same period, the total collected e-waste increased by 67.9%, from 3.0 million tonnes to 5.0 million tonnes, while treated e-waste grew by 56.8%, from 3.1 to 4.9 million tonnes. Recovered e-waste rose by 72.1%, from 2.6 million tonnes to 4.5 million tonnes, and e-waste recycled and prepared for reuse grew by 66.6%, from 2.4 to 4.0 million tonnes (Figure 3).

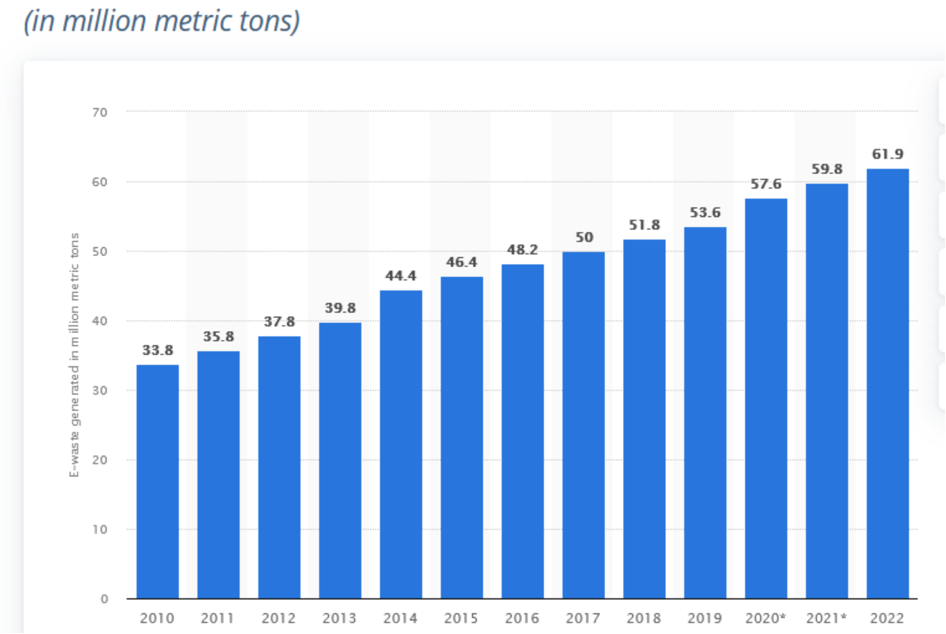


Figure 1: Electronic waste generated worldwide from 2010 to 2022.
Source: Statista 2025

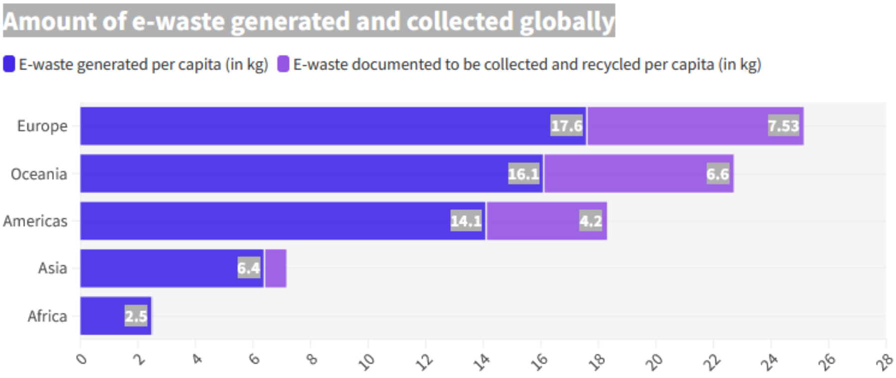
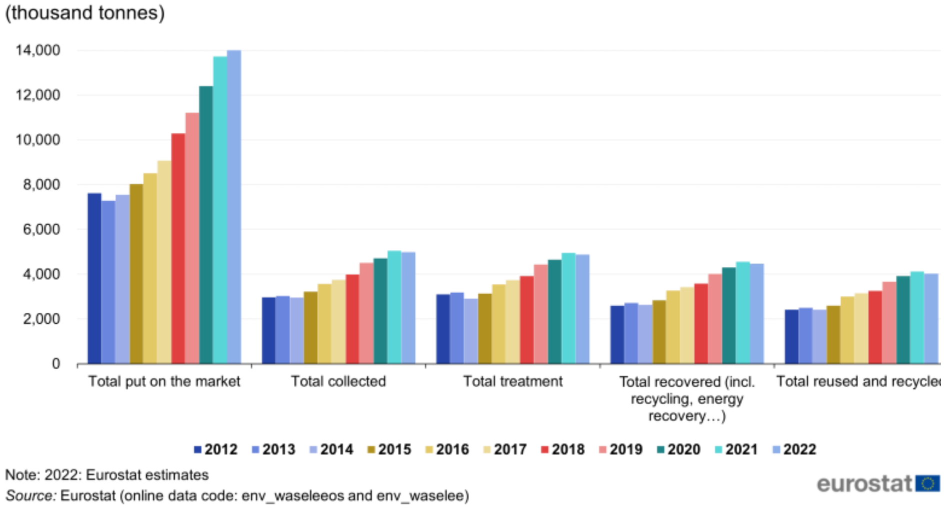


Figure 2: Amount of e-waste generated and collected globally
Source: Unitar 2024



Note: 2022: Eurostat estimates
Source: Eurostat (online data code: env_waseleeos and env_waselee)

Figure 3: E-waste put on the market and waste EEE collected, treated, recovered, recycled and prepared for reuse, EU, 2012–2022.
Source: Eurostat, 2025

2 Definition and classification of e-waste

E-waste has a highly heterogeneous composition, consisting of both hazardous and non-hazardous materials. It contains polymers, glass fiber, flame retardants, and various ferrous and non-ferrous metals. Additionally, e-waste includes precious metals (e.g., Au, Ag, Pt-group metals), base metals (Al, Co, Cu, Ni, Zn, Fe), rare earth elements (e.g., In, Nd, Ta), and other elements (e.g., Be, Cd, Cr, Hg, Pb, Sb, Sn, Ti). Due to the high metal content, often exceeding that of some natural ores, e-waste is considered a valuable secondary resource (Fu et al., 2021; Rautela et al., 2021).

On the other hand, e-wastes also contain hazardous, making recycling and extraction of and valuable materials, such as critical raw materials (CRMs) and rare earth elements (REE) very complex task. Properly managing and recycling e-waste is not just a necessity, but a crucial step towards EU's 2050 climate neutrality targets under the EU Green Deal (2019), contributes to the EU policy in the field of critical and strategical raw materials, and supports the transition to a circular economy and decarbonisation. The most essential parts of e-wastes are PCBs (printed circuit boards). Today, a significant portion of e-waste and PCBs end up being incinerated or landfilled, where they are covered up, which can lead to environmental contamination (Yaashikaa et al., 2022). The urgent need for effective and sustainable e-waste management is underscored by its severe risks to human health and the environment (Jain et al., 2023; N. Perkins et al., 2014).

Innovative strategies are needed to improve awareness, collection, pre-treatment, recycling, and reuse of electronic products. Both society and researchers are encouraged to develop new technologies for recovering critical raw materials (CRMs) from e-waste. Sustainable PCB processing methods, such as bioleaching, can tackle environmental and economic challenges while strengthening the value chain and creating jobs in the EU's recycling and raw materials sectors.

2.1.1 Environmental and Health Effects of E-Waste

The improper management of e-waste poses a serious threat to both the environment and human health. E-wastes is made up of a number of toxic organic and inorganic compounds such as polybrominated diphenyl ethers – polychlorinated biphenyls, brominated flame retardants, dioxins and a whole range of heavy metals which are harmful to any ecosystem and living organisms. Most of these toxins find their way into the environment in various forms (Yaashikaa et al., 2022; Rautela et al., 2021; Li & Achal, 2020).

There are several different ways through which a person might be exposed to e-waste. Fine and coarse particles from disintegrated wastes can be inhaled, or leached skin contaminants from the e-waste can be ingested directly, as well as hazardous dust. The high toxicity of pollutants such as e-waste increases concentration as an individual moves up the food chain. This heightened concentration can lead to serious health consequences including heart failure, skin dermatitis, various types of cancer, DNA damage and even birth defects (Adetunji et al., 2023; Anaya-Garzon et al., 2021). Improper disposal also releases dust particles and toxins such as dioxins into the environment, contributing to air pollution and respiratory problems (Rautela et al., 2021).

3 What is bioleaching?

Bioleaching, also known as biomining, is a biotechnological process that utilizes microorganisms to extract valuable metals from e-waste. It has gained attention as an environmentally friendly alternative to traditional methods like pyrometallurgy and hydrometallurgy (Pathak et al., 2017). Printed circuit boards (PCBs) are particularly suitable for bioleaching (Figure 4). Microorganisms such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* play a key role due to their ability to oxidize iron and sulfur compounds, leading to sulfuric acid formation and iron mineral oxidation (Mostafavi et al., 2018). During bioleaching, microorganisms interact with metal-bearing particles, facilitating oxidation, reduction, and acidolysis reactions that dissolve solid metals into the leaching solution. Several factors influence the process, including pH, temperature, pulp density, bacterial growth, and particle size (Arshadi et al., 2019).

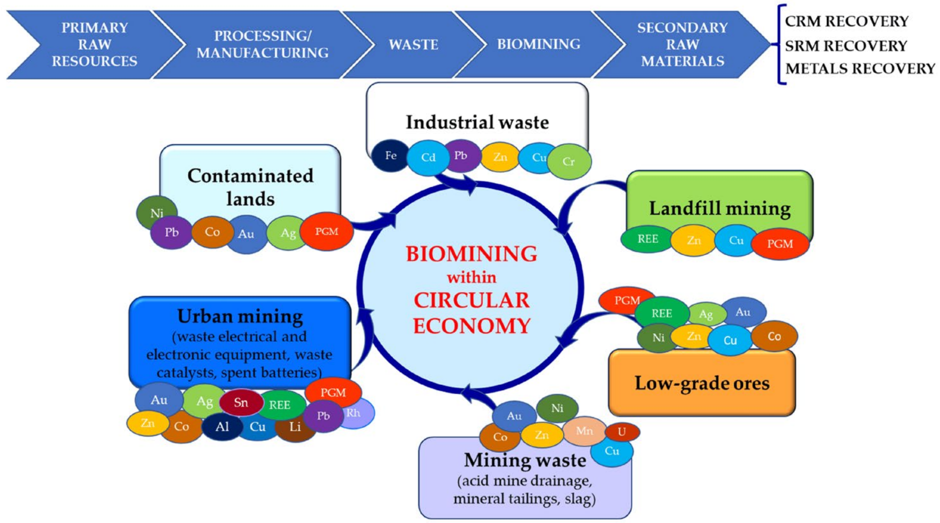


Figure 4: Bioleaching within circular economy

Source: Cozma et al., 2024

Like any other technique, bioleaching has some advantages and some disadvantages, which are presented in Table 1.

Table 1: Advantages and disadvantages of bioleaching.

Advantages	Disadvantages
Environmentally sustainable	Slow process kinetics
Low cost of operation and energy requirement	Long processing time
Minimal use of strong chemical reagents	Not feasible in highly toxic environments
High metal recovery efficiency	Low efficiency at high pulp density
No toxic fume release	Hard process control measures

4 Materials and methods

The study included PCB and mobile phoned samples codes SP-1, PG-2, and PM-2, each with distinct origins and processing characteristics (Table 2). SP-1 consisted of mobile phone materials from the MSH (Metal Shredder Hungary) new batch, which were processed using a hammermill to an intermediate stage with particles smaller than 1 mm. PG-2 represented PCB samples from the Gorenje batch, categorised as communication intermediate products with particle sizes below 1 mm. Similarly, PM-2 comprised PCB materials from the MSH, also processed with a hammermill to achieve an intermediate stage with particle sizes under 1 mm (Figure 5). At first, samples had to be grinded up to a size below 100 µm. Composition of samples: copper (Cu), zinc (Zn), nickel (Ni) and barium (Ba) are the dominant elements in all the samples.

Table 2: E-waste samples used in our research

Sample	Batch	Description
SP-1	Mobile phones - MSH new	hammermill intemediate II <1 mm
PG-2	PCB Gorenje	< 1 mm, communication intermediate product
PM-2	PCB MSH new	hammermill <1mm, intermediate

Figure 5: Codes of e-waste samples used in the bioleaching process.

Before initiating the bioleaching process, the e-waste samples were autoclaved at 121 °C for 15 minutes to ensure sterility. The process began with SP1 smartphone samples, PM2 printed circuit boards, and PG2 printed circuit board samples. The next step involved preparing the MIX media for culturing *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* in a 50:50 ratio (Table 3).

Table 3: Chemicals needed for MIX medium preperation

Growth media	**MIX medium**
Bacteria	*Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans (50:50)*
Media composition (g)	
$(NH_4)_2SO_4$	4.00
KCl	0.10
K_2HPO_4	0.50
$MgSO_4 \times 7H_2O$	0.50
$Ca(NO_3)_2$	0.01
$FeSO_4 \times 7H_2O$	22.10
S	5.00

Once the MIX was ready, 200 mL of the medium was dispensed into 250 mL Erlenmeyer flasks, each containing 3 grams of electronic waste. A 10% inoculum of the bacteria (50% *Acidithiobacillus ferrooxidans* and 50% *Acidithiobacillus thiooxidans*) was added to the medium. The flasks were placed in a shaking incubator set to 30 °C for 25 days (Figure 6). Samples were collected and analysed after 2, 6, 8, 11, 14, 18, 21, and 25 days.

Figure 6: Bioleaching setup

The entire process was conducted in a sterile environment. Each sample was first centrifuged at 9,000 rpm for 10 minutes, then filtered through a 0.22 µm filter. The filtrate was analysed using ICP-MS (7900x, Agilent Technologies, Tokyo, Japan). To ensure reliable results, every experimental condition was run in parallel.

5 Results

The results for the MIX medium showed differences in pH and elemental concentrations over 25 days for SP1, PM2, and PG2 samples (Figure 7).

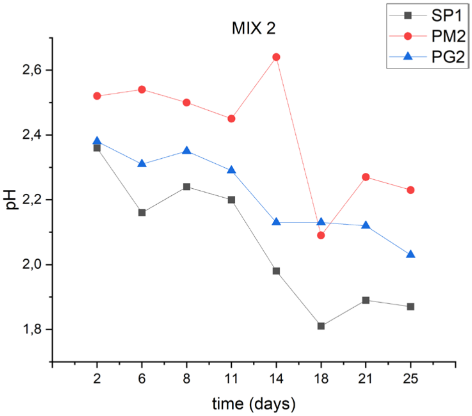


Figure 7: pH results for SP1, PM2 and PG2 samples.

For SP1, the pH steadily dropped from 2.3 to below 1.9 by day 25. Copper (Cu) peaked early on day 6, while zinc (Zn) reached its maximum on day 18. Nickel (Ni), cobalt (Co), and chromium (Cr) didn't reach their highest concentrations during the experiment (Figure 8).

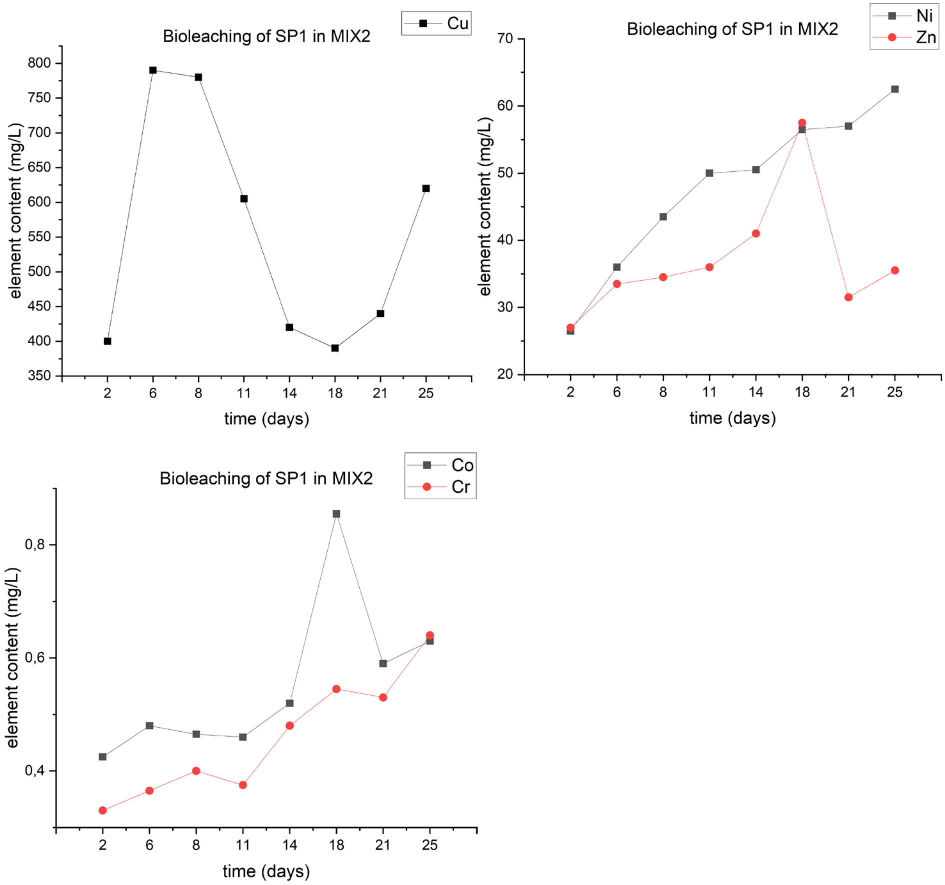


Figure 8: Results for SP1 – mobile phone samples

PM2 had a more stable pH, staying between 2.4 and 2.6 with a spike around day 14. Copper (Cu) peaked on day 21, and nickel (Ni) on day 18. Zinc (Zn), cobalt (Co), and chromium (Cr) showed lower activity and didn't reach maximum levels (Figure 9). Some of the data in the graphs is missing, due to unreliable results.

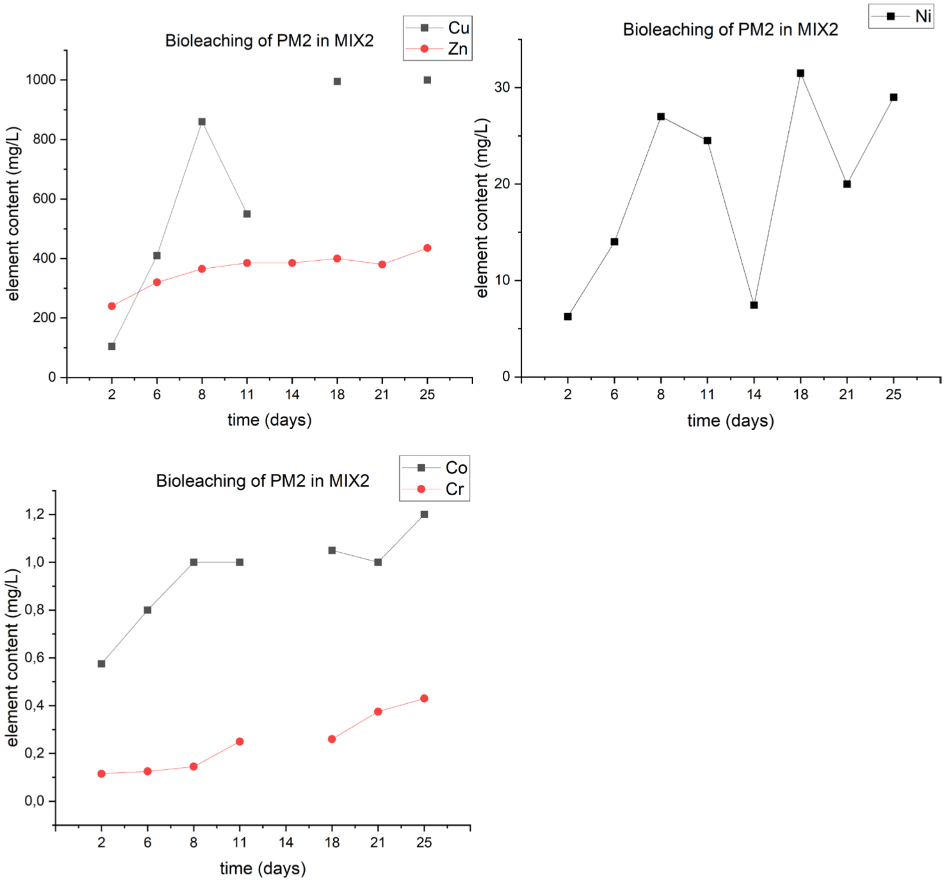


Figure 9: Results for PM2 – printed circuit boards.

For PG2, the pH decreased gradually, staying between 2.1 and 2.4. None of the elements, including Cu, Ni, Zn, Co, or Cr, reached their peak concentrations, suggesting slower bioleaching progress (Figure 10).

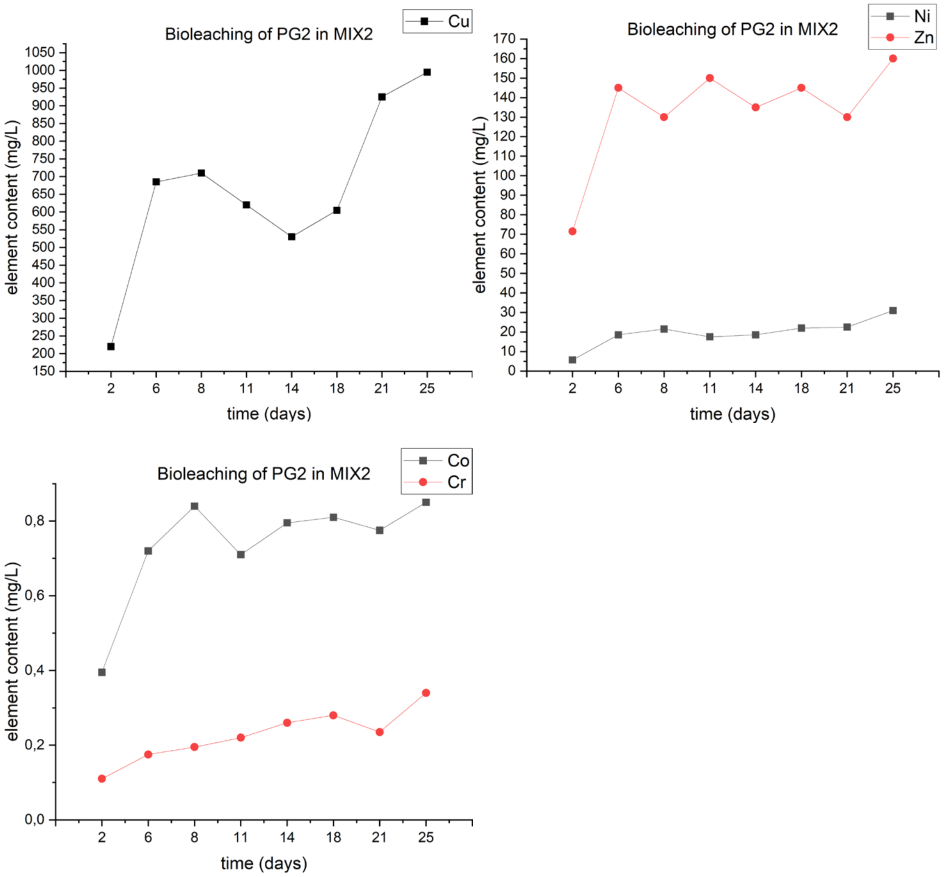


Figure 10: Results for PG2 – printed circuit boards

6 Conclusion

E-waste presents a growing threat to both the environment and human health due to the improper handling of its potentially toxic components. As the electronics and electrical industries expand globally, the challenges associated with e-waste management become increasingly urgent. Innovative strategies, such as recycling and bioleaching, are gaining atraction as sustainable solutions. Recycling plays a crucial role in mitigating environmental harm, while bioleaching offers a modern, environmentally friendly approach to recovering valuable metals from waste.

Bioleaching stands out as a promising method for e-waste management, using microorganisms to extract precious metals and reduce reliance on traditional mining. This process not only supports resource sustainability but also minimises the quantity of hazardous waste. Microorganisms such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* are commonly used in bioleaching. To fully harness its potential, further advancements are needed, including the optimisation of bioprocesses, the development of novel catalysts, genetic enhancements of microorganisms, and the exploration of hybrid technologies and innovative microbial substrates. If these enhancements are made, it may be possible to optimise bioleaching for efficient waste management.

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