A Business Model Framework for Scaling Bioleaching Technology: From Laboratory to Semi-Industrial Applications for CRM Recovery from E-Waste PCBs

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Innovative technological solutions for waste electrical and electronic equipment are critical for circular and sustainable economy. E-waste, generating 57.4 million tonnes annually, includes around 6 million tonnes of printed circuit boards (PCBs), which are rich in critical raw materials (CRMs) such as copper, nickel, zinc, cobalt, lead, and chromium. Despite this potential, less than 40% of e-waste is recycled in the EU. Bioleaching, employing acidophilic autotrophic bacteria to extract metals at ambient temperature, provides a sustainable alternative to pyrometallurgical and hydrometallurgical methods, yet industrial-scale deployment remains challenging. This study presents a complete bioleaching value chain—from mechanical pre-treatment and froth flotation to stirred-tank bioleaching and solvent extraction—demonstrated at three reactor scales (2 L, 20 L, and 100 L) over 30 days at 30 °C. Metal recovery was quantified by X-ray fluorescence. At 2 L, a mixed *Acidithiobacillus ferrooxidans*/*A. thiooxidans* inoculum recovered 47.3% Cu, 93.4% Ni, and 96.3% Cr. At 20 L, *A. thiooxidans* achieved 64.3% Cu and 90.3% Ni, and at 100 L, recoveries reached 53.5% Cu and 92.0% Ni. Coupled with an estimated 64% reduction in CO_2 emissions, these results confirm that bioleaching is a technically viable and commercially deployable method for CRM recovery from e-waste.

Keywords:
e-waste,
PCBs,
bioleaching,
Acidithiobacillus ferrooxidans,
Acidithiobacillus thiooxidans

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1 Introduction

Innovative technological solutions for waste electrical and electronic equipment (WEEE or e-waste) are crucial for the transition to a circular and sustainable economy and a key priority for the European Union (EU). According to the European Commission (EC), the circular economy rate in the EU was 11.8% in 2023, a slight increase compared to 2022 (EC, 2023).

The rapid proliferation of electronic devices has created one of the world's fastest-growing waste streams. In 2021, global e-waste reached 57.4 million tonnes, with printed circuit boards (PCBs) alone accounting for approximately 6 million tonnes (Baldé et al., 2024). PCBs contain copper, nickel, zinc, cobalt, lead, chromium and precious metals at levels often matching or exceeding those found in primary ores, making them a strategically important secondary raw material. The EU Directive 2012/19/EU on WEEE and the Critical Raw Materials Act both mandate higher recycling rates, yet less than 40% of e-waste is recovered currently (Lundberg, 2025).

Metal recovery from e-waste has relied mainly on pyrometallurgical and hydrometallurgical processes. Pyrometallurgy uses high temperatures to separate the metals, while hydrometallurgy employs acids and chemical leaching to dissolve the metal ions from the solid waste (Debbarma et al., 2023; Dhiman, 2023). Although effective, both methods consume large amounts of energy and chemicals and generate hazardous residues, making them unsustainable in the long term (Upadhyay and Ramayya, 2023). These drawbacks have encouraged researchers to explore greener and more sustainable recovery technologies, such as bioleaching. Bioleaching, which uses bacteria such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* to extract critical raw materials (CRMs) with much lower environmental impact and relatively low cost, is one of the most important areas of laboratory research in the field of Innovative Technological Processes for E-waste Recycling (Manikandan et al., 2021; Ji et al., 2024; Marinič et al., 2025).

However, most research of this kind ends in the laboratory testing phase (Technology Readiness Levels (TRL 4–5)), as the transition to a pilot or semi-industrial scale (TRL 7) requires greater financial investment, additional research to adapt the process to a bigger scale and a longer validation period (Ellwood et al., 2020; EC, 2022). This has led to the emergence of the so-called 'funding gap' or 'valley of death', which can be overcome through public–private partnerships, among other things (Probst et al., 2013).

Our research is a part of the WEEE-NET9.SPEED project, and is a good practical example where this phenomenon has been eliminated with the financial support of EIT RawMaterials. It is an upgrade of the WEEE-NET9 project, which was finalised in 2024, and enabled the transfer of the knowledge and implementation of bioleaching technology from the laboratory scale to pilot and semi-industrial scales (TRL 7) in the company Monolithos Catalysts & Recycling Ltd (Athens, Greece).

Despite strong laboratory performance – copper recoveries exceeding 95% have been reported in the literature under optimised small-scale conditions (Arshadi et al., 2019; Fu et al., 2021) – the scale-up of bioleaching beyond the bench scale is reported rarely. The transition from a well-controlled 2 L laboratory reactor to a 20 L pilot or 100 L semi-industrial vessel introduces substantial engineering challenges: less uniform mixing, reduced oxygen transfer efficiency, pH and temperature gradients, and greatly increased logistical demands for sterile inoculum production. These challenges halt development at the laboratory stage frequently.

This study presents the results of a structured three-stage scale-up campaign conducted at ZAG (Slovenian National Building and Civil Engineering, Ljubljana, Slovenia) and Monolithos Catalysts & Recycling Ltd (Athens, Greece), progressing from 2 L through 20 L to 100 L. The article describes the complete processing chain from PCB shredding to solvent extraction, and presents XRF-based solid-phase metal removal as the primary evidence of the bioleaching performance at each scale.

2 Process of the Value Chain and Business Model

The bioleaching process demonstrated here is structured as a modular five-stage service chain, summarised in the process flow diagram – business model (Figure 1). Each stage can be offered independently, or as an integrated package to WEEE recycling clients. The chain progresses from raw PCB collection through mechanical preparation, bacterial leaching, liquid–solid separation and solvent extraction, to generate market-ready metal concentrates.

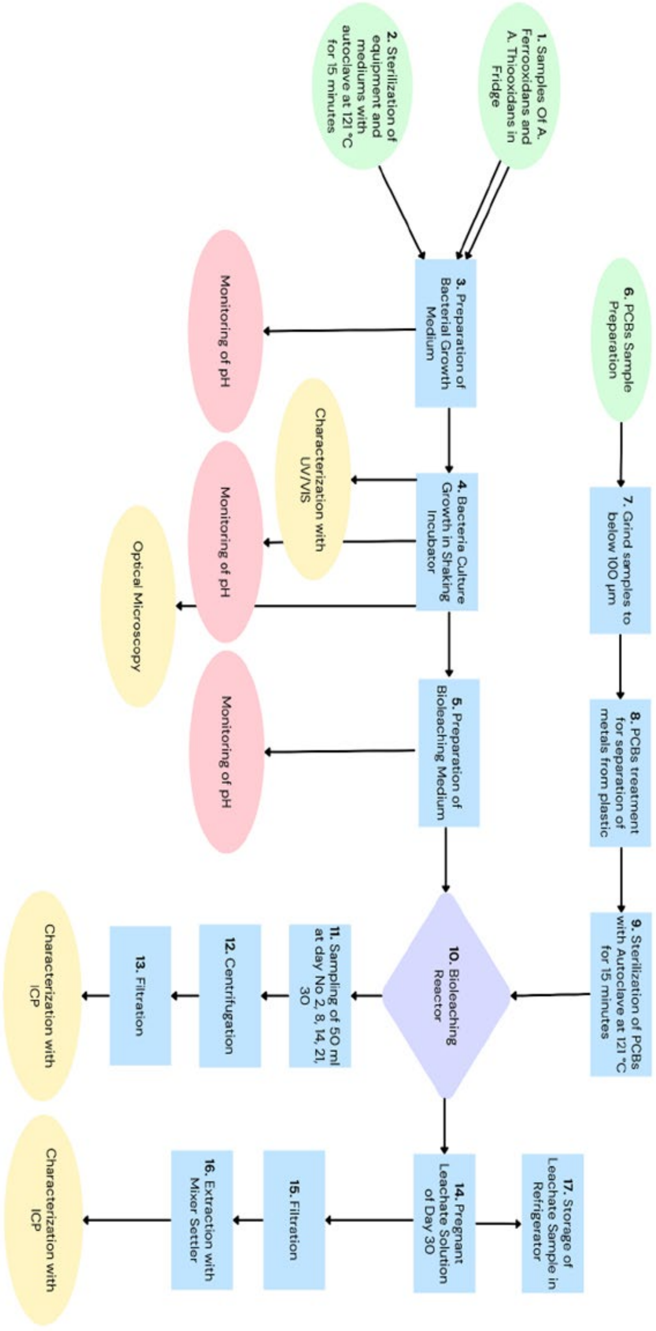

Figure 1: Flow chart of the experiment
Source: own.

2.1 Stage 1: Mechanical Pre-Treatment and Plastic Separation

PCBs of the first and second grades are sourced from decommissioned LCD displays, laptops, tablets and industrial electronics. The feedstock is compositionally heterogeneous: LCD boards have standard copper tracks with tin–lead solder, while laptop boards contain thicker copper layers, lead-free solder and surface finishes such as ENIG (Electroless Nickel Immersion Gold) or immersion silver. Higher-grade laptop boards are enriched disproportionately in gold and nickel, making feedstock characterisation an important initial step.

Pre-treatment starts with manual dismantling to remove the large discrete components (batteries, capacitors, connectors). The boards are then processed through an industrial cutting machine to produce centimetre-scale fragments, which enter a grinding circuit. After each pass the material is sieved; oversized fragments are returned for re-grinding until the entire batch passes through a 125 μm aperture sieve, producing a fine metallic powder in which the individual PCB layers are fully disaggregated. This controlled particle size is critical: finer material maximises the surface area for bacterial attack while avoiding excessive energy consumption.

Before entering the bioleaching process, the ground material undergoes froth flotation. This step exploits the difference in hydrophobicity between plastics and the denser metallic fraction: air injected through the slurry carries hydrophobic plastic particles to the surface, where they overflow with the froth, while the metallic concentrate sinks and is collected. Retaining significant amounts of plastic in the bioleaching reactor suppresses bacterial activity, increases acid consumption, and introduces organic contamination that interferes with the downstream solvent extraction. The separated metallic fraction is then sterilised by autoclaving at 121 °C for 15 minutes before entering the reactor, to prevent external microorganisms from competing with the inoculated culture.

2.2 Stage 2: Bacterial Culture Preparation

Two bacterial strains are used: *Acidithiobacillus ferrooxidans* (DSM 583) and *Acidithiobacillus thiooxidans* (DSM 9463), both obtained from the German Collection of Microorganisms and Cell Cultures (DSMZ). Both are acidophilic, chemoautotrophic bacteria commonly found in acidic, metal- or sulphur-rich environments. *A. ferrooxidans* oxidises ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), the primary oxidant responsible for attacking metal alloys in the PCB matrix, while *A. thiooxidans* oxidises the reduced sulphur compounds to sulphuric acid, lowering the solution pH below 2 and maintaining the acidic conditions required for metal solubilisation.

A key practical constraint identified during scale-up was that *A. ferrooxidans* growth could be maintained reliably only in the 2 L experiment, which was conducted in a dedicated sterile laboratory environment. At 20 L and 100 L, logistical constraints and contamination risks in a shared research facility restricted the inoculum to *A. thiooxidans* alone. This finding has important implications for future scale-up: maintaining dual-strain inoculum at larger volumes requires dedicated sterile fermenters for inoculum production, separated from the main reactor facility.

2.3 Stage 3: Bioleaching Reactor Operation

The bioleaching step is performed in stirred-tank reactors at three volumes. In all cases, the e-waste loading is 15 g/L, aeration is continuous via air pumps, the temperature is 30 °C and each run lasts 30 days. The bioleaching medium differs between scales: the 2 L experiment used a MIX medium (pH 2.5) formulated to support both bacterial strains simultaneously, containing per litre $(NH_4)_2SO_4$ 4.00 g, KCl 0.10 g, K_2HPO_4 0.50 g, $MgSO_4{\cdot}7H_2O$ 0.50 g, $Ca(NO_3)_2$ 0.01 g, $FeSO_4{\cdot}7H_2O$ 22.10 g, and elemental sulphur 5.00 g. The 20 L and 100 L experiments used an S-medium (pH 2.5) formulated for *A. thiooxidans* alone, containing per litre $(NH_4)_2SO_4$ 0.40 g, K_2HPO_4 3.00 g, $MgSO_4{\cdot}7H_2O$ 0.50 g, $FeSO_4{\cdot}7H_2O$ 0.01 g, and elemental sulphur 10.00 g.

The reactor contents are pre-conditioned for 24 hours – medium and PCB powder mixed without bacteria — after which the pH is adjusted to 2.5 using concentrated H_2SO_4 and the bacterial inoculum (10 % v/v) is added. Samples are collected on days 0, 2, 8, 14, 21, and 30 under a strict sterile technique: the workspace is cleaned with 70 % ethanol; a 100 mL aliquot is withdrawn by peristaltic pump and centrifuged at 9,000 rpm for 10 minutes to separate the solid from the supernatant. The supernatant is filtered through a 0.22 μm membrane; 15 mL is transferred to ICP cups and refrigerated; the remainder is frozen for archiving. The solid pellet is retained from each sampling day. A control reactor without bacterial inoculation is run in parallel, and sampled at day 21 to quantify the abiotic dissolution.

2.4 Stage 4: Liquid–Solid Separation and Solvent Extraction

At the end of the 30-day run, the entire reactor contents are filtered through a 15-20 µm filter press to separate the pregnant leach solution (PLS) from the depleted solid residue. The solid cake is dried, weighed and submitted for XRF analysis to quantify the residual metal content. The PLS – containing dissolved copper, nickel, zinc, cobalt and iron in an acidic sulphate matrix – is processed through a mixer-settler solvent extraction (SX) circuit. An oxime-based organic extractant transfers copper selectively into the organic phase; the loaded organic is stripped with dilute sulphuric acid to yield a copper-rich aqueous concentrate suitable for electrowinning or direct sale as copper sulphate. The copper-depleted raffinate is treated for nickel and zinc recovery. Under optimised conditions at the 100 L scale, the Cu SX efficiency reached 75-85 %, Ni 30-45 % and Fe 60-75 %, with a raffinate pH of approximately 2.4-2.6.

2.5 Commercial Framework

The modular nature of the process enables several independent service offerings: feedstock characterisation and bioleachability assessment, bench-scale or pilot-scale bioleaching trials, and integrated SX with product generation. A patent application for the process has been submitted to the Slovenian Intellectual Property Office. The process achieves approximately 64 % less CO_2 per kilogram of treated PCBs compared with the pyrometallurgical benchmarks, making it an attractive option for companies seeking to reduce the environmental footprint of their metal recovery operations.

3 Materials and Methods

3.1 PCB Feedstock

All three experiments used PCBs from the same pre-processed batch, prepared by Monolithos. The XRF analysis of the raw solid confirmed copper as the dominant metal at 342,900 ppm (342.9 kg/tonne dry solid), with secondary metals at 1–3 kg/tonne: nickel (3.20 kg/t), cobalt (2.20 kg/t), cadmium (2.75 kg/t), zinc (2.65 kg/t), lead (2.19 kg/t) and chromium (1.01 kg/t).

3.2 Experimental Conditions at Each Scale

Table 1: Experimental parameters for the bioleaching trials at 2 L, 20 L, and 100 L scales

Parameter	2 L	20 L	100 L
Reactor vessel	5 L	20 L	100 L
Working volume	2 L	14 L	14 L
Duration	30 days	30 days	30 days
Inoculum (10 % v/v)	*A. ferrooxidans* + *A. Thiooxidans* (50:50)	*A. Thiooxidans* only	*A. Thiooxidans* only

3.3 XRF Analysis

The solid-phase elemental composition was determined by X-ray fluorescence (XRF) spectrometry on samples from the initial PCB powder (before inoculation) and from the dried filter cake at day 30. The samples were dried at 60 °C to constant weight before the analysis. The concentrations are reported in kg/tonne (equivalent to g/kg dry solid). The recovery yield was calculated according to Equation (1):

$$\text{Recovery (\%)} = [(C_0 - C_{\text{end}}) \,/\, C_0] \times 100 \qquad (1)$$

where C_0 is the initial metal concentration and C_{end} is the residual concentration after bioleaching. Higher values indicate a greater transfer of metal from the solid phase into the leach solution. Control experiments (no bacteria) were run in parallel, to separate the biologically driven removal from the abiotic acid dissolution.

4 XRF Results: Solid-Phase Metal Removal

4.1 2 L Reactor

The XRF analysis of the solid before and after the 30-day trial at 2 L demonstrated effective metal removal across all seven elements. The copper – dominant at 342,900 ppm – decreased to 180,700 ppm, a recovery yield of 47.3 %. The moderate copper recovery at this scale reflects the layered, encapsulated nature of copper in the PCB laminate: the inner copper layers and thick electroplated pads require sustained acid exposure for full dissolution, and 30 days under batch conditions was insufficient for complete solubilisation (Arshadi et al., 2019; Mostafavi et al., 2018; Saldaña et al., 2023).

The trace and minor metals showed markedly higher removal. Nickel recovery reached 93.4 %, chromium 96.3 %, cobalt 90.9 % and zinc 86.0 %. These elements are associated predominantly with surface coatings –ENIG layers, solder masks and component metallisations – that are accessible to bacterial attack rapidly at fine particle size. Cadmium (71.6 %) and lead (62.9 %) showed intermediate removal consistent with the partial dissolution of the solder materials. The control samples confirmed that abiotic acid dissolution alone produced substantially lower solid-phase depletion, validating the biological contribution.

Table 2: XRF solid-phase concentrations before and after bioleaching — 2 L reactor (30 days, 30 °C, mixed *A. ferrooxidans* + *A. Thiooxidans*)

Element	Before (kg/tonne)	After (kg/tonne)	Recovery (%)
Copper (Cu)	342.9	180.7	47.3
Nickel (Ni)	3.20	0.21	93.4
Chromium (Cr)	1.01	0.04	96.3
Cobalt (Co)	2.20	0.20	90.9
Zinc (Zn)	2.65	0.37	86.0
Cadmium (Cd)	2.75	0.78	71.6
Lead (Pb)	2.19	0.81	62.9

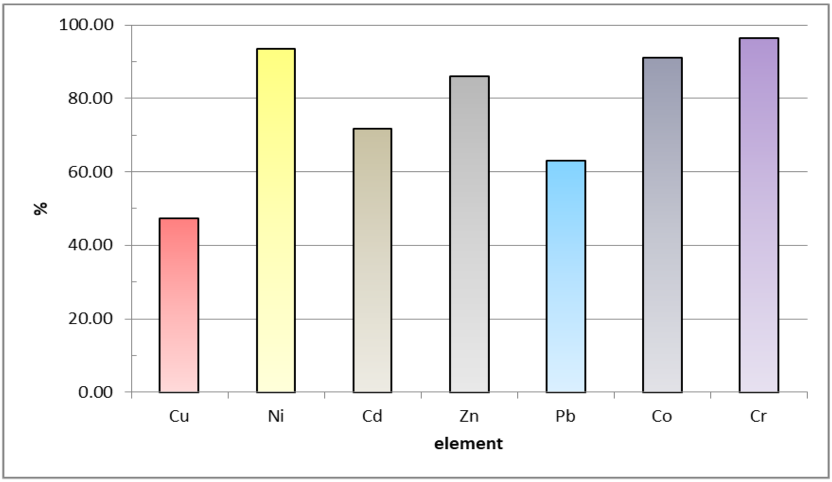

Figure 2: Yield potential for the 2 L experiment
Source: own.

4.2 20 L Reactor

The XRF analysis of the solid before and after the 30-day trial at 2 L demonstrated effective metal removal across all seven elements (Table 3 & Figure 3). The 20 L experiment, conducted with *A. Thiooxidans* alone in S-medium, yielded the highest copper recovery of any scale: 64.3 % (from 342,900 ppm to 122,300 ppm, a removal of 220,600 ppm). Nickel recovery remained high at 90.3 %, cadmium at 72.5 % and chromium at 74.1 %. Zinc recovery was 66.5 %, cobalt 56.1 % and lead 38.7 % – the last showing the greatest relative decline compared with the 2 L run. The transition from the dual-strain MIX medium to single-strain S-medium did not reduce the performance for the majority of elements, confirming *A. Thiooxidans* as an effective standalone leaching organism at this scale.

Table 3: XRF solid-phase concentrations before and after bioleaching — 20 L reactor (30 days, 30 °C, *A. Thiooxidans* only)

Element	Before (kg/tonne)	After (kg/tonne)	Recovery (%)
Copper (Cu)	342.9	122.3	64.3
Nickel (Ni)	3.20	0.31	90.3
Chromium (Cr)	1.01	0.26	74.1
Cobalt (Co)	2.20	0.96	56.1
Zinc (Zn)	2.65	0.89	66.5
Cadmium (Cd)	2.75	0.76	72.5
Lead (Pb)	2.19	1.34	38.7

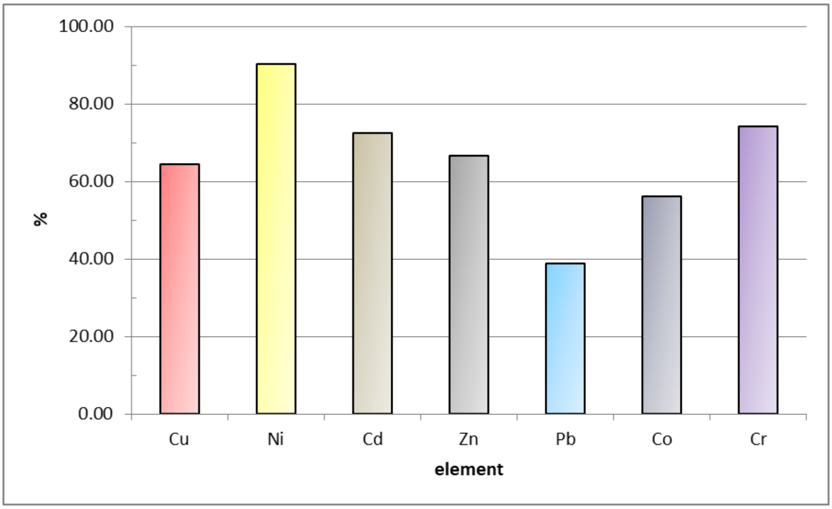

Figure 3: Yield potential for the 20 L experiment
Source: own.

4.3 100 L Reactor

At 100 L, the XRF analysis of the day-30 solid residue confirmed commercially relevant metal removal across all the elements (Table 4 & Figure 4). Copper recovery was 53.5 %, intermediate between the 2 L and 20 L values. Nickel recovery was 92.0 %, the highest of any scale, demonstrating the excellent robustness of nickel solubilisation at semi-industrial volumes. Chromium recovery was 74.7 %, consistent with the 20 L result. Cobalt dropped to 47.7 % and zinc to 74.2 %; cadmium (57.1 %) and lead (57.2 %) showed moderate removal. The control data confirmed that the observed solid-phase depletion was primarily biological in origin.

Table 4: XRF solid-phase concentrations before and after bioleaching — 100 L reactor (30 days, 30 °C, *A. Thiooxidans* only)

Element	Before (kg/tonne)	After (kg/tonne)	Recovery (%)
Copper (Cu)	342.9	159.6	53.5
Nickel (Ni)	3.20	0.26	92.0
Chromium (Cr)	1.01	0.26	74.7
Cobalt (Co)	2.20	1.15	47.7
Zinc (Zn)	2.65	0.69	74.2
Cadmium (Cd)	2.75	1.18	57.1
Lead (Pb)	2.19	0.94	57.2

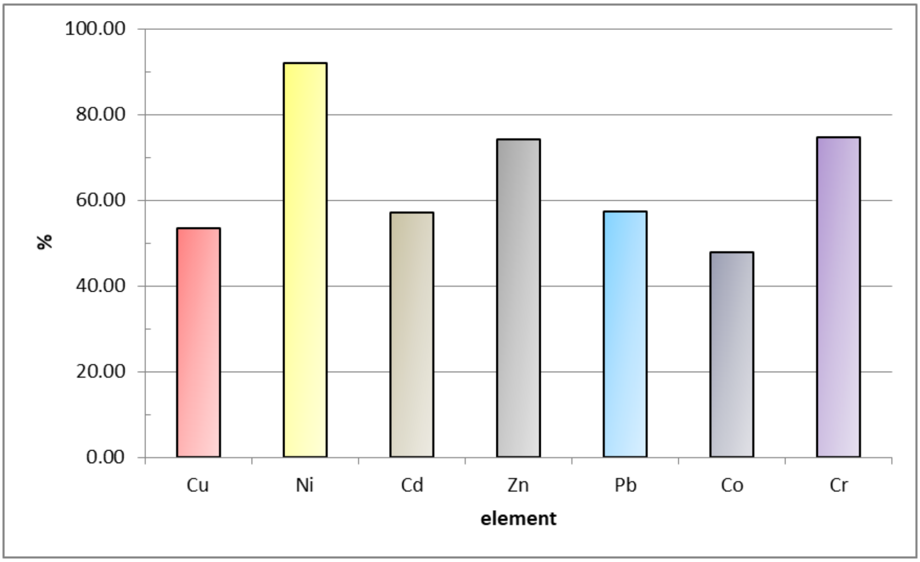

Figure 4: Yield potential for the 100 L experiment
Source: own.

5 XRF Results: Solid-Phase Metal Removal

Table 5 consolidates the XRF-based recovery yields across all three scales, revealing patterns that have direct implications for further scale-up.

Table 5: XRF-based solid-phase recovery yields (%) across all three reactor scales

Element	2 L (%)	20 L (%)	100 L (%)
Copper (Cu)	47.3	64.3	53.5
Nickel (Ni)	93.4	90.3	92.0
Chromium (Cr)	96.3	74.1	74.7
Cobalt (Co)	90.9	56.1	47.7
Zinc (Zn)	86.0	66.5	74.2
Cadmium (Cd)	71.6	72.5	57.1
Lead (Pb)	62.9	38.7	57.2

Copper recovery showed a non-monotonic trend, rising from 47.3% at 2 L to 64.3% at 20 L before falling to 53.5% at 100 L, contrary to the typical scale-up expectations of decreasing recovery due to mass transfer limitations (Saldaña et al., 2023). The improved performance at 20 L may result from using *A. thiooxidans* alone, which avoids competition with *A. ferrooxidans* and enhances sulphuric acid production, as well as more favourable mixing conditions. Nickel remained highly stable across the scales (90.3–93.4%), reflecting its presence in easily accessible ENIG coatings that dissolve readily (Arshadi et al., 2019). Chromium recovery dropped from 96.3% at 2 L to approximately 74% at larger scales due to the absence of *A. ferrooxidans*, which reduces Fe^{3+}-driven oxidative dissolution (Blaby-Haas, 2022; Potysz et al., 2016). Cobalt showed the steepest decline (90.9% to 47.7%), confirming its dependence on ferric iron (Adetunji et al., 2023; Saldaña et al., 2023). Zinc followed an intermediate pattern (86.0% → 66.5% → 74.2%), influenced by the mixing intensity and particle suspension (Fu et al., 2021; Mostafavi et al., 2018). Cadmium remained relatively consistent (71–72%) before declining at 100 L (57.1%), likely due to the higher pH reducing solubility (Rautela et al., 2021). Lead showed high variability (62.9% → 38.7% → 57.2%), due primarily to $PbSO_4$ precipitation, which underestimates the true recovery in the XRF analysis (Potysz et al., 2016; Srichandan et al., 2019).

6 Conclusions

A complete bioleaching process value chain for critical raw material recovery from e-waste PCBs has been demonstrated at three successive scales – 2 L, 20 L, and 100 L – each operated for 30 days at 30 °C. The XRF analysis of the solid phase at each scale provided the following key findings:

At 2 L, a mixed *A. ferrooxidans* / *A. thiooxidans* culture achieved Cu recovery of 47.3 %, Ni 93.4 %, Cr 96.3 %, and Co 90.9 %, establishing a strong laboratory benchmark. At 20 L, the single-strain *A. thiooxidans* produced the highest Cu recovery of any scale (64.3 %) while maintaining Ni above 90 %, validating the scale transfer. At 100 L, the Cu recovery was 53.5 % and Ni 92.0 %, confirming semi-industrial viability with only modest losses in Co and Zn recovery relative to the laboratory scale.

The primary recommendations for future work are: (i) develop dedicated inoculum fermenters for *A. ferrooxidans* to recover Co and Cr performance at a large scale; (ii) extend the bioleaching period beyond 30 days to approach the maximum Cu recovery; (iii) optimise the aeration and agitation at 100 L and beyond to reduce the performance gaps for Co and Zn; and (iv) implement real-time pH and ORP feedback control to maintain optimal conditions throughout the run. Together, these improvements are expected to bring large-scale copper recovery to 70 % or above, while sustaining the already excellent Ni and Cr yields, supporting commercialisation of the process as a low-carbon alternative to conventional e-waste smelting.

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