

# Sustainable Recovery of Critical Metals from PCBs via Integrated Bioleaching

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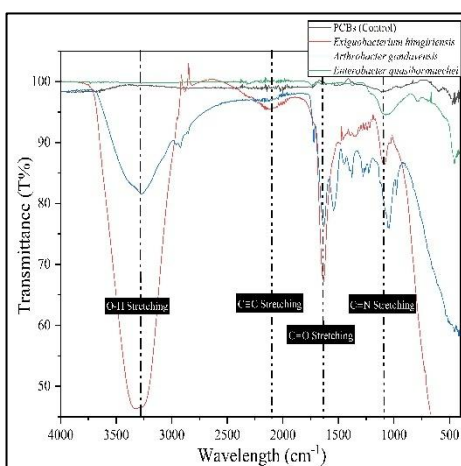
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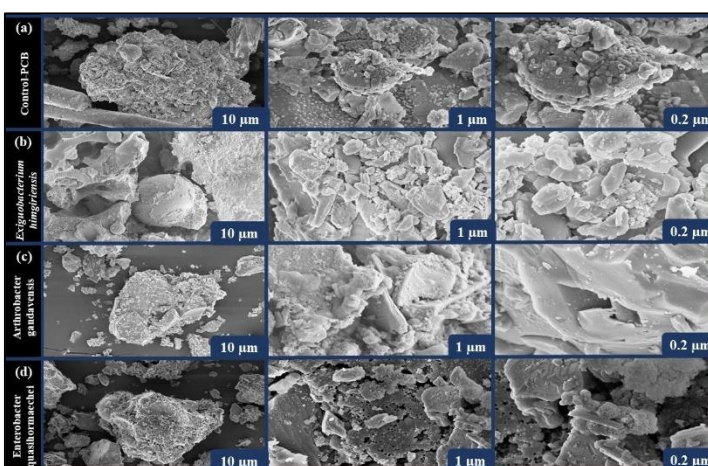
Bioleaching has evolved as a low-energy alternative to traditional pyrometallurgical and hydrometallurgical routes for recovering valuable metals from e-waste. In addition to valuable metals, such as Ag and Cu, PCBs contain toxic metals, including Pb, Cr, Ni, and Sb, which are embedded into complex polymer metal matrices and have great resistance to recycling (Priya and Hait, 2017, 2018; Trivedi and Hait, 2020). The current study integrates experimental and environmental evaluation of three bacterial strains, *Arthrobacter gandavensis*, *Exiguobacterium himgiriensis*, and *Enterobacter quasihormaechei* isolated from raw PCBs and evaluated for their bioleaching efficiency under identical conditions at 37 °C, 150 rpm for 5 days with the purpose to (i) compare the strain-specific metal recovery profiles, (ii) consolidate physicochemical evidence of microbial leaching mechanisms, and (iii) quantify cradle-to-gate environmental impacts by using an LCA model informed by experimental inventories. Materials and methods followed consistent protocols across strains to allow direct comparison and data integration. PCB feedstock was collected without pre-treatment for removing the chemical coating. Heterogenous PCB powder was produced by muffle-furnace treatment and sieved to particle size fractions suitable for bench-scale assays (Halder et al., 2025a, 2025b). For each strain, bioleaching used 5 g·L<sup>-1</sup> PCB load in supplement-free nutrient broth inoculated with actively growing culture and incubated at 37 °C with agitation (150 rpm) for 5 days (Arshadi and Yaghmaei, 2020). Post-incubation, samples were centrifuged and supernatants and residues were prepared using microwave digestion for ICP-OES metal quantification. Complementary characterization included FE-SEM/EDS for surface morphology and elemental mapping, FT-IR for functional-group changes, and XRD for crystalline phase transformations. LCA was performed in open LCA with Ecoinvent 3.11 background datasets. The system boundary is cradle-to-gate with a functional unit of 1 kg of processed PCB (LCA model inputs derived from the experimental inventory)(He et al., 2025). Results show complementary strengths across the three strains (**Table 1**).

**Table 1.** Recovery efficiency (%) of target metals by each strain (5 d, 37 °C, 150 rpm)

Sl. No.	Target Metal	Metal recover efficiency (%) from PCBs		
		<i>E. himgiriensis</i>	<i>E. quasihormaechei</i>	<i>A. gandavensis</i>
1.	Copper (Cu)	95.55	86.49	90.78
2.	Silver (Ag)	93.5	95.45	96.77
3.	Calcium (Ca)	62.41	51.97	74.36
4.	Iron (Fe)	79.29	84.99	86.75
5.	Manganese (Mn)	95.63	87.27	93.33
6.	Zinc (Zn)	42.66	61.07	55.74



**Figure 1:** FTIR spectra of untreated PCBs(control) and bioleached PCBs processed with all three bacterial strains



**Figure 2:** FE-SEM micrographs of PCBs (a) before and (b), (c)&(d) after bioleaching with all three bacterial strains

These strain-level results were independently confirmed by FE-SEM/EDS (surface corrosion and metal adsorption onto biomass) (**Figure 1**), FT-IR (appearance of hydroxyl, carboxyl, amine and other ligand bands consistent with organic-acid and ligand-mediated complexation) (**Figure 2**), and XRD (loss or attenuation of metal-bearing crystalline phases), supporting a mixed mechanism of acidolysis, complexolysis and surface adsorption. The LCA parameterized with the experimentally measured inventories (energy use for mechanical pretreatment, incubator electricity, filtration, chemical inputs for downstream precipitation/solvent extraction, and transport) indicates a baseline climate change impact of 0.03511 kg CO<sub>2</sub>-eq per kg PCB processed with freshwater ecotoxicity and climate change identified as dominant impact categories (Dada *et al.*, 2025). Sensitivity analysis within the LCA highlights that electricity source and improved effluent handling are primary levers for reducing impacts at scale. These findings show that under the present laboratory inventory, bioleaching can achieve significant metal mobilization while maintaining relatively low cradle-to-gate greenhouse-gas intensity compared with published values for conventional routes, provided downstream solvent and effluent management are optimized. Operational implications include: sequential or targeted application of strains to maximize total metal recovery by exploiting complementary specificities, for example, toxic-metal removal can be done first to reduce hazards, followed by targeted recovery of base and precious metals. It is essential to maintain a favourable environmental profile by media-free cultivation and minimization of external chemical inputs. From the point of view of scale-up, the principal challenges are: energy use for mechanical pretreatment and robust downstream separation of mixed metal streams. Subsequent work will focus on reactor scale-up trials, dynamic optimization of residence times for sequential leaching, and process integration with closed-loop effluent treatment to avoid ecotoxicity hotspots. An integrated experimental and LCA study has been carried out to illustrate that a multi-strain bioleaching strategy has the capacity to extend the spectrum of recoverable metals from PCBs, offers mechanistic evidence of microbial leaching pathways, and, when combined with optimized downstream practice, can provide a feasible low-impact route for urban mining of critical metals.

## References

1. Arshadi, M., & Yaghmaei, S. (2020). Advances in bioleaching of copper and nickel from electronic waste using *Acidithiobacillus ferrooxidans*: evaluating daily pH adjustment. *Chemical Papers*, 74(7), 2211–2227. <https://doi.org/10.1007/s11696-020-01055-y>
2. Dada, S. R., Okoye, E., & Hamed, V. (2025). Environmental and economic impacts of sustainable e-waste management: a life cycle assessment approach. *International Journal of Multidisciplinary Research and Growth Evaluation*, 6(1), 1851–1854. <https://doi.org/10.54660/IJMRGE.2025.6.1-1851-1854>
3. Halder, B., Nigam, V. K., & Sampath, M. K. (2025a). Bioleaching of different types of metals by *Exiguobacterium himgiriensis* isolated from printed circuit board. *Environmental Technology*, 1–13. <https://doi.org/10.1080/09593330.2025.2560589>
4. Halder, B., Nigam, V. K., & Sampath, M. K. (2025b). Bioleaching of valuable metals from printed circuit boards (PCBs) using *Enterobacter quasihormaechei* isolated from E-waste. *Journal of Environmental Science and Health, Part A*, 1–11. <https://doi.org/10.1080/10934529.2025.2582340>
5. He, S. W., Paz, F. A. G., Aromaa, J., Aromaa-Stubb, R., Li, Y., Sajjad, M., & Parvez, A. M. (2025). Conceptual Process Design and LCA Evaluation of Precious Metals Recovery from Waste PCBs. *Journal of Sustainable Metallurgy*. <https://doi.org/10.1007/s40831-025-01150-y>
6. Priya, A., & Hait, S. (2017). Comparative assessment of metallurgical recovery of metals from electronic waste with special emphasis on bioleaching. *Environmental Science and Pollution Research*, 24(8), 6989–7008. <https://doi.org/10.1007/s11356-016-8313-6>
7. Priya, A., & Hait, S. (2018). Feasibility of Bioleaching of Selected Metals from Electronic Waste by *Acidiphilium acidophilum*. *CCC*, 9(5), 871–877. <https://doi.org/10.1007/s12649-017-9833-0>
8. Trivedi, A., & Hait, S. (2020). Bioleaching of Selected Metals from E-Waste Using Pure and Mixed Cultures of *Aspergillus* Species. In *Energy, Environment, and Sustainability* (pp. 271–280). Springer Nature. [https://doi.org/10.1007/978-981-15-0540-9\\_13](https://doi.org/10.1007/978-981-15-0540-9_13)

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