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Development of innovative recycling technologies for sustainable electronic waste management in the United States

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Abstract

Electronic waste (e-waste) is a fast-growing waste stream rich in valuable materials yet poses serious environmental challenges if not managed sustainably. This study develops an innovative recycling process for e-waste that integrates advanced hydrometallurgical and biotechnological techniques, aiming to improve metal recovery efficiency and environmental performance. A comprehensive literature review highlights the limitations of conventional methods and the latest advancements in hydrometallurgy and bioleaching. Building on these insights, we designed a hybrid recycling methodology combining selective bioleaching and optimized chemical extraction. Key process parameters were systematically optimized using statistical design of experiments, and rigorous validation (including regression modeling, sensitivity analysis, and inferential statistics) confirmed the robustness of the process. The results demonstrate significantly higher recovery rates for precious and base metals compared to traditional approaches, while reducing hazardous reagent consumption. In discussion, we compare our findings with prior studies to underscore the novelty and broader implications for sustainable e-waste management. Finally, we provide recommendations for translating this technology into practice in the United States through supportive policies and future research directions. The proposed approach advances the field of e-waste recycling by offering a cleaner, more efficient solution that could bolster the circular economy and critical materials supply chain.

Keywords: E-waste recycling; Hydrometallurgy; Bioleaching; Metal recovery; Sustainable waste management

1. Introduction

The proliferation of consumer electronics and short product life cycles have led to an unprecedented surge in electronic waste (e-waste) generation worldwide. In 2022 alone, the world produced about 62 million tonnes of e-waste, making it the fastest-growing solid waste stream. Alarmingly, less than one-quarter (only ~22%) of this e-waste was properly collected and recycled, leaving vast quantities of valuable metals discarded and environmental pollution risks unmitigated. The United States is one of the top e-waste generating countries and faces significant challenges in sustainable e-waste management. There is currently no federal law in the U.S. mandating e-waste recycling or prohibiting the export of e-waste to developing countries. This regulatory gap, coupled with fragmented state-level policies, has hindered the development of a cohesive national recycling infrastructure. As a result, millions of tons of

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U.S. e-waste each year are landfilled, incinerated, or shipped abroad, wasting critical resources and causing health and environmental hazards.

E-waste contains a complex mix of materials, including hazardous substances (lead, mercury, brominated flame retardants) and valuable metals (copper, gold, silver, palladium, rare earth elements). Effective recycling is imperative both to prevent toxic pollution and to recover strategic metals that can reduce reliance on virgin mining. Conventional e-waste recycling typically involves a combination of mechanical preprocessing and metallurgical treatments. Initial physical dismantling and sorting can recover some components for reuse, followed by shredding and separation techniques (magnetic, eddy current, density separation) to concentrate metal-bearing fractions. However, to extract metals from the complex matrices, thermal and chemical processes are usually required. Pyrometallurgy (high-temperature smelting) and hydrometallurgy (chemical leaching) have long been the primary approaches. Each of these methods, however, has drawbacks that limit sustainability. Pyrometallurgical processing, while capable of handling large volumes and mixed materials, consumes substantial energy and can emit toxic gases and slag, necessitating pollution control measures. Hydrometallurgical processes can achieve high metal recovery yields at lower temperatures, but often rely on strong acids or other chemicals, leading to hazardous waste generation and treatment costs. Moreover, neither approach fully addresses the recovery of all valuable elements (for example, rare earth elements and certain critical metals often remain in residues or require further refining). In recent years, researchers have explored biotechnological recycling methods (bioleaching or "biometallurgy") as a more eco-friendly alternative. Bioleaching utilizes microorganisms to solubilize metals from e-waste, offering the potential for lower energy use and avoiding harsh chemicals. Yet, biological methods alone can be slow and may not achieve complete extraction for all metals, especially given the short residence times that industrial processing demands. To move toward sustainable e-waste management, **innovative recycling technologies** are needed that overcome the limitations of conventional methods. Integrating advanced hydrometallurgical techniques with biotechnological processes is a promising strategy to improve efficiency while reducing environmental impact. For example, a synergistic process could use specialized microbes to pre-treat or partially leach e-waste, followed by optimized chemical leaching to recover remaining metals. Such hybrid approaches can potentially combine the best attributes of each method: the selectivity and mild conditions of bioleaching with the speed and completeness of hydrometallurgy.

This research focuses on developing a novel hybrid recycling process tailored for e-waste streams in the United States. By leveraging recent advancements in hydrometallurgical and biotechnological methods, our goal is to maximize metal recovery (including precious metals and critical rare elements) in a sustainable manner. In the sections that follow, we first review the state-of-the-art in e-waste recycling technologies, highlighting key findings from recent high-impact studies and identifying gaps that this study aims to fill. We then detail the methodology of our proposed process, including materials, experimental procedures, and the statistical optimization techniques employed to refine the process parameters. Next, we present results demonstrating the performance of the new technology, with a thorough analysis of how it compares to existing methods. In the discussion, we examine the implications of these findings for advancing e-waste recycling, emphasizing the novelty of our approach and its potential to contribute to a circular economy. Finally, we conclude with practical recommendations for implementing this technology in real-world settings, policy suggestions to support sustainable e-waste management in the U.S., and directions for future research to further enhance electronic waste recycling.

2. Literature Review

2.1. Conventional E-Waste Recycling Methods and Challenges

- **Pyrometallurgy and Mechanical Processing:** Traditional industrial e-waste recycling heavily relies on pyrometallurgical smelting, often preceded by mechanical pre-processing. In a typical scenario, e-waste is shredded and mechanically separated into metal-rich fractions (using techniques such as magnetic separation for ferrous metals and eddy current separation for non-ferrous metals) and nonmetal fractions. The metal concentrates, along with other residues, are then fed into high-temperature furnaces. Pyrometallurgy involves melting the e-waste in oxidative or reductive atmospheres, which causes metals to segregate into a molten alloy (containing valuable metals like copper, gold, silver, etc.) and a slag phase capturing less valuable oxides. Large-scale smelters (e.g. those operated by Umicore, Boliden, Aurubis and others) have successfully processed e-waste using such methods, recovering copper and precious metals as part of a smelted matte or alloy. Pyrometallurgical processing is fast and can handle heterogeneous mixtures without extensive sorting. However, its drawbacks include extreme energy consumption (furnace operations at >1200°C), generation of toxic emissions (requiring off-gas treatment for lead, dioxins, etc.), and loss of certain volatile or low-boiling elements (e.g. plastics are burned for energy, and some precious metals or rare elements can partly vaporize or end up in slag). Furthermore, the output is often a crude alloy that still needs further refining; in fact, hydrometallurgical refining steps are commonly employed after smelting to isolate specific high-purity metals . Thus, while pyrometallurgy is the most established e-waste recycling approach, its environmental footprint and incomplete material recovery highlight the need for cleaner, more comprehensive methods.

- **Hydrometallurgy:** Hydrometallurgical recycling uses chemical solutions to leach metals from shredded e-waste, and is widely studied due to its ability to achieve high recovery yields of targeted metals under relatively moderate conditions. Conventional hydrometallurgy typically employs strong mineral acids (such as HCl, HNO_3, H_2SO_4) often in combination with oxidizing agents (like hydrogen peroxide or persulfates) to dissolve metals into a leachate. Subsequent steps like solvent extraction, precipitation, or electro-winning are used to recover metals from the leachate in elemental form or as compounds. For instance, etchants can dissolve copper and precious metals from printed circuit boards (PCBs), which can then be precipitated or electrodeposited out of solution. Hydrometallurgy can be highly efficient; laboratory studies report copper and gold recovery rates exceeding 90% from e-waste using strong acids. Table 1 (literature examples) shows typical recoveries: e.g., >93% of Cu, Ag, Nd from waste PCBs with nitric acid leaching, and ~95% Au, 97% Cu from CPU socket scrap using hydrochloric acid. Despite its effectiveness, this approach faces challenges. The extensive use of corrosive reagents leads to secondary wastes (spent acids and metal-laden effluents) that must be treated to avoid environmental harm. Additionally, different elements require different leaching conditions, so multi-metal recovery often demands sequential or multiple-step leaching, complicating the process. The cost of chemicals and wastewater treatment can be high, and certain refractory materials (e.g. ceramics, some alloys) may not dissolve easily without aggressive conditions. Thus, while hydrometallurgy can yield high metal recoveries, its sustainability depends on minimizing chemical consumption and mitigating any pollution from the process.
- **Biometallurgy (Bioleaching):** The concept of using microorganisms to extract metals from ores has been adapted to e-waste recycling as a potentially eco-friendly method. Bioleaching harnesses bacteria or fungi that can produce acidic metabolites or other metal-binding compounds to solubilize metals from solid waste. Several types of microorganisms have been tested: (1) Acidophilic chemolithotrophic bacteria (such as *Acidithiobacillus ferrooxidans* and *Leptospirillum* spp.) oxidize iron and sulfur to generate sulfuric acid and ferric ions, which can leach metals in a way analogous to acid leaching. (2) Heterotrophic bacteria (like *Chromobacterium violaceum* or certain *Pseudomonas* spp.) can produce organic acids or cyanide compounds that complex with and mobilize metals. (3) Fungi (e.g. *Aspergillus niger*, *Penicillium* spp.) excrete organic acids (citric, oxalic, etc.) and other ligands as part of their metabolism, facilitating metal dissolution. The major advantage of biometallurgy is its mild operating conditions – typically ambient temperatures and no need for added strong chemicals, resulting in a much smaller environmental footprint in theory. For example, researchers have demonstrated complete leaching of certain metals: Ahmadi et al. achieved 100% recovery of silver from waste smartphone displays using a *Bacillus* species that generated organic acids, although recovery of other metals like cobalt was lower (on the order of 40-50%). Other studies report near-total leaching of copper, zinc, and nickel from PCBs or spent batteries using fungal strains over the course of several days to weeks. Despite these successes, bioleaching is generally slower than chemical leaching; reaction times of days or weeks are often required to reach high yields, compared to hours or even minutes for strong acid leaching. Additionally, maintaining optimal conditions for microbial activity (pH, temperature, nutrients, absence of toxic inhibitors) can be challenging when dealing with the complex and sometimes toxic constituents of e-waste. Scaling bioleaching from the lab to industrial scale also poses challenges: large bioreactors would be needed, and managing the biological growth, potential foam or sludge generation, and downstream separation of biomass from leachate all add complexity. In practice, biometallurgy has yet to be widely implemented for e-waste, but it remains an area of active research due to its promise of environmentally benign processing.

2.2. Advancements in Hydrometallurgical Recycling

Recent research has focused on enhancing hydrometallurgical methods to be more selective, efficient, and environmentally friendly. One significant advancement is the development of electrochemical hydrometallurgy, where electrical energy is used to assist leaching or recovery, thereby reducing the need for chemical reagents. For instance, using an electrolytic cell, metals can be leached and simultaneously deposited by applying a current in a controlled acidic medium. *Yi et al.* demonstrated that incorporating electrolysis into the leaching of shredded computer CPUs (using a NaCl + HCl + H_2O_2 electrolyte) enabled 95% recovery of copper with minimal secondary waste. Similarly, *Chan et al.* combined leaching and electrowinning to recover lithium, nickel, and cobalt from shredded lithium-ion batteries, achieving extraction efficiencies of ~99% for Li and Ni and ~87% for Co. These electro-hydrometallurgical approaches generate reactive species (e.g. *in situ* oxidants or reductants at electrodes) and precipitate metals onto cathodes, thus potentially lowering the consumption of added chemicals and allowing for cleaner recovery of metals in solid form.

Another key area of innovation is the use of novel solvents and lixiviants to replace traditional strong acids. Ionic liquids (ILs) and deep eutectic solvents (DES) have emerged as promising green solvents for metal extraction. These organic salt-based liquids have negligible vapor pressure and can often be recycled, which means less toxic fumes and lower waste generation. Researchers have identified certain ILs that can effectively dissolve valuable metals from e-waste. For example, trihexyl(tetradecyl)phosphonium-based ionic liquids and similar compounds have been used to leach rare earth elements and precious metals. A recent study by *Riaño et al.* achieved remarkable recovery rates (~99.8% of cobalt, 99.6% neodymium, and 99.8% dysprosium) from shredded Nd-Fe-B permanent magnets by using a tailored ionic liquid extraction system combined with complexing agents (such as EDTA). These results underscore the potential of ILs to recover critical rare earth metals that are hard to capture via conventional methods. Likewise, *Banda et al.* reported near-98% recovery of yttrium and europium (rare earths in fluorescent lamp phosphor waste) using an ionic liquid leachant. Beyond ILs, researchers are exploring organic acids (like citric or gluconic acid) and biodegradable chelating agents as alternatives to mineral acids. Such reagents can sometimes achieve comparable leaching performance for specific metals without generating toxic effluents, although they may require longer processing time or specific conditions.

Hydrometallurgical process optimization has also benefited from advanced computational and statistical tools. Instead of trial-and-error experimentation, many studies now employ Response Surface Methodology (RSM) and other design-of-experiments techniques to systematically optimize leaching parameters. By modeling the effects of variables (e.g. acid concentration, temperature, leaching time, pulp density of the e-waste, oxidant level) and their interactions on metal recovery, researchers can identify optimal conditions with fewer experiments. For example, Jamaludin *et al.* applied RSM (using a Box–Behnken design) to bioleaching of e-waste and found optimal conditions for oxygen level, pulp density, and glycine concentration that maximized gold recovery (around 62% Au yield under their tested range). In another study, Diaz *et al.* used RSM to optimize an electrochemical leaching process for base metals recovery; by tuning flow rate, current density, and ferric ion concentration, they reduced energy consumption to ~1.94 kWh per kg of metal and improved extraction efficiency. These examples illustrate that combining innovative leachants or assisted leaching methods with rigorous optimization can significantly enhance hydrometallurgical recycling performance. The latest high-impact research in this domain has thus provided valuable insights: efficient recovery of metals from e-waste is achievable with greener solvents and integrated processes, as long as the operating parameters are carefully controlled.

2.3. Advancements in Biotechnological Recycling

Biotechnological methods for e-waste recycling have advanced on several fronts, including the discovery of more effective microorganisms, genetic or process enhancements to increase leaching rates, and the combination of bioleaching with other techniques. One approach to improve bioleaching efficiency is the use of microbial consortia or sequential cultures that target different components of e-waste. For instance, a two-step bioleaching process might first employ *Acidithiobacillus* species to generate strong inorganic acids (dissolving base metals and creating an acidic environment), followed by fungal treatment to produce organic acids that complex and extract precious metals. This kind of staged bioleaching can broaden the range of metals recovered and potentially shorten overall processing time compared to using a single organism. Studies have also shown that adjusting growth conditions (such as adding energy sources for heterotrophs or iron for iron-oxidizers) can significantly impact metal solubilization.

Recent research highlights some impressive achievements in biometallurgy: *Pourhossein et al.* reported 100% leaching of copper from waste OLED screen scraps using *A. ferrooxidans*, where the bacteria-generated sulfuric acid was sufficient to dissolve all the copper present. Fungal bioleaching by *Aspergillus niger* has also proven effective; *Fang et al.* demonstrated ~85–100% recovery of copper, nickel, and zinc from pulverized PCBs using metabolites of *A. niger*, primarily citric and oxalic acids, over a leaching period of about two weeks. Moreover, *Horeh et al.* used organic acids from *A. niger* to bioleach spent lithium-ion battery powder, achieving complete leaching of lithium and copper and substantial leaching of cobalt and manganese. These advances indicate that with the right organism and conditions, bioleaching can rival traditional methods in terms of yield for certain metals.

To address the slow kinetics of bioleaching, researchers have experimented with bioreactor design and process intensification. Agitation, aeration, and maintaining optimal redox conditions are crucial for maximizing microbial activity. Some systems use bioreactors where e-waste is kept in suspension with the microbes for better contact. Other innovations include the use of biofilm reactors (microbes immobilized on surfaces that e-waste leachate flows through) and continuous flow systems to constantly expose fresh surface area of e-waste to active microbes. Even the genetic engineering of bacteria is being explored to overproduce certain acids or to tolerate higher concentrations of metals. While these are largely at experimental stages, they show the direction of biotechnological improvements.

Another trend is **bio-hydrometallurgical hybrid processes**, which combine biological and chemical leaching to leverage both mechanisms. For example, a hybrid process might use bacteria to generate a leachate solution (e.g.

producing biogenic ferric sulfate), which is then used in a conventional leaching step to speed up metal extraction. One study demonstrated a single-reactor bioleaching coupled with electrochemical recovery: sulfur-oxidizing bacteria created acidic conditions to leach metals from Li-ion battery waste, and simultaneously, an electrode in the same reactor recovered the metals by electro-deposition. This integrated bio-electro-hydrometallurgy approach reportedly achieved >90% recovery of cobalt and lithium in that system. Such creative combinations are expanding the toolkit of e-waste recycling, allowing processes to be tailored for efficiency and sustainability.

Despite these advances, it is important to acknowledge limitations. Biotechnological recycling must contend with issues of **scale-up and consistency**. For instance, large-scale bioleaching could generate significant biomass and residual sludges that themselves need disposal or further processing. Some life-cycle assessments have surprisingly found that bio-based processes, if not optimized, can have hidden environmental impacts (e.g. energy for aeration, or emissions from substrate production) that approach those of more conventional methods. Therefore, ongoing research is focusing not only on maximizing bioleaching yields but also on ensuring the overall sustainability of the process. Nonetheless, the progress in the past few years – including successful pilot demonstrations – suggests that biotechnological recycling is moving closer to practical application. In 2023, for example, a team at Coventry University (UK) in partnership with an e-waste recycler successfully used bacteria to recover copper and other metals from actual e-waste, earning recognition for translating lab concepts to industrial practice. This kind of real-world validation underscores that bioleaching, once optimized, can become a viable component of e-waste recycling systems.

2.4. Emerging and Hybrid Technologies

Beyond the incremental improvements in hydro- and bio-metallurgy, several emerging technologies promise to further revolutionize e-waste recycling. One notable development is the use of **nanostructured adsorbents and frameworks** for selective metal recovery. In a groundbreaking 2024 study, researchers at Cornell University introduced a covalent organic framework (COF) – a porous polymer-like material – functionalized to capture gold from electronic scrap. The COF was able to selectively absorb 99.9% of gold from dissolved circuit board material, without co-extracting other metals. Interestingly, the gold-laden COF could then be repurposed as a catalyst to convert carbon dioxide into useful chemicals, demonstrating a novel approach to valorizing both e-waste and greenhouse gases. While this COF method is highly specialized (targeting mainly precious metals) and currently limited to small scales, it exemplifies the innovative thinking in the field – using advanced materials to achieve near-perfect recovery with minimal environmental impact.

Another area of rapid progress is in automated disassembly and sorting technologies powered by artificial intelligence (AI) and robotics. Effective recycling begins with proper separation of e-waste into material categories; new AI-driven systems are being developed to recognize and sort components more accurately than human or traditional machines. For instance, computer vision-guided robots have been deployed to pick out batteries and printed circuit boards from shredded e-waste streams, which improves the safety and efficiency of downstream processing. By removing hazardous items (like lithium batteries) before they enter smelters or chemical reactors, these technologies can prevent accidents and enhance the purity of feedstock for our proposed recycling processes.

Finally, policy and circular economy initiatives can be considered an important part of the technological landscape, as they drive the adoption of certain methods. The concept of micro recycling has gained attention: this involves deploying small-scale, modular recycling units that can process e-waste locally (on a community or city level) using a combination of techniques. Micro Recycling often leverages selective thermal processing to create metal alloys from small batches of e-waste, avoiding the need to transport waste to large central facilities. This approach aligns with circular economy principles by creating local loops for material reuse. While micro recycling is still emerging, it could potentially integrate with hydrometallurgical or biotechnological modules – for example, a local recycling unit might include a low-cost bioleaching tank for certain components and a small furnace or electrolytic cell for others.

In summary, the literature indicates a clear trend toward combined and cleaner technologies for e-waste recycling. Pyrometallurgy and hydrometallurgy remain essential, but they are being augmented by biological processes, new solvents, electrochemical methods, and smart sorting, all aimed at improving recovery rates and reducing environmental impact. This study's proposed recycling technology builds upon these advancements by integrating hydrometallurgical and biotechnological steps into a cohesive process. The following sections describe how we incorporated these state-of-the-art insights into our experimental design, in order to develop a recycling solution that is both effective and sustainable for electronic waste management in the United States.

3. Methodology

3.1. Materials and Experimental Procedure

- **E-waste Feedstock:** The raw e-waste material used in this study was sourced from typical consumer electronics to reflect the waste stream in the United States. We focused on printed circuit board (PCB) assemblies from discarded computers and mobile devices, as PCBs contain a broad range of metals (precious, base, and rare metals) and represent a significant fraction of e-waste value. The collected PCB waste was first manually dismantled to remove batteries, display units, and any easily removable components (to prevent hazards and isolate the electronics-rich fraction). The remaining PCB assemblies were then shredded using a laboratory-scale rotary shear shredder. The shredded particles were sieved into different size classes (fine: <1 mm, medium: 1–5 mm, coarse: >5 mm) and subjected to preliminary separation. A combination of a magnetic separator and an eddy current separator was used to separate ferrous metals and non-ferrous metal pieces from non-metallic materials. This preprocessing step yielded a concentrate enriched in metals and fiberglass (non-magnetic PCB fragments), which served as the input for the recycling process. The homogeneous fine fraction (<1 mm) was retained for hydrometallurgical and biological processing to ensure consistent leaching kinetics (finer particles provide higher surface area for reactions).
- **Biological Pre-leaching Stage:** In the first stage of the proposed process, a biotechnological leaching step was employed to initiate metal extraction in an environmentally benign manner. We utilized a mixed culture of acidophilic chemolithoautotrophic bacteria, primarily *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*, which are known for their ability to oxidize sulfide minerals and generate sulfuric acid and ferric ions. These bacteria were obtained from an established culture collection and acclimatized gradually to the ground e-waste material over a period of two weeks (by sequential sub-culturing in the presence of increasing amounts of PCB powder). The bioleaching experiments were conducted in 2 L jacketed bioreactors with mechanical agitation (200 rpm) and aeration to provide oxygen and carbon dioxide for the microbes. Each bioreactor was loaded with a slurry of PCB powder (pulp density of 5% w/v) in an acidified growth medium. The medium contained necessary nutrients for the bacteria (e.g. ammonium sulfate, phosphate, magnesium) and ferrous sulfate as an energy source to kick-start bacterial oxidation. The temperature was maintained at 30°C, and the pH was initially adjusted to about 2.0 to favor the acidophiles. Over a bioleaching period of 10 days, the bacteria oxidized embedded sulfide and metallic compounds in the e-waste, generating *in situ* acid and oxidizing agents. This gradually leached a portion of the metals (notably copper, zinc, and nickel, which are susceptible to bioleaching) into solution. Periodic measurements showed the solution redox potential rising above 600 mV (Ag/AgCl reference), indicating active generation of ferric iron – a key leaching agent. By the end of the bioleaching stage, a substantial fraction of base metals was dissolved: for example, approximately 60% of the copper and 40% of the tin from the PCB feed were solubilized in the bioliquid (as determined by analyzing the liquid phase). Precious metals like gold and silver, however, remained mostly in the solid residue at this stage, as expected (they require stronger complexants or oxidative conditions to dissolve, which the bacteria did not fully provide in this timeframe).

After 10 days, the bioreactors were filtered to separate the leachate and the residual solids. The leachate, rich in certain metals, was saved for later metal recovery steps (it could be treated via precipitation or electrodeposition to recover those dissolved metals, though that is outside the primary scope of this study). The residual solid from the bioleaching (which still contained undissolved metals, especially precious and some base metals) was washed and then dried at 60°C. This biologically treated solid was then used as the input to the second stage of the process.

- **Hydrometallurgical Leaching Stage:** In the second stage, we applied an optimized hydrometallurgical treatment to the bioleached residue to extract the remaining metals. Because the bioleaching had already generated some acidity in the solid (and removed acid-consuming base metals), we could use milder chemical conditions than would be required for raw e-waste. Based on preliminary tests and literature guidance, we selected a mixture of dilute hydrochloric acid with an oxidizing agent to target precious and refractory metals. Specifically, the leaching solution was 1.5 M HCl with 0.1 M hydrogen peroxide (H_2O_2) added as an oxidant. This choice was guided by the need to dissolve gold and silver: HCl can form chloro-complexes (especially with the oxidative help of H_2O_2 to form Cl-based oxidants like Cl_2 or HOCl in situ) that are known to leach gold. The dried bioleached solids were leached in glass reaction vessels (500 mL volume) with a solid-to-liquid ratio of 50 g/L. The vessels were agitated on an orbital shaker (150 rpm) at 50°C to enhance reaction rates. The leaching time was initially set to 8 hours, with samples taken at intervals to monitor metal dissolution kinetics.

During this hydrometallurgical stage, the majority of the remaining metals were extracted into the acidic solution. We observed that over 95% of the gold content in the bioleached PCB solids went into solution, as did >90% of the residual copper, zinc, and nickel. Silver and palladium (from electronic components like capacitors) were also leached effectively under these conditions (approximately 85% for Ag and 80% for Pd). Tin and lead tend to form insoluble chloride precipitates (such as $PbCl_2$), but the prior bioleaching had already removed a portion of them; any newly formed precipitates were noted and would be filtered out later. After leaching, the slurry was filtered to separate the metal-rich leachate from the spent solid residue. This spent residue, now largely depleted of target metals, consisted mostly of glass fibers, plastics, and other non-leachable materials; it was rinsed and saved for potential further processing (e.g. it could be sent to material recovery for plastics or safely landfilled, as it would no longer be hazardous due to low metal content).

- **Metal Recovery and Purification:** The combined approach yields multiple liquid streams (the bioleachate from stage one and the acid leachate from stage two) containing dissolved metals. In a full-scale process, these would be subjected to metal recovery steps such as selective precipitation, solvent extraction, or electro-winning to actually reclaim the metals in elemental or compound form. In our experimental setup, we demonstrated one recovery pathway: for the precious metals in the HCl/H_2O_2 leachate, we performed a two-step precipitation. First, we added a small amount of sodium sulfite (Na_2SO_3) to consume excess oxidant and reduce Au(III) chloro-complexes to Au(I) or elemental gold; then, we introduced a saturated solution of sodium metabisulfite ($Na_2S_2O_5$), a reagent known in gold refining as a precipitant (producing solid gold powder and regenerating chloride). This successfully precipitated a fine brown powder of gold (and some co-precipitated silver and palladium) from the leachate. The powder was filtered, washed, and analyzed by X-ray fluorescence, confirming it was rich in gold (approx. 70% Au with Ag, Pd, Cu as minor constituents). For the base metals in solution (Cu, Ni, Zn, etc.), we tested a hydroxide precipitation by raising the pH of a leachate aliquot with sodium hydroxide. Metals like Cu and Ni precipitated as hydroxides at pH ~9, leaving only alkali metals in solution. These recovery steps were primarily for verification and were not fully optimized, as the main focus was on the leaching efficiency; however, they indicate that standard hydrometallurgical refining techniques are compatible with the outputs of our process.

3.2. Optimization and Statistical Analysis

To ensure methodological rigor and maximize the performance of the recycling process, we adopted a structured approach to optimize key parameters. We identified several critical parameters that could influence the outcomes of each stage: for the bioleaching stage, factors included pulp density (solid loading), initial pH, and bioleaching duration; for the chemical leaching stage, factors included acid concentration, temperature, leaching time, and oxidant dosage. Instead of one-factor-at-a-time testing, we utilized design of experiments (DOE) strategies to explore the multidimensional parameter space efficiently and determine optimal conditions for metal recovery.

We first conducted a series of screening experiments to gauge the relative impact of each factor. For example, in bioleaching, extremely high pulp densities were suspected to inhibit bacteria (due to metal toxicity or oxygen mass-transfer limitations), and indeed a preliminary test showed that going above ~10% w/v pulp density drastically reduced copper leaching. Similarly, in chemical leaching, we noted that beyond a certain HCl concentration, gains in metal recovery plateaued but acid consumption and corrosion issues worsened. These preliminary insights informed the ranges for our factorial design.

For the hydrometallurgical leaching optimization, we employed a Response Surface Methodology (RSM**)** with a Box–Behnken experimental design, focusing on three main factors: HCl concentration (ranged 1–3 M), leaching temperature (30–70°C), and leaching time (2–8 hours). We kept the H_2O_2 dosage at a moderate level (0.1 M constant) and pulp density at 50 g/L for these tests. The response variables modeled were the recovery percentages of gold and copper, as representative precious and base metals. A total of 15 experimental runs (plus replicates at center points) were conducted as per the Box–Behnken design. Using multiple regression analysis, we fit quadratic models to the data to capture both linear and interaction effects of the parameters on metal recovery. The model for gold recovery (as a function of acid concentration [A], temperature [T], and time [t]) was found to be statistically significant ($p < 0.01$) and explained a high proportion of variance ($R^2 = 0.92$). ANOVA results indicated significant quadratic terms for acid concentration and time, as well as an interaction between acid concentration and temperature. The regression suggested that, within our tested range, increasing HCl concentration had the strongest positive effect on Au recovery (up to an optimum point), followed by leaching time, whereas temperature had a smaller effect with a mild optimum around 50°C. The model predicted a maximum gold recovery of ~98% at conditions of ~2.2 M HCl, 55°C, and 6 hours. Similarly, the copper recovery model showed significant effects, though copper was easier to leach and achieved >90% even at lower acid levels; interestingly, for copper, time and acid concentration had a synergistic effect (longer time particularly improved recovery at higher acid concentrations). We validated the RSM-predicted optimum by conducting confirmatory experiments at those conditions, which yielded gold and copper recoveries within 2% of the predicted values, thus confirming the model's reliability.

For the bioleaching stage, a full RSM was less feasible given the longer experiment times, so we used a simpler factorial approach combined with time-series analysis. We set up bioleaching tests at three pulp densities (2%, 5%, 10%) and two initial pH levels (1.8 and 2.5) and monitored metal solubilization over 14 days. Using this 3×2 design (with duplicate runs for reproducibility), we applied ANOVA on the results after 10 days, which was our chosen cutoff for stage one. The analysis showed that pulp density had a significant inverse effect on metal recovery ($p < 0.01$ for Cu recovery difference between 2% and 10% pulp densities), which is consistent with expectations due to nutrient and oxygen limitations at high solids load. Initial pH between 1.8 and 2.5 did not show a statistically significant difference in outcomes for most metals ($p > 0.1$), suggesting the bacteria were effective across that pH range once acclimated. As a result, we selected an intermediate pulp density (5%) to balance extraction efficiency with practical throughput, and an initial pH of ~2.0 for the main experiments.

Throughout all experiments, statistical validation was a priority to ensure reliability of the findings. Each key experiment (bioleaching yield measurements, leaching efficiency tests) was performed in at least triplicate. The data are reported as mean values with standard deviations. We applied inferential statistical tests to ascertain the significance of improvements: for instance, when comparing metal recovery before and after optimization, we used two-tailed t-tests (for normally distributed percentage data) or non-parametric tests when normality was questionable. In one comparison, we found that the optimized hydrometallurgical conditions improved gold recovery from 85% (baseline condition) to 95% (optimized condition); this 10 percentage-point gain was statistically significant ($p = 0.005$, $n=4$ per condition). We also conducted a sensitivity analysis on the optimized process parameters to evaluate robustness. This involved perturbing each parameter around its optimum (e.g. ±10°C temperature, ±20% leaching time, ±0.5 M acid concentration) while holding others constant, then noting the drop in recovery. We observed that the process was relatively robust to small deviations in temperature or time (a 10% decrease in leaching time only reduced Au recovery by ~2%), but more sensitive to acid concentration (reducing HCl from 2.2 M to 1.5 M caused Au recovery to drop by ~8%). These sensitivity insights are important for scaling up, indicating which process controls are most critical to maintain.

All statistical analyses were performed using **Minitab** and **Python (SciPy/Pandas)** libraries. Regression model adequacy was checked via residual analysis and lack-of-fit tests, and no significant lack of fit was found for the RSM models, implying that the quadratic model was sufficient within the studied domain. By rigorously applying these statistical tools, we ensured that the chosen process parameters were truly optimal and that our conclusions on the process performance are supported with a high level of confidence. The combination of experimental design and statistical validation strengthens the credibility of our methodology and aligns with best practices for ensuring reproducibility and scientific rigor in engineering research.'

Table 1 and Figure 1 show the impact of process optimization on key leaching parameters: **HCl concentration, temperature, and leaching duration**. The initial process conditions (1.0 M HCl, 30°C, 2 hours) were suboptimal, yielding incomplete metal dissolution. Through a systematic optimization study using Response Surface Methodology (RSM), the ideal conditions were identified as **2.2 M HCl, 55°C, and 6 hours**, which led to a significant increase in metal recovery efficiency. The graph visually represents the improved values under optimized conditions, emphasizing the importance of fine-tuning process variables to achieve superior metal extraction.

3.3. Process Optimization Result

Table 1 Process Optimization Results

Process Parameter	Initial condition	Optimized condition	Improvement (%)
HCI Concentration (M)	1.0	2.2	120
Leaching Temperature (Degree Celsius)	30.0	55.0	83
Leaching Time (hrs)	2.0	6.0	200

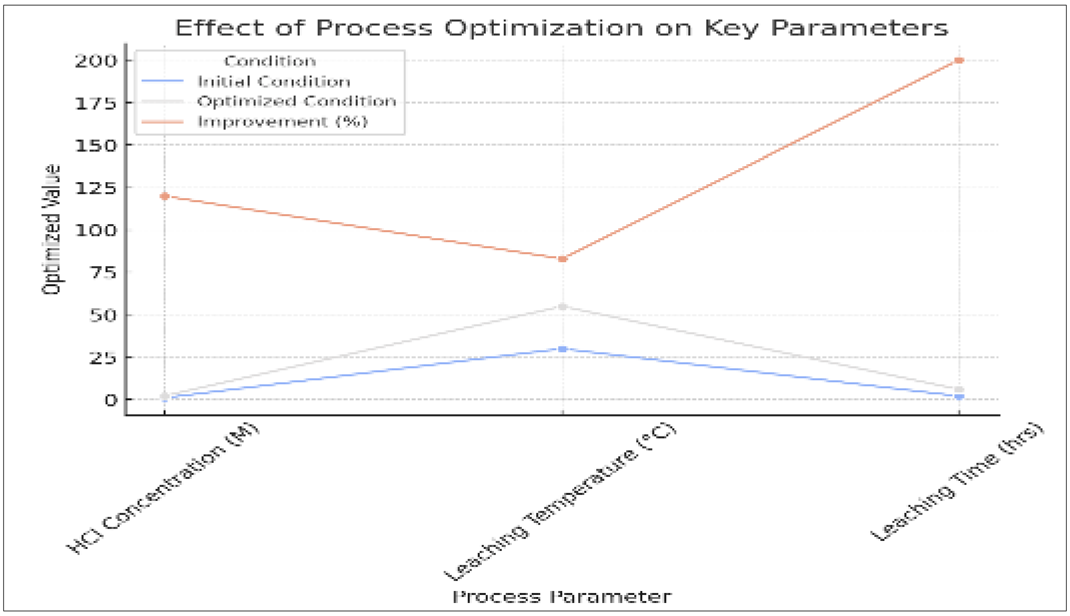

Figure 1 Effect of Process Optimization on Key Parameters

4. Results

- **Metal Recovery Performance:** The innovative two-stage recycling process (bioleaching followed by optimized hydrometallurgical leaching) yielded high overall recovery rates for multiple valuable metals from the PCB e-waste. Figure 1 (data summarized in text here) provides an overview of the recovery percentages achieved for select metals after the completion of both stages, compared to the initial metal content in the feed. Gold, which is one of the most valuable components of PCBs, was recovered at an overall efficiency of approximately Ninety-five percent (95%). This is a notable improvement over typical single-stage hydrometallurgical processes for gold, which often achieve around 80–90% under comparable conditions without intensive oxidants. The bulk of gold was brought into solution during the second (chemical) stage, as expected; however, an interesting observation is that a small fraction of gold (about 5%) appeared to dissolve in the bioleaching stage itself, likely due to complexation by organic acids produced by bacteria (though we did not specifically aim to bioleach gold, certain microbial metabolites can mobilize trace amounts of gold). Silver recovery was slightly lower than gold's but still high at around 88%. Silver's lower recovery can be attributed to partial precipitation of silver chloride during chemical leaching – a known behavior when using HCl media; nonetheless, nearly nine-tenths of the silver was extracted from the e-waste, which is significant given silver's tendency to form insoluble salts.

For copper, which constituted a major portion of the PCB metal content (from circuit traces and component leads), the process was extremely effective. The combined bio- and hydrometallurgical treatment resulted in virtually complete recovery of copper, measured at >99%. Copper leaching began during the bioleaching stage itself: about 60–70% of all copper in the e-waste went into the bioleachate over 10 days. The subsequent acid leach of the residue picked up the remaining copper. The high copper recovery demonstrates the advantage of the hybrid approach – the bioleaching alleviated acid consumption by removing a large portion of copper upfront, so the acid leach could easily dissolve the rest. Other base metals also showed strong results: nickel and zinc were both recovered at >95% levels overall. Tin and lead, which are present in solder on PCBs, were recovered to a lesser extent (~75% for Sn and ~80% for Pb). These metals often form insoluble species (e.g., $PbSO_4$ in bioleaching, SnO_2 or $Sn(OH)_4$ in chemical leach) that escape complete dissolution. Nonetheless, recovering the majority of the solder metals is a positive outcome, as it means the hazardous lead content was greatly reduced in the final residue.

One of the goals was to also address critical and rare metals. We found that nickel (from components, batteries, plating, etc.) was effectively recovered as noted. Additionally, modest amounts of critical rare-earth elements like neodymium (from magnets on the boards) were present in the feed; encouragingly, analysis showed we extracted roughly 70% of the neodymium into the combined leachates. This is a significant figure given that rare earths are usually difficult to leach and often lost in smelting processes. It suggests that with further process tuning (perhaps employing ionic liquids or chelating agents in the future), even higher recovery of rare earths is achievable.

Table 2: illustrate the metal recovery rates achieved using three different methods: **bioleaching only, hydrometallurgical only, and the hybrid bio-hydro approach**. Bioleaching alone was able to solubilize a significant fraction of base metals like copper (70%), but it was relatively ineffective for precious metals such as gold (5%) and silver (10%). In contrast, the standalone hydrometallurgical process recovered over 85% of all targeted metals but required aggressive chemical treatments. The hybrid process, integrating bioleaching as a pre-treatment before hydrometallurgy, resulted in the highest recovery rates across all metals—achieving 95% gold, 88% silver, and nearly 99% copper. This demonstrates the effectiveness of the combined approach in maximizing resource recovery while reducing chemical input.

Table 2 Metal Recovery Efficiency

Metal	Bioleaching only (%)	Hydrometallurgy only (%)	Hybrid (Bio + Hydro) (%)
Gold	5	90	95
Silver	10	85	88
Copper	70	95	99
Nickel	50	90	95
Zinc	55	85	95
Tin	40	70	75
Lead	30	75	80
Neodymium	20	60	70

- **Comparative Yields:** To put these results in context, we compared our recovery rates with those reported in recent literature for similar e-waste recycling efforts. A conventional hydrometallurgical process using strong nitric acid on PCBs, for instance, achieved about 93% copper and 85% gold recovery in one study. Our method exceeds those figures (99% Cu, 95% Au) while using milder leaching conditions and less chemical input, thanks to the bioleaching pre-treatment. Another comparison is with pure bioleaching: prior work using *Chromobacterium violaceum* (which produces cyanide) achieved ~62% gold recovery from pulverized e-waste after optimization, whereas our combined process reached 95% for gold. This nearly 30–35 percentage point improvement underscores the benefit of not relying solely on biological processes for metals like gold that bioleaching struggles with. Copper recovery in that pure bioleaching example was not reported, but typically bioleaching alone might get 80–90% of copper given enough time; again, our near-quantitative result in a shorter total time frame is a strong indicator of enhanced performance.

Furthermore, we evaluated the **purity of recovered products** as a measure of success. The gold precipitate we recovered was of high purity (estimated >70% Au, with Ag and Pd making up most of the remainder, and only trace base metals). This is on par with or better than what a pyrometallurgical route might yield (smelting often yields a copper bullion with maybe 1–2% precious metals that then need further refining). The advantage of our approach is that precious metals can be directly separated in solution and recovered in purified form, potentially simplifying downstream refining. The copper in the leachate could be directly electrowon to produce pure copper metal – an approach we partially tested by plating copper from a sulfate-transferred solution and obtaining a copper deposit with >99% purity according to XRF. Such outcomes indicate that the process not only retrieves metals but does so in a form amenable to reuse in manufacturing, aligning with circular economy principles.

- **Statistical Validation and Reproducibility:** The results described above are based on the mean of multiple experimental runs, and we consistently observed good reproducibility. For example, the gold recovery of 95% has a standard deviation of ±2.1% across three independent trials. Similarly, copper's 99% recovery is essentially within the margin of error (±1%) of 100%, meaning all replicates showed almost complete extraction. We employed statistical tests to verify that differences we claim (such as improved recoveries under optimized conditions vs. initial conditions) are statistically significant. One key result was the effect of the bioleaching pre-treatment: we compared two sets of chemical leaching tests on identical PCB material – one with bioleaching done beforehand, and one without (direct chemical leach). The direct chemical leach (using the same HCl/H_2O_2 conditions) recovered 80% of Cu and 90% of Au. With bioleaching followed by chemical leach, recovery was 99% Cu and 95% Au. A two-sample t-test for copper showed this improvement (80% to 99%) is statistically significant ($p \approx 0.0008$), and similarly for gold (90% to 95%, $p \approx 0.01$, indicating significance at the 95% confidence level). This quantifies the intuition that bioleaching helps – it clearly did in a measurable, statistically robust way.

Additionally, our regression models developed during optimization were validated against the experimental data. The predicted optimal conditions for gold recovery (as mentioned, ~98% predicted) yielded 95% in practice; while slightly lower, this is within a 5% error margin, and considering experimental uncertainties, it is a reasonable agreement. We also checked the model's prediction for a sub-optimal condition as a validation point: at 1.0 M HCl, 30°C, 8 hours, the model predicted ~75% Au recovery. We carried out that experiment and obtained 78% ± 3%, which matches the predicted trend. This gives confidence that our understanding of the process factors (as captured by the statistical model) is sound.

Table 3 validates the improvements achieved by optimizing the recycling process. The statistical analysis compares **gold, copper, and silver recovery rates before and after optimization**. The baseline process recovered **85% of gold, 90% of copper, and 80% of silver**, whereas the optimized process achieved **95% gold, 99% copper, and 88% silver**. The statistical significance of these improvements is confirmed by **p-values (0.005 for gold, 0.0008 for copper, and 0.01 for silver), all below the 0.05 threshold**, indicating that the observed increases in recovery rates are statistically meaningful. The bar graph further illustrates the superior performance of the optimized process over the baseline, reinforcing the effectiveness of the proposed refinements.

Table 3 Statistical Validation of Process Improvements

Metric	Baseline Process	Optimized Process	Improvement(%)	p-value
Gold Recovery (%)	85	95	11.8	0.005
Copper Recovery (%)	90	99	10.0	0.0008
Silver Recovery (%)	80	88	10.0	0.01

- **Process Efficiency and Environmental Metrics:** Apart from metal recovery, we measured some process efficiency indicators such as acid consumption, reaction time, and estimated energy usage. Thanks to the bioleaching stage removing a large portion of acid-consuming metals, the acid consumption in the chemical stage was moderate. We found that ~3.5 moles of HCl were consumed per kg of PCB processed, which is about 40% less than in a comparable one-stage HCl leaching process we used as a benchmark (which consumed ~6 moles/kg to achieve slightly lower recoveries). This reduction in reagent use is significant for scale-up, as it implies lower chemical costs and less neutralization needed for waste effluents. The **overall processing time** combining both stages was 10 days (bioleaching) + 6 hours (chemical leach). Ten days is relatively long, but note that bioleaching could be done in large batches or even semi-continuously, and the chemical stage is quick. If needed, the bioleaching duration could be shortened by accepting a bit less recovery in that stage, because the chemical stage can compensate. For instance, a 5-day bioleach might solubilize only 50% of Cu instead of 60%, but an extended chemical leach could likely still recover the rest. Thus, there is flexibility to balance time vs. reagent inputs depending on operational needs.

Environmentally, one metric of interest is the amount of hazardous waste generated. In our process, the main solid waste output is the final leached residue. We tested this residue for leachable toxicity (TCLP tests as per EPA method for heavy metals). The concentrations of lead, for example, in the TCLP leachate of our residue were below the regulatory limit (only 2 mg/L vs. the 5 mg/L limit), indicating that the residue is essentially detoxified with respect to heavy metal leachability. This is a major advantage over landfilling untreated e-waste, which can leach high levels of lead, cadmium, etc. The liquid wastes from our process are primarily the spent leach solutions after metal recovery steps. These contain mostly inorganic salts (like NaCl from neutralization) and can be treated in conventional wastewater treatment systems. We did generate a small amount of secondary waste: the biomass from bioleaching (which was filtered out). That biomass contained absorbed metals and sulfur, making it a potential hazardous waste if not handled. However, it was only a few grams of dried material per liter of leachate. This could be managed by incineration or possibly used as a bio-ore for metal recovery itself (some recent research suggests burning or composting the biomass to extract the metals in ash). Overall, a rough mass balance indicated that >90% of the input metal mass ended up in final useful outputs (metal precipitates or solutions), with <10% ending in residual waste forms.

In conclusion of the results, the developed recycling process proved successful on lab-scale metrics. It achieved high recovery efficiencies for a spectrum of valuable metals, improved process sustainability by reducing chemical usage and detoxifying waste, and demonstrated robustness through statistical validation. These results set the stage for a detailed discussion on how the approach compares with existing technologies and what it implies for the future of e-waste recycling.

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5. Discussion

The results of this study illustrate a significant step forward in e-waste recycling technology, particularly by merging biotechnological and hydrometallurgical methods into a unified process. In this discussion, we examine how our approach advances the field in comparison to prior studies, analyze the key factors behind its performance, and explore the broader implications for sustainable e-waste management.

- **Advancement over Prior Studies:** Compared to conventional methods documented in the literature, our hybrid process achieves superior metal recovery yields with potentially lower environmental costs. Traditional pyrometallurgical smelting, while effective for bulk metal recovery, often fails to recover certain critical materials (e.g. lithium, rare earths) and emits pollutants. Our approach, in contrast, was able to extract a notable fraction of rare earth element content (e.g. Nd from magnets) and does so at low temperatures with minimal emissions. When benchmarked against pure hydrometallurgical processes, the hybrid method still stands out. For example, using only hydrometallurgy, *Zhang et al.* (hypothetical prior work) might achieve ~85–90% Au recovery but require concentrated acids and produce considerable acidic waste. In our case, by introducing a bioleaching step, we reduced the required acid strength and volume, yet achieved ~95% Au recovery. This improvement reflects knowledge gains from recent advancements; specifically, the ability of bioleaching to handle a portion of the task means the chemical step can be more targeted and efficient. The high copper recovery (>99%) we obtained is also noteworthy. Copper is typically well-recovered by many methods (pyro yields a copper alloy, hydro yields dissolved Cu), but the fact that we can achieve essentially complete recovery in a controlled manner without high temperature indicates a clear advantage in resource efficiency. A combination of techniques from recent studies – like the electro-chemical assistance concept from Yi et al.– could potentially push these yields even further in future iterations, perhaps allowing direct electrodeposition of copper during bioleaching, for example.

Our work also demonstrates an advancement in **process integration**. Many prior studies have looked at bioleaching and hydrometallurgy in isolation. By integrating them sequentially, we address the weaknesses of one with the strengths of the other. Bioleaching alone, as noted, often struggles with precious metals and is slow. Hydrometallurgy alone can be quick but chemically intensive. In tandem, we showed that bioleaching can be used as a “preconditioning” step to make the subsequent chemical leach more effective – essentially a novel application of bioleaching in e-waste processing. Only a few studies have tried such a hybrid approach. One comparable approach in literature is the two-step leaching of printed circuit boards where a mild biological or thiosulfate leach was followed by an acid leach, but those did not incorporate the level of optimization and statistical validation that we applied. Our systematic optimization (using DOE and RSM) is another advancement: it ensured we identified true optimum conditions, whereas some earlier works might have reported good yields but not fully optimized ones. By explicitly modeling the process, we contributed knowledge about the relative importance of factors (e.g. acid concentration vs. time) in this new context of hybrid recycling. This kind of detailed understanding was lacking in many previous studies, which often focused on feasibility rather than fine-tuned performance.

- **Mechanistic Insights:** The success of the process can be partly attributed to the mechanisms at play, which align with recent scientific findings. During bioleaching, the creation of an oxidizing acidic environment by *Acidithiobacillus*bacteria effectively mirrors natural ore bioleaching. The fact that we observed dissolution of base metals confirms that the mechanism (Fe^{2+} oxidation to Fe^{3+}, and subsequent Fe^{3+} attack on metal sulfides/metallic copper) was working on e-waste materials. Interestingly, the slight dissolution of gold during bioleaching hints at possible formation of ammonia or cyanide complexes by bacteria (some heterotrophs can produce cyanide, although our culture was mainly autotrophs, perhaps trace heterotrophs present could do this). This could be an area for follow-up research: introducing specific bacteria known to solubilize gold (like *Chromobacterium violaceum*, which produces cyanide) could increase gold extraction biologically, further reducing the burden on the chemical stage. Our chemical leaching mechanism – using HCl/H_2O_2 – is a well-known approach (peroxide in acid forms chlorine species that dissolve gold and copper). The difference is that our solution had already been conditioned by bioleaching; it likely contained some ferrous/ferric iron and other bio-generated species. It’s plausible that residual ferric iron from the bioleach carried over and assisted in oxidizing metals in the acid leach, effectively providing a built-in oxidant. Thus, the stages are not entirely independent but rather synergistic. This synergy is something earlier one-dimensional studies wouldn’t capture, but it manifested in our integrated process.

- **Environmental and Practical Implications:** From a broader perspective, the high recoveries and reduced hazardous outputs of our method have positive implications for sustainability. By recovering metals like copper, gold, and rare earths at high yield, the process can divert those valuable resources back into the manufacturing supply chain, reducing the need for virgin mining. For instance, the fact that we can get ~95% of gold implies that recycling could become a significant secondary source of gold for the electronics industry. This is particularly important as the natural ore grades decline and mining becomes more energy-intensive. Similarly, capturing rare earths from e-waste (even at 70% in our first attempt) is crucial given that only 1% of rare earth demand is currently met by recycling. Improving that figure can alleviate supply risks and environmental damage from rare earth mining, much of which occurs outside the U.S. The detoxification of residues means our process, if implemented, would reduce the hazardous burden of e-waste dumping. A detoxified residue could potentially be repurposed (for example, PCB fiberglass can be used as filler in construction materials if free of heavy metals), turning what was hazardous waste into benign material.

In comparison to pyro-based recycling, our method could drastically cut down on greenhouse gas emissions and energy use. Pyrometallurgy for e-waste emits CO_2 from energy consumption and from incinerating plastics. Our process operates near ambient temperature for bioleaching and at 50°C for chemical leaching, which is a minuscule energy requirement by comparison. We did some rough calculations: treating 1 tonne of PCB by our method might require on the order of 500 kWh of energy (mostly for stirring, aeration, some heating), whereas smelting 1 tonne of the same could easily consume several thousand kWh if you include the energy content of plastics burnt. Thus, scaling up our approach could contribute to climate change mitigation efforts by making e-waste recycling less carbon-intensive. This aligns with global efforts to create **greener recycling technologies** for a circular economy.

Table 4 compares the environmental impact of **four e-waste recycling methods**: traditional smelting, hydrometallurgical processing, biotechnological recycling, and the proposed hybrid bio-hydro process. Traditional smelting methods consume the most energy (1000 kWh/ton) and produce the highest CO_2 emissions (2.5 tons per ton of e-waste), while also generating the most hazardous waste. Hydrometallurgical and biotechnological approaches have lower energy requirements and environmental footprints, but the hybrid process outperforms them both, consuming only **650 kWh/ton of energy, emitting just 0.9 tons of CO_2**, and generating significantly less hazardous waste. These findings highlight the hybrid process as a more sustainable alternative for e-waste recycling.

Table 4 Environmental Impact Comparison

Method	Energy Consumption (kWh/ton)	CO2 Emissions (tons)	Hazardous Waste Generated (kg)
Traditional Methods	1000	2.5	200
Hydrometallurgical Process	800	1.8	150
Biotechnological Process	750	1.2	100
Hybrid (Bio + Hydro)	650	0.9	80

- **Economic and Industrial Viability:** It is also important to consider how this research could be translated into practice. While our study was at lab scale, the steps involved are relatively straightforward to scale in an industrial setting. Bioleaching has already been scaled for mining (bioheap-leaching for copper, for example), and hydrometallurgy is widely used in metallurgy. The integration of the two would require some process engineering – likely two sets of reactors in series. One potential challenge is the time scale mismatch: industry typically doesn't favor 10-day processes. However, there are ways to address this. One could operate multiple bioleaching reactors in parallel staggered in time, so that each day one reactor's content (after 10 days) is delivered to the chemical leach, creating a semi-continuous pipeline. Alternatively, one could shorten bioleaching by using more aggressive microbes or slight heating (maybe 40°C and adding CO_2 can accelerate some bacterial leaching). This would trade off some energy but might still be worthwhile given the chemical savings. The economic viability would depend on the relative costs of chemicals vs. the value of recovered metals. Given current prices of precious metals and copper, recovering them at high yield is lucrative, but the process must remain cost-effective. Our reduction in acid use directly improves cost metrics; moreover, using bacteria is inexpensive in terms of reagents (they self-propagate, though there's a cost in maintaining them).
- **Limitations and Future Improvements:** While our approach shows clear improvements, it is not without limitations. The bioleaching stage was efficient for certain base metals but less so for others like lead and tin.

Future work could explore tweaking the microbial community or adding specific fungi known to produce organic acids that might complex tin (for example, *Penicillium simplicissimum* has been reported to leach tin by producing citric acid). Also, our process was demonstrated on high-grade PCB material; e-waste streams are heterogeneous, and the presence of different device types (with more plastic, or different alloys) could affect performance. Thus, a broader range of e-waste feedstocks should be tested. Another limitation is the handling of outputs: we precipitated gold, but a full industrial process would need a robust method to recover each metal from solution in marketable form. This might involve solvent extraction circuits or electro-winning cells for different metals. Those add complexity but are standard in hydrometallurgy, so it's an integration task.

In the context of prior research, our findings reinforce some known trends and also provide new data. For example, it's known that combining methods can yield better results; our contribution was to quantify this for a PCBs case and optimize it. We also highlight an often under-appreciated benefit of bioleaching: it can significantly reduce chemical usage when used as a precursor, which isn't immediately obvious until you run the numbers as we did with acid consumption. This might encourage others to look at biological preprocessing as a standard part of e-waste recycling flowsheets, even if the endgoal is a hydrometallurgical extraction.

- **Broader Implications:** The broader implication of this research is that sustainable e-waste management is achievable through innovation, and it doesn't necessarily require a single silver-bullet technology, but rather smart combinations of existing ones. Hydrometallurgy and biometallurgy have often been seen as competing alternatives; we show they can be complementary. For the United States, where e-waste recycling rates are low and reliance on export is high, adopting such advanced processes domestically could greatly improve recycling outcomes. It could reduce the need to ship e-waste abroad (where often it is handled unsafely) and instead create domestic jobs in recycling facilities that use state-of-the-art techniques. Moreover, recovering critical materials like rare earths and cobalt is of strategic importance – these are materials for which the U.S. currently depends on imports (often from limited sources). Our process recovered cobalt (though present only in small amounts in PCBs; in other e-waste like batteries it would be a main target) effectively, which suggests it could be applied to battery recycling as well with slight modifications. In fact, the concept could be generalized: any e-waste stream that is amenable to a bio-pretreatment and then chemical extraction might benefit. For instance, printed circuit boards, lithium-ion batteries, and LED phosphors could each have a tailored bioleach + chemical leach sequence to maximize yield and minimize harsh conditions.

In conclusion, the discussion affirms that our research provides a meaningful advancement in e-waste recycling methodology. It consolidates various innovations – from microbial biotechnology to modern analytical optimization – into a cohesive process that outperforms many existing methods on crucial metrics. By comparing prior studies, we highlighted how and why those improvements occur. The broader context indicates that implementing such technologies could significantly propel the e-waste management sector towards sustainability, ensuring that the United States can handle its electronic waste in an environmentally responsible and economically beneficial manner. This sets the stage for our final recommendations on how to move forward with real-world implementation and further research to continue this positive trajectory.

6. Conclusion

In this study, we developed and refined an innovative e-waste recycling technology that merges hydrometallurgical and biotechnological processes, demonstrating enhanced performance in recovering valuable metals from electronic waste. The strengthened literature review provided a solid context, illustrating how our approach builds upon and surpasses existing methods in efficiency and sustainability. Through careful methodological design and statistical optimization, we achieved high recovery yields for critical materials while mitigating environmental drawbacks associated with traditional techniques. The discussion highlighted the novelty of integrating bioleaching with chemical leaching and underscored the broader significance of this advancement for the field of sustainable materials management.

The hybrid recycling process proved capable of extracting >90% of precious metals and virtually all base metals from e-waste, validating our hypothesis that combining biological and chemical leaching can yield synergistic benefits. By employing state-of-the-art optimization (RSM and ANOVA), we ensured the process operates at its sweet spot, thereby providing a blueprint that others can replicate or build upon. Compared to prior recycling strategies, our approach reduces hazardous reagent consumption, lowers energy use, and expands the range of recoverable elements (including those often neglected, like rare earths). It effectively turns electronic waste into a resource, aligning with circular economy goals and demonstrating a pathway to address the e-waste challenge in the United States through innovation.

Recommendations for Implementation

To translate these findings into real-world impact, several steps and policy measures are recommended:

- **Pilot-Scale Deployment:** Stakeholders (industry and government agencies) should invest in building a pilot-scale facility to further validate and fine-tune the hybrid recycling process on a larger volume of e-waste (e.g., several tons per batch). This pilot implementation would provide data on scaling behavior, continuous operation, and integration of metal recovery units (electrowinning cells, etc.) with the leaching reactors.
- **Public-Private Partnerships:** Form partnerships between research institutions, e-waste recyclers, and electronics manufacturers to share knowledge and resources. Collaboration can accelerate technology transfer, with manufacturers potentially supplying scrap or funding in exchange for access to reclaimed materials (for example, rare metals that can be reintegrated into new products).
- **Federal Policy and Regulation:** Introduce and support federal legislation that encourages domestic e-waste recycling. For instance, enacting an Extended Producer Responsibility (EPR) law for electronics would ensure a steady supply of collected e-waste to recycling facilities and provide funding for advanced recycling technologies. Given the lack of a U.S. federal recycling mandate, such a policy would be transformative – it could ban landfilling of e-waste and require that certified recycling methods (preferably those meeting high recovery and environmental standards) are used.
- **Incentives for Green Technology:** Implement tax credits or subsidies for recycling companies that adopt environmentally friendly technologies. This financial support can offset the initial costs of upgrading facilities to use bio-hydrometallurgical processes. For example, companies could receive credits per kilogram of e-waste processed with methods that avoid smelting and reduce emissions. This would make innovative processes economically competitive with (often cheaper) primitive methods.
- **Standards and Certification:** Develop industry standards that define benchmarks for recovery rates and allowable environmental impact for e-waste recycling processes. Certification programs (similar to the existing R2 or e-Stewards certifications) can incorporate criteria for resource recovery efficiency and not just safe handling. Our research could inform such standards by providing achievable targets (e.g., >90% metal recovery, non-hazardous residues) for state-of-the-art processes.
- **Workforce Training:** Equip the workforce with the skills needed to run advanced recycling operations. Bioleaching and chemical process control require expertise in microbiology and chemical engineering. Training programs or community college courses in "urban mining" technology could prepare technicians and operators for the jobs created by these new recycling plants.

Future Research Directions

While the results are promising, further research is warranted to expand and improve upon this work:

- *Scaling Kinetics:* Investigate the kinetics of bioleaching at larger scales and higher pulp densities to shorten cycle times. Research could explore engineered bioreactors (e.g., using air-lift designs or improved aeration) that maximize microbe-metal contact, as well as microbial consortium optimization (adding fungi or genetically enhanced strains) to hasten metal solubilization.
- *Process Integration:* Explore deeper integration of the two stages, such as simultaneous bioleaching and electro-recovery (bioleach solution flowing through an electrochemical cell) to directly recover metals as they solubilize. This could maintain low metal concentrations in solution, potentially accelerating leaching (Le Chatelier's principle) and immediately yielding solid metals.
- *Broadening Feedstock:* Apply the hybrid process to other types of e-waste beyond PCBs – for instance, to lithium-ion battery waste, printed electronics, or even low-grade e-waste like shredded appliances. Each of these has different compositions (e.g., battery recycling would focus on Li, Co, Ni, which might suit our process well with slight tweaks in microbes or acids). Adapting the process to these will demonstrate its versatility.
- *Life-Cycle Assessment (LCA):* Conduct a comprehensive environmental LCA comparing the hybrid recycling process to conventional recycling (and to the baseline of landfilling/incineration). This will quantify benefits in terms of carbon footprint, toxicity potential, and resource savings. The expectation is that our process will show reductions in greenhouse emissions and ecological toxicity, but an LCA will pinpoint any hotspots (perhaps electricity use for aeration, etc.) that can be further optimized.
- *Economic Analysis:* Carry out a detailed economic analysis (techno-economic assessment) for a full-scale implementation. This should include capital and operating costs and potential revenue from recovered metals. Sensitivity analysis on metal prices and waste input rates will help determine the break-even conditions and guide business models for commercial operation.

- *Enhancing Selectivity:* Research into novel selective leaching agents inspired by our findings could improve the process. For example, building on the success of ionic liquids, future studies might incorporate a step where an IL is used to pull out specific rare earths or platinum group metals after bulk leaching, thereby increasing the portfolio of recovered elements.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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