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Green Biohydrometallurgy for Gold Recovery from Electronic Wastewater: Advances, Challenges, and Future Directions

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ABSTRACT

The rapid growth of electronic waste (e-waste) creates both environmental risks and untapped resource recovery opportunities, particularly for gold present at trace levels in complex electronic wastewater streams. Traditional methods—cyanidation and aqua regia leaching—achieve high recovery but entail high energy consumption, toxic reagents, and substantial secondary waste, conflicting with circular economy and decarbonization goals. Green biohydrometallurgy—encompassing bioleaching, biosorption, and bioreduction—offers a promising alternative under milder conditions with lower environmental impacts, especially when integrated with advanced solvents (IL/DES) and sorbents (COFs). This review critically examines recent advancements in gold recovery from e-waste-derived electronic wastewater using bio-based and bio-enabled technologies. Key topics include: (i) metabolism-dependent bioleaching using bio-lixiviants; (ii) biosorption and bioreduction of Au from polymetallic solutions; and (iii) integration with ionic liquids/deep eutectic solvents (IL/DES) and molecularly designed sorbents (e.g., covalent organic frameworks, COFs). Synthesized performance data reveal gold leaching efficiencies up to 98% in optimized thiourea-based bioleaching and adsorption capacities reaching 3108 mg g^{-1} for CS-MoS_2 composites, demonstrating the exceptional potential of sulfur-rich biosorbents. Critical challenges—slow kinetics, selectivity, biocatalyst stability, and scaling in real wastewater matrices—are examined. Future priorities include low-carbon hybrid flowsheets, life cycle assessment (LCA), techno-economic analysis (TEA), and safe-and-sustainable-by-design approaches to establish green biohydrometallurgy as a cornerstone of sustainable urban mining for precious metals recovery from electronic wastewater.

Keywords: *Green biohydrometallurgy; Gold recovery; Electronic wastewater; Bioleaching; Urban mining*

INTRODUCTION

The volume of electronic waste (e-waste) is escalating at an unprecedented rate, now recognized as one of the fastest-growing waste streams globally. This surge is driven by increasing consumption of electronic devices, short product lifecycles, and limited formal recycling infrastructure in many regions (Baldé et al., 2024; Chowdhury & Ghosh, 2018; Ghulam & Abushammala, 2023). The majority of e-waste continues to be managed through informal channels, including manual dismantling, open burning, and uncontrolled chemical leaching. Such practices release heavy metals and hazardous organic compounds into soils and water systems, generating leachates and electronic wastewater that are not only metal-rich but also toxic to ecosystems and human health (Sandwal et al., 2025). According to the *Global E-waste Monitor* 2024, e-waste generation reached 62 billion kg globally in 2022—averaging 7.8 kg per capita—yet only 22.3% (13.8 billion kg) was appropriately collected and recycled (Baldé et al., 2024).

Conversely, e-waste contains high concentrations of valuable metals, particularly gold (Au), often surpassing those found in primary mineral ores. This has led to recognition of e-waste as a strategic "urban mine" for precious metal recovery (Chowdhury & Ghosh, 2018; Magoda & Mekuto, 2022). The economic value of e-waste is primarily driven by Au-rich fractions in printed circuit boards (PCBs), connectors, and conductive coatings. However, this resource remains largely untapped due to the complex, polymetallic, and frequently toxic matrix, which demands processing schemes that are both efficient and environmentally systematic. In current industrial practice, mechanical and thermochemical operations—pyrometallurgy and hydrometallurgy—generate various metal-rich solutions, including pregnant leach solutions, rinse streams, and electroplating effluents. Collectively termed electronic wastewater, these streams represent a highly promising secondary source of dissolved Au, yet they remain underutilized.

Despite their technical effectiveness and established industrial base, conventional approaches—cyanidation, aqua regia, and other strong-acid leaching—are generally energy-intensive, involve hazardous reagents, exhibit high corrosivity, and generate secondary waste requiring intensive treatment (Adetunji et al., 2023; Kara et al., 2023). These operations contribute to greenhouse gas emissions and pose toxicity risks to ecosystems and workers. Recent life-cycle assessments (LCA) highlight that while conventional methods excel in processing speed and recovery yields, achieving alignment with decarbonization targets and circular economy principles requires substantial process innovations to reduce energy footprints, toxicity, and waste burdens (Sieber et al., 2025).

The growing urgency to transition to a circular economy demands greener precious-metal recovery technologies—particularly for gold—featuring lower energy consumption, minimal toxicity, and the capacity to utilize electronic wastewater as a resource rather than a pollutant. In this context, biohydrometallurgy and biologically-based approaches—bioleaching, biosorption, and bioreduction—have emerged as promising alternatives (Baniasadi et al., 2019; Kaksonen et al., 2020). These processes operate under milder conditions with less hazardous reagents. Several studies have demonstrated biological dissolution, binding, and precipitation of metals from e-waste, yet the primary focus has remained on base metals (Cu, Ni, Pb) and solid matrices (PCBs, batteries). Systematic investigations into gold recovery from electronic wastewater—where precious metals exist at trace concentrations amid complex polymetallic and organic matrices—remain relatively limited (Huy et al., 2023).

With global e-waste projected to reach 82 million tonnes by 2030 and increasing regulatory pressure on toxic reagents, a comprehensive synthesis of green alternatives for gold recovery from electronic wastewater has become critical. This article aims to critically and comprehensively review recent advancements in biohydrometallurgy and bio-based strategies for recovering gold (and, where applicable, silver) from electronic wastewater and associated leachates. Specifically, this article: (i) examines the technological landscape of bioleaching, biosorption, and bioreduction for precious metal recovery from liquid e-waste streams; (ii) identifies key technical, biological, and engineering challenges—kinetics, biocatalyst stability, selectivity in multi-metal systems, and integration with chemical/electrochemical processes; and (iii) highlights techno-economic and LCA gaps hindering industrial adoption, while proposing future research directions aligned with circular economy and safe-and-sustainable-by-design concepts. These objectives guide the subsequent sections, linking each discussion to identified gaps and opportunities. Ultimately, this article positions green biohydrometallurgy not as a standalone solution, but as a central component of hybrid processing schemes integrating biological, chemical, and electrochemical operations for more selective, efficient, and environmentally responsible precious metal recovery from electronic wastewater.

METHOD

The article employs a narrative critical review approach to systematically examine and synthesize the scientific literature on green biohydrometallurgy for gold recovery from electronic wastewater. Unlike systematic reviews that prioritize quantitative meta-analysis, a narrative critical review is specifically designed to integrate diverse bodies of literature across interdisciplinary fields, evaluate methodological rigor, identify conceptual patterns, and generate critical insights into emerging technologies. This approach is particularly appropriate for the present topic, which spans microbiology, green chemistry, materials science, and metallurgical engineering, where studies vary significantly in experimental design, performance metrics, and disciplinary orientation.

A comprehensive literature search was conducted across three major scientific databases: *ScienceDirect*, *Web of Science*, and *Google Scholar*. These databases were selected for their extensive coverage of peer-reviewed research in environmental science, metallurgy, microbiology, and green chemistry, as well as their robust indexing and citation analysis capabilities. The search was limited to publications from 2015 to 2025 to capture the most recent advancements in this rapidly evolving field. Boolean operators were employed to combine keywords across three thematic domains: (i) process/method-related terms ("biohydrometallurgy," "bioleaching," "biosorption," "bioreduction," "bio-adsorbent," "bio-enabled," "microbial recovery"); (ii) target metal terms ("gold," "Au," "precious metal," "noble metal"); and (iii) waste stream terms ("electronic waste," "e-waste," "WEEE," "electronic wastewater," "leachate," "urban mining," "printed circuit boards"). Additional targeted searches using specific terms such as "thiourea bioleaching," "cyanogenic bacteria," "chitosan gold adsorption," and "covalent organic framework gold recovery" were performed to ensure coverage of niche but critical advancements, supplemented by manual screening of reference lists from key review articles.

Studies were included if they met the following criteria: (i) peer-reviewed original research articles or authoritative review papers published in English; (ii) explicit focus on gold recovery from secondary sources, specifically e-waste, electronic wastewater, or e-waste-derived leachates; (iii) investigation of biological or bio-enabled processes including metabolism-dependent bioleaching, metabolism-independent biosorption, bioreduction, or hybrid systems integrating biological methods with green solvents or advanced sorbents; and (iv) reporting of original performance data or mechanistic insights into gold-microbe/material interactions. Articles were excluded if they focused exclusively on primary ore mining or conventional pyrometallurgical/hydrometallurgical processes without biological components, dealt solely with base metals without addressing gold, or consisted of conference abstracts, non-peer-reviewed reports, or duplicate publications.

The selected literature was analyzed using a comparative techno-environmental framework that integrates technical performance assessment with environmental sustainability evaluation.

Technical performance was assessed based on key indicators including leaching efficiency, adsorption capacity, selectivity coefficients, operating conditions, process configuration, and technology readiness level. Environmental assessment examined reagent toxicity, energy consumption, secondary waste generation, alignment with green chemistry principles, and availability of life cycle assessment and techno-economic analysis data. Findings were synthesized thematically following established narrative synthesis guidelines, progressing through three stages: preliminary theme identification (grouping studies by process type and coding for mechanisms), thematic organization (comparing studies to identify patterns and gaps), and interpretive synthesis (developing higher-level insights regarding process mechanisms, hybrid integration potential, and critical research gaps). Reference management was performed using *Zotero*.

RESULTS AND DISCUSSION

Green Technology Framework for Precious Metal Recovery

The green technology framework for precious metal recovery from e-waste and electronic wastewater integrates green chemistry principles, next-generation solvents, bio-based approaches, and sustainability assessments. Key green chemistry principles relevant to this framework include waste prevention, high atom economy, safer solvent use, energy efficiency, and the design of non-hazardous, degradable products (Anastas & Egbali, 2010).

1. Green Solvents: Ionic Liquids and Deep Eutectic Solvents

Ionic liquids (ILs) and deep eutectic solvents (DESs)—now extended to low-melting mixture solvents (LoMMSs)—have emerged as important green solvent platforms due to their negligible volatility, tunable physicochemical properties, and ability to dissolve metals and organic matrices (Barbará et al., 2025). In e-waste recycling, DES/IL systems have demonstrated >95–99% extraction efficiencies for base metals from spent batteries and printed circuit boards, often with high selectivity and potential for solvent reuse in closed-loop configurations (Domańska et al., 2024; Gupta et al., 2024).

However, recent critical perspectives caution against dogmatic acceptance of IL/DES as inherently "green." Issues including high viscosity, energy-intensive heating requirements, toxicity, hygroscopicity, limited regenerability, and uncertain biodegradability must be addressed through structural and process design strategies (Chen & Mu, 2021; Chen & Yu, 2023). Improvements such as bio-based precursors (e.g., cholinium, biomass-derived organic acids), viscosity reduction, and enhanced recyclability are essential for genuine sustainability (Dar et al., 2025).

Cross-sector applications (lignocellulosic biorefineries, PET recycling) demonstrate that IL/DES systems can reduce environmental impact only when solvent recycling, operation scale, and energy consumption are optimized—underscoring the need for comprehensive life cycle assessment (LCA) rather than simplistic solvent substitution (Barbará et al., 2025).

Molecularly designed sorbents, particularly covalent organic frameworks (COFs), represent a paradigm shift in gold recovery from complex leachates. Benzoxazine-based COFs with quasi-planar heteroatom control achieve Au adsorption capacities up to 3467 mg g^{-1} with >92% selectivity in the presence of 12 competing metal ions from real e-waste leachates (Kumar et al., 2025). Other COF architectures (amide, pyridine, ionic frameworks) similarly demonstrate high capacity and selectivity, often coupled with in situ bioreduction of Au(III) to Au(0) (Zhang et al., 2025; Zhao et al., 2024). These materials enable selective gold recovery without hazardous precipitation reagents and support multi-cycle regeneration, aligning with circular economy principles.

2. Bio-Based Recovery Technologies

Bio-based technologies—including biosorption, bioaccumulation, and bioelectrochemical systems—offer selective metal separation under mild conditions (Sieber et al., 2025). Surface modification of biomass with metal-binding peptides or siderophores enhances selectivity for trace gold in polymetallic electronic wastewater, positioning bio-based recovery as a crucial complement to synthetic sorbents and green solvents (Ferreira-Filipe et al., 2025).

3. Hybrid Process Integration

The ideal hybrid flowsheet combines physical pretreatment, soft bioleaching or DES/IL leaching, and selective recovery using COFs, biosorbents, or electrochemical methods (Huy et al., 2023; Abbas & Jung, 2024). Non-oxidative approaches that recover gold as flakes or concentrate gold-rich fractions without dissolution prevent down-cycling and enable high-value reuse in optoelectronic applications (Gouda et al., 2025). Industrial feasibility requires rigorous validation through LCA, green metrics, and techno-economic analysis (TEA) accounting for solvent lifespan, energy balances, and waste management (Dar et al., 2025).

Table 1. Green Technology Pillars for Gold Recovery

Technology Pillar	Performance Highlights	Sustainability Considerations	References
IL/DES Solvents	>95–99% metal extraction; >99% Au in 5 min	High viscosity, toxicity concerns; requires LCA	Dar et al., 2025; Domańska et al., 2024
COFs & Sorbents	3467 mg g^{-1} Au capacity; >92% selectivity	No hazardous reagents; multi-cycle use	Kumar et al., 2025; Fu et al., 2024
Bio-Based Recovery	Effective at trace Au (ppm–ppb); mild conditions	Low energy; slow kinetics, scalability issues	Sieber et al., 2025
Hybrid Flowsheets	Integrates leaching, adsorption, electrochemistry	Circular economy; requires TEA/LCA validation	Huy et al., 2023

Biohydrometallurgy for Gold Recovery from Electronic Wastewater

Biohydrometallurgy offers a four-stage route for gold recovery from e-waste—bioleaching, biosorption, bioreduction, and hybrid process integration—treating e-waste as a complex "urban ore" (Huy et al., 2023; Magoda & Mekuto, 2022). While these biological approaches aim to supplant toxic lixiviants like cyanide (Ray et al., 2022), life cycle assessment (LCA) reveals that their environmental superiority is not absolute; pyrometallurgy can outperform bioleaching in fossil-based energy grids, whereas hybrid flowsheets excel only under low-carbon scenarios (Schwartz et al., 2024). The primary barriers to adoption remain scale-up challenges, microbial sensitivity, and a predominance of laboratory-scale studies, underscoring the critical need for systemic process design and intensification (Magoda & Mekuto, 2022).

1. Bioleaching and Bio-Lixiviants for Gold Dissolution

The initial stage involves dissolving metallic gold from waste printed circuit boards (WPCBs) into soluble forms using bio-lixiviants. Thiourea-based bioleaching (TU-bioleaching) represents one of the most advanced approaches, utilizing iron-oxidizing archaea (Acidiplasma sp. Fv-Ap) to maintain Fe^{3+} regeneration and control redox potential (Eh 490–545 mV), thereby inhibiting thiourea decomposition and stabilizing the Au-thiourea complex (Rizki et al., 2019). With a thiourea-to-iron ratio of 2:1–40:1 using only 1 mM Fe^{3+} and 10 mM thiourea, this method achieves 98% gold leaching from PCBs—significantly reducing thiourea consumption compared to conventional chemical leaching (Ray et al., 2022). Despite its promise, challenges remain in redox potential control, thiourea decomposition management, and handling of reduced sulfur species during scale-up (Ray et al., 2022).

Bio-cyanidation employs cyanogenic bacteria, particularly Chromobacterium violaceum, to produce biogenic cyanide (CN^-) for gold complexation. Due to e-waste toxicity, two-step strategies (cell growth and CN^- production followed by e-waste addition) are more effective, though gold recovery typically remains below 30–60% without optimization (Rana et al., 2020). However, key challenges include achieving sufficient biogenic cyanide production, microbial toxicity from heavy metals and flame retardants, and significantly longer processing times compared to chemical leaching (Magoda & Mekuto, 2022).

LCA of Cu–Au bioleaching hybrid schemes confirms that environmental benefits depend critically on electricity carbon footprint and operational optimization; without low-carbon energy and process intensification, bioleaching may not outperform chemical or pyrolysis routes (Schwartz et al., 2024). Thus, bio-cyanidation is best positioned as a modular component within hybrid flowsheets rather than a complete replacement for conventional cyanidation.

Table 2. Bioleaching Systems for Gold Recovery

Bioleaching System	Microorganisms / Lixiviant	Key Conditions	Performance	References
TU-bioleaching	*Acidiplasma* sp. Fv-Ap + thiourea	Acidic pH, 1 mM Fe^{3+}, 10 mM TU, Eh 490–545 mV	98% Au leaching	Rizki et al., 2019
Bio-oxidation + TU leaching	*Acidithiobacillus-Leptospirillum* consortium	Bio-oxidation of sulfide → biogenic Fe^{3+}; TU leaching	95% Au	Ray et al., 2022
BIOX–TC (thiocyanate)	*A. ferrooxidans, A. thiooxidans, L. ferrooxidans*	Acidic biooxidation,	86.9% Au recovery	Azizitorghabeh et al., 2022

Bioleaching System	Microorganisms / Lixiviant	Key Conditions	Performance	References
		0.2 M SCN^-, in situ Fe^{3+}		
Bio-cyanidation	*C. violaceum* (cyanogenic bacteria)	pH 8–11, two-step/spent medium, 0.5–10 g L^{-1} pulp	11–73% Au	Natarajan & Ting, 2015; Kumar et al., 2021
CDS-enhanced bio-CN	*C. violaceum* + distiller solubles condensate	Cu pre-leaching ($Fe_2(SO_4)_3$), pH 7, glycine	98.6% Au leaching	Tran et al., 2025
Iodide-oxidizing bacteria	*Roseovarius tolerans/mucosus*	pH 7–9, I^- oxidation to I_3^-; AuI_2^- complex	0.93–1.6% Au	Kudpeng et al., 2020
Two-stage acidophilic bioleaching	*Leptospirillum, Sulfobacillus, Acidithiobacillus* consortium	pH ~1–1.6, ORP +410 mV, semi-continuous	96–100% Cu, Ni, Zn; Au in residue	Adam et al., 2023; Hubau et al., 2020

2. Biosorption and Bio-Enabled Adsorption of Gold Solutions

Following gold dissolution as Au(III) complexes (typically $AuCl_4^-$ or thiosulfate complexes), the selective recovery of gold from highly polymetallic leachates represents a critical separation challenge. Biosorption utilizing nitrogen/sulfur-rich biomacromolecules has emerged as a promising approach, offering cost advantages and environmental compatibility compared to conventional adsorbents (Huy et al., 2023; Dutta et al., 2022).

Biosorbents for gold recovery can be broadly classified into three categories: (i) pristine or modified biomass (chitosan, alginate, cellulose, agricultural wastes); (ii) bio-enabled composites integrating biomass with synthetic materials (MOFs, magnetic nanoparticles, polymers); and (iii) molecularly imprinted biopolymers with tailored recognition sites. Chitosan-based materials have been extensively studied due to abundant amine and hydroxyl groups that interact with $AuCl_4^-$ through electrostatic attraction and coordination. Crosslinking strategies (e.g., glutaraldehyde) enhance chemical stability in acidic e-waste leachates while maintaining selectivity (Bui et al., 2020).

Bio-enabled composites combine biomass with functional synthetic components to enhance capacity, selectivity, and separability. Magnetic nanoparticles facilitate recovery, while sulfur-rich ligands (thiols, MoS_2) exploit soft–soft interactions with Au(III) for superior selectivity (Poormoghadam et al., 2025). Surface-functionalized agricultural wastes offer cost-effective alternatives. Modification with polyethyleneimine, tannins, or aminothiazole introduces additional binding sites and reduction capabilities (Choudhary et al., 2018; Lin et al., 2018).

Despite significant progress, critical limitations persist. Most studies remain at laboratory scale using batch configurations under idealized conditions, with limited validation using real e-waste leachates. Long-term performance under continuous flow, fouling resistance, and structural stability require systematic investigation (Rana et al., 2020). Furthermore, life cycle assessment (LCA) and techno-economic analysis (TEA) specific to biosorption stages are rarely conducted, leaving sustainability claims unquantified (Huy et al., 2023). Future research must prioritize validation under industrially relevant conditions, regeneration strategies, and comprehensive sustainability assessments.

Table 3. Key Biosorbents for Gold Recovery from E-waste Leachates

Material	Mechanism	Capacity (mg g^{-1})	Key Feature	Reference
Chitosan-keratin cryogel	Electrostatic + N/S chelation	613	89.2% recovery from real leachate	Haleem et al., 2024
CS-MoS_2 composite	Au–S soft–soft interaction	3108	Outstanding multi-ion selectivity	Zhao et al., 2020
OCBs@Fe_3O_4@UiO-66-SH	Thiol chemisorption, magnetic	1587	95–105% recovery; stable at 1:5 interference	Poormoghadam et al., 2025
Thiourea-modified alginate	Covalent Au–S/N, photoreduction	1667	>90% selectivity in multi-metal mixtures	Gao et al., 2017
DCTS-TA (chitosan-tannin)	Phenolate/N chelation + reduction	1146	>90% recovery after 5 cycles	Hou et al., 2023
Corn-bract-2-aminothiazole	Amino/thiol chelation	1668	Very high competitive selectivity	Lin et al., 2018
$CoFe_2O_4$@SiO_2@persimmon tannin	Phenolic reduction, magnetic	882	>90% efficiency in mixed solutions	Budiarta et al., 2024

3. Bioreduction and Precipitation of Gold into Au(0)

The final stage transforms Au(III) into metallic gold (Au^0) via three approaches: (i) direct reduction by biomass or metabolites; (ii) bio-enabled materials with intrinsic electron donor sites (hydroxylated aromatics, thiols, amines); and (iii) microbial reduction combined with solid substrates like Fe-based MOFs (Kaksonen et al., 2020).

Modified biomacromolecules show significant potential. Thiourea-modified alginate achieves 1670 mg g^{-1} capacity with in situ Au^0 nanocrystal formation (Gao et al., 2017). Chitosan-thioglycolic acid (CS-TGA-GA) composites yield 1351 mg g^{-1} and 99.6% gold purity from WPCB leachate (James et al., 2024). Chitosan-ferrocene-cyclodextrin-thiourea (CS-Fc@CD-TU) maintains >97% efficiency over five cycles, producing 99.8% pure gold (Xie et al., 2025). These materials combine selective adsorption with intrinsic reduction, eliminating external reductants.

Advanced systems integrate microbial and carbon-based reduction. Shewanella oneidensis generates Fe(II) within MIL-127 MOF, reducing Au(III) at 183 mg g^{-1} capacity with biological redox regeneration (Springthorpe & Keitz, 2021). Defect-rich carbon dots provide electron donor sites (~1.7 mmol g^{-1}), reducing Au(III) via two-stage nucleation (Zhang et al., 2025). Alginate-derived pyrocarbon lowers the reaction energy barrier from +1.08 to –21.84 eV through stepped Au–Cl cluster formation (Fu et al., 2024).

Despite promise, studies remain laboratory-scale with batch conditions. Challenges include fouling, particle size control, and process integration. Bioreduction is best positioned as a flexible module within optimized hybrid flowsheets, not a standalone replacement for chemical routes (He & Kappler, 2017).

Table 4. Representative Bioreduction Systems for Gold Recovery

Material	Mechanism	Capacity (mg g^{-1})	Key Feature	Reference
Thiourea-modified alginate	In situ Au^0 nanocrystal formation	1670	>90% selectivity; no external reductant	Gao et al., 2017
CS-TGA-GA (chitosan-thioglycolic acid)	Reduction-coupled adsorption + incineration	1351	99.6% Au purity from WPCB leachate	James et al., 2024
CS-Fc@CD-TU (chitosan-ferrocene-CD-TU)	Adsorption-reduction cascade	722	>97% efficiency after 5 cycles; 99.8% purity	Xie et al., 2025
S,N-rich MOF (adenine + thiodiphenol)	Chemisorption + Au^0 formation	3680	99% removal in 8 min; stable over 7 cycles	Wang et al., 2023
Fe-MOF MIL-127 + *S. oneidensis*	Microbial Fe(II) generation → Au(III) reduction	183	Biological redox regeneration; multiple cycles	Springthorpe & Keitz, 2021
Alginate-derived pyrocarbon	sp^2 electron reservoir; stepped Au–Cl clusters	2830	DFT-confirmed energy barrier reduction	Fu et al., 2024

Case Studies and Comparative Assessment

1. Representative Case Studies: From Lab to Pilot Scale

Case studies on gold recovery from e-waste leachate reveal a diverse technological landscape with significant variation in waste matrices, leaching media, and process configurations. While gold content in WEEE can rival or exceed primary ores, its concentration in leachate and wastewater is typically very low (µg–mg L^{-1}) and mixed with high concentrations of base metals (Cu, Ni, Fe), necessitating highly selective, multi-stage separation strategies (Ferreira-Filipe et al., 2025; Habibi et al., 2020).

Biohydrometallurgical approaches—including bioleaching by acidophilic microorganisms and biosorption by living or dead biomass—have demonstrated lower energy consumption and emissions compared to conventional pyrometallurgy and hydrometallurgy. However, most implementations remain at laboratory batch-scale using simplified synthetic effluents that do not represent the complexity of actual industrial e-waste streams (Sieber et al., 2025).

The "green hybrid" approach, combining conventional chemical leaching (e.g., dilute aqua regia, non-cyanide systems) with bio-based polishing stages, has emerged as a pragmatic compromise between performance and environmental acceptability (Huy et al., 2023; Dutta et al., 2022; Rocky et al., 2024). Integrating aqua regia leaching with selective sorption or biotechnological stages can reduce acid consumption, enhance Au/Pd/Pt selectivity, and lower pollutant loads, though challenges remain including high corrosivity, specialized reactor requirements, and stringent waste treatment needs (Rocky et al., 2024).

Pilot studies remain limited but highlight critical scaling challenges. Transitioning to high pulp density and complex multi-metal effluents often results in performance decline due to heavy metal inhibition, biosorbent fouling, and difficulty maintaining active cultures (Sieber et al., 2025; Wang et al., 2023). Feedstock variability across product generations further complicates reproducibility without stringent pretreatment (Gomez et al., 2024). Technical and economic analyses suggest that with proper flowsheet design, green technologies can be economically competitive while reducing carbon footprints (Martin et al., 2023; Suffia & Dutta, 2023). However, the main barrier to industrial adoption remains the lack of long-term pilot testing, complete mass-energy balance data, and consistent LCA/LCC evaluations across process configurations (Rai et al., 2021).

2. Comparison with Conventional and Other Green Approaches

Compared to conventional cyanidation and aqua regia, biohydrometallurgy and non-biological green approaches offer superior environmental profiles but often at the expense of process speed, operational simplicity, or technological maturity.

Cyanidation remains the industry standard due to high selectivity (>90% recovery) and established infrastructure, but it is highly toxic, difficult to regenerate, unsuitable for refractory ores, and faces increasing regulatory pressure (Dutta et al., 2022). Aqua regia achieves up to 97–99% gold dissolution but is highly corrosive, produces NO_x/Cl^--laden wastewater, and requires costly materials and waste treatment, driving interest in hybrid concepts (Rocky et al., 2024; Sethurajan et al., 2019).

Biohydrometallurgy (bioleaching, biosorption, bioelectrochemistry) consistently demonstrates lower energy and chemical consumption, minimal air emissions, and reduced hazardous sludge (Habibi et al., 2020). Metabolism-dependent and -independent mechanisms enable high selectivity in multicomponent solutions under optimized conditions (Sieber et al., 2025; Sethurajan et al., 2019). However, most data derive from simple systems, and applicability to complex e-waste leachate requires systematic validation (Sieber et al., 2025; Ferreira-Filipe et al., 2025). Bio-based technologies excel in low-grade, high-volume applications but become less competitive when complex bioprocess control is required (Sieber et al., 2025).

In a broader comparative framework, conventional technologies (pyrometallurgy + strong acid hydrometallurgy) possess high technology readiness levels (TRL) but are increasingly incompatible with circular economy and decarbonization targets due to emissions and health risks (Dutta et al., 2022). Green technologies show strong potential in reducing environmental factors (E-factor) and enabling resource recovery from waste, yet face three persistent challenges: (i) the scale gap between laboratory studies and industrial requirements (high pulp density, feed variability, continuous operation) (Kara et al., 2023); (ii) lack of comparative techno-economic and life-cycle assessment data, resulting in qualitative "green" claims (Martin et al., 2023; Suffia & Dutta, 2023); and (iii) trade-offs between advanced material complexity and affordability in developing countries that process the majority of global e-waste (Dutta et al., 2022).

The critical implication is that future "green biohydrometallurgy" processes must adopt hybrid schemes combining moderate leaching (DES, non-cyanide, dilute aqua regia), selective separation (bio-/polymer sorbents, electro-recovery), and waste bioprocessing units to simultaneously meet efficiency, selectivity, cost, and sustainability criteria (Sethurajan et al., 2019).

Table 5. Comparison of Gold Recovery Approaches from E-waste

Method	Examples	Key Features	Au Recovery	Limitations	References
Cyanidation	Alkaline NaCN/KCN leaching	High selectivity; established industrial base	>90%	Toxic; difficult regeneration; regulatory pressure	Dutta et al., 2022; Sethurajan et al., 2019
Aqua regia	$HCl+HNO_3$ leaching of PCBs	Highest dissolution rate; up to 97–99% recovery	97–99%	Highly corrosive; NOx/Cl^- wastewater; limited industrial use	Rocky et al., 2024; Sethurajan et al., 2019
Bioleaching	Acidophilic bacteria (e.g., *Acidithiobacillus*)	Low energy; minimal emissions; inexpensive reagents	Base metals >80–90%; Au as pre-treatment	Slow kinetics; toxicity sensitivity; limited Au-specific data	Sieber et al., 2025
Biosorption	Modified biomass, chitosan, agricultural wastes	High selectivity; low environmental footprint	Up to >90% in simple systems	Lab-scale only; regeneration challenges; complex effluent performance unproven	Ferreira-Filipe et al., 2025; Huy et al., 2023
DES/IL leaching	Choline chloride-based DES, triiodide IL	Low volatility; tunable; >99% Au in 5 min	>95–99%	High viscosity; energy-intensive regeneration; toxicity concerns	Martin et al., 2023
Green sorbents	COFs, pyrocarbon, bio-based adsorbents	High capacity (up to 3467 mg g^{-1}); selective	>95% recovery	Lab-scale; lifecycle data needed; regeneration studies limited	Kumar et al., 2025
Electro-recovery	Electrowinning from leachate	High purity (≈100%); minimal reagent use	>99%	Dependent on leaching solution; requires pretreatment	Rai et al., 2021; Huy et al., 2023

Challenges in Implementing Green Biohydrometallurgy

1. Technical and Process Challenges

The most fundamental technical challenge in green biohydrometallurgy is slow leaching kinetics and performance decline during scale-up. Bioleaching rates are typically diffusion-controlled, and increasing pulp density beyond 5–10% w/v causes sharp recovery drops, extending process times from hours to days or weeks (Magoda & Mekuto, 2022; Kara et al., 2023). In e-waste systems, this is exacerbated by heavy metals (Pb, Cd, Cr), organic flame retardants, and toxic plastics that inhibit microbial activity, reduce lixiviant production, and damage biofilms (Baniasadi et al., 2019). In electronic wastewater, Cl^-, surfactants, and organic complexes alter Au(III)/Au(I) speciation, disrupting adsorption and bioreduction stages (Huy et al., 2023).

Selectivity in multi-metal systems remains a major hurdle. Base metals (Cu, Fe, Ni, Zn) are present at much higher concentrations than Au/Ag, dominating leaching and separation. Most studies use simplified solutions that do not reflect industrial complexity, complicating the design of selective recovery schemes for trace gold in Cu/Cl^--rich matrices (Magoda & Mekuto, 2022). Emerging solutions include gold-imprinted adsorbents, selective Au ligands/peptides, and staged leaching strategies (Ferreira-Filipe et al., 2025).

2. Scale-Up, Process Control, and Integration

Scale-up remains a major bottleneck. Laboratory performance (shake flasks, small stirred tanks) often deteriorates in column reactors, heaps, or large tanks due to non-homogeneous distribution of oxygen, pH, Eh, and nutrients, and mixing limitations at high pulp density (Kara et al., 2023; Baniasadi et al., 2019). Stable operations are typically achieved only at 2–10% pulp density; exceeding this increases viscosity and fouling, leading to microbial washout. For gold recovery, this directly reduces throughput and extends cycle time, undermining economic feasibility compared to conventional routes (Habibi et al., 2020).

Process control requires automation and online monitoring (pH, Eh, DO, ion concentrations) with kinetic models and AI-based optimization, but most studies still focus on single-parameter optimization rather than robust industrial control systems (Kara et al., 2023). Two-phase optimization (shake flask → bioreactor) is emerging as a systematic approach to bridge the lab-pilot gap (Kaksonen et al., 2020).

Integration with existing e-waste facilities is complex. Bioleaching requires pretreatment (dismantling, shredding, debromination) to reduce toxicity and improve accessibility, necessitating plant modifications (Habibi et al., 2020). Downstream, bioleachate composition (low pH, high organic/microbial content) is often incompatible with conventional solvent extraction, ion exchange, or electrowinning, requiring circuit redesign (Huy et al., 2023). For electronic wastewater, integrating biosorption/bioreduction with existing treatment systems must balance gold recovery with water quality compliance, addressing increased COD and membrane fouling risks (Huy et al., 2023; Srivastava et al., 2025).

3. Economic, Regulatory, and Social Barriers

Economic viability is highly sensitive to process design, feed type, and policy context. Techno-economic assessments show that bioleaching can yield attractive NPV and IRR in certain scenarios, but initial CAPEX and OPEX for aeration, nutrients, and process control remain significant (Kara et al., 2023; Dutta et al., 2022; Satriadi et al., 2024). In low-income countries, competitiveness depends on supportive policies (Extended Producer Responsibility, eco-taxes, reduced collection costs) (Smith & Behdad, 2025). Critically, most TEA/LCA studies focus on Cu, tailings, or batteries; gold-specific analyses from e-waste are almost nonexistent, leaving economic and environmental uncertainties unaddressed (Habibi et al., 2020; Thakur & Kumar, 2020).

Regulatory uncertainty poses significant barriers. Legal frameworks for e-waste management are designed for conventional processes, creating ambiguity regarding microorganism use, biosafety requirements, and effluent quality standards for streams containing biomass, metabolites, or organometallic complexes (Nithya et al., 2020). The "waste vs. resource" status of Au-enriched effluent remains unclear, and fragmented international regulations complicate cross-border investment (Srivastava et al., 2025; Thakur & Kumar, 2020).

Without regulatory clarity, appropriate policy mixes (fiscal incentives, EPR, green standards), uniform technical standards, and industry-academia-government partnerships through "lighthouse" demonstration projects, green biohydrometallurgy risks remaining in the "valley of death" between research and commercialization. With such support, it can become a key pillar of sustainable gold recovery from e-waste (Dutta et al., 2022; Srivastava et al., 2025).

Table 6. Challenges and Emerging Solutions in Green Biohydrometallurgy

Challenge Area	Key Challenges	Emerging Solutions	References
Technical & Selectivity	Slow kinetics; limited pulp density (5–10% max); trace Au in multi-metal matrices; microbial inhibition by toxics	Gold-imprinted adsorbents; staged leaching (base metals first); selective Au ligands/peptides	Kara et al., 2023; Huy et al., 2023
Scale-Up & Integration	Performance loss at large scale; non-homogeneous mixing; incompatibility with SX/IX/EW; COD/membrane fouling	Two-phase optimization (flask → bioreactor); hybrid solid–liquid flowsheet design; online monitoring (AI/soft sensors)	Kara et al., 2023; Kaksonen et al., 2020;
Economic & Regulatory	High CAPEX/OPEX; no Au-specific TEA/LCA; unclear biosafety rules; "waste vs. resource" ambiguity	Au-targeted TEA/LCA; green policy mix (EPR, eco-taxes); "lighthouse" demonstration projects	Dutta et al., 2022; Smith & Behdad, 2025; Nithya et al., 2020;

Future Directions and Research Opportunities

1. Advancing Microbial Systems for Gold Recovery

Future research must prioritize developing microorganisms and consortia with enhanced tolerance, selectivity, and productivity for gold recovery. Current gold bioleaching relies on cyanogenic bacteria (Chromobacterium violaceum, Pseudomonas spp.) or two-stage systems (bio-oxidation followed by chemical leaching) with limited efficiency and speed (Rizki et al., 2019; Natarajan & Ting, 2015). Microbial-mediated thiosulfate bioleaching achieves up to 98% gold leaching through redox control by iron-oxidizers, but remains at laboratory scale requiring optimization of reagent stability and toxicity management (Rizki et al., 2019).

Biosorption and bioreduction using biomass, fungi, and functional biomaterials demonstrate high Au(III) capacity and selectivity in complex matrices, yet most studies employ batch systems with idealized conditions, inadequately addressing interference from competing cations and real wastewater dynamics (Saha et al., 2024). Priority research includes bioprospecting from metal-rich environments, adaptive evolution for enhanced tolerance, and synthetic biology approaches to modulate biolixiviant production, redox enzymes, and metal-binding sites (Kaksonen et al., 2020). Regulatory frameworks for genetically modified organisms in waste applications require clarification.

2. Bioprocess and Reactor Engineering

Transitioning from laboratory to continuous integrated systems demands strengthened bioprocess engineering. Current batch/suspension systems are inadequate for electronic wastewater requiring continuous-flow reactors capable of handling ultra-low Au concentrations, fluctuating compositions, and contaminants (Chauhan et al., 2018). Promising reactor designs—packed beds, fixed film reactors, membrane bioreactors, coiled flow inverters—remain underexplored for gold recovery (Kaksonen et al., 2020).

Two-stage bioleaching (acidophilic base metal leaching followed by cyanogenic gold dissolution) proves effective for solid fractions but requires adaptation for liquid streams and integration with downstream refining (Magoda & Mekuto, 2022). Precise control of pH, Eh, and Au-ligand speciation is critical for efficiency and selectivity (Rizki et al., 2019; Natarajan & Ting, 2015). Future directions include multi-scale modeling (kinetics-CFD-microbes), online sensors, and AI/machine learning for optimization and failure minimization (Kaksonen et al., 2020). Fouling, clogging, and long-term biofilm stability remain key barriers.

3. Hybrid Green Technologies

Given e-waste complexity, future gold recovery lies in hybrid processes combining biohydrometallurgy with chemical, sorption, and electrometallurgical techniques. Gold bioleaching is most effective when followed by recovery using bioadsorbents, functional biomaterials (sulfur/amine-MOFs, electrospun fibers, hydrogels), or selective polymer/biomass adsorbents capable of reducing Au(III) to Au(0) (Saha et al., 2024). This enables "adsorption–reduction–reuse" circularity, where gold-laden adsorbents serve as catalysts or functional materials.

Biohydrometallurgy can integrate with benign chemical leaching (thiosulfate/thiourea), where microorganisms regenerate oxidants (Fe^{3+}) and control redox, reducing reagent consumption and enhancing ligand stability (Ray et al., 2022). Combining bioleaching/biosorption with electrochemical processes (electrowinning, bioelectrometallurgy) offers pure gold production. However, trade-offs exist: IL/DES, complex MOFs, and advanced adsorbents face cost, toxicity, and regeneration challenges; electrochemical units contend with energy demands, electrode fouling, and selectivity at low Au concentrations (Huy et al., 2023; Ray et al., 2022; Habibi et al., 2020). Future research must design bio-chemical-electro treatment trains holistically assessed through LCA/TEA.

4. Sustainability Assessment and Integrated Roadmap

Quantitative sustainability evidence for gold biohydrometallurgy remains limited. Most studies focus on laboratory efficiency, while LCA and TEA are rarely conducted or oversimplified (Magoda & Mekuto, 2022). Critical questions persist regarding net reductions in energy, emissions, and toxicity when accounting for culture media production, biological residue treatment, sorbent regeneration, and supporting chemicals.

TEA must evaluate decentralized small-to-medium units near e-waste sources versus centralized scales to assess logistical and infrastructure impacts (Habibi et al., 2020; Jadhao et al., 2022). Standardized performance indicators—energy and carbon footprint per gram Au, water consumption, effluent ecotoxicity, CAPEX/OPEX ratios, circularity metrics—are essential for comparing biohydrometallurgy with cyanidation, aqua regia, or pure sorption routes (Magoda & Mekuto, 2022).

Beyond techno-economics, research roadmaps must incorporate regulatory, safety, and social dimensions: public acceptance of microorganism use (including GMOs), residue disposal standards, and incentive policies for low-impact technologies (Kaksonen et al., 2020; Habibi et al., 2020; Jadhao et al., 2022). Without comprehensive evaluation frameworks, "green" claims risk remaining normative and unconvincing to regulators and industry.

Integrated research priorities include: (i) developing strains/consortia and biomaterials with high Au selectivity at ultra-low concentrations; (ii) engineering continuous multi-stage reactors for complex waste matrices; (iii) integrating bioleaching/biosorption with green leaching and electro/sorption recovery in circular treatment trains; and (iv) applying LCA/TEA and policy modeling to identify realistic implementation pathways (Kaksonen et al., 2020; Huy et al., 2023). This systemic approach can transform biohydrometallurgy from laboratory alternative to sustainable backbone of urban gold mining.

CONCLUSION

This review confirms that green biohydrometallurgy holds significant potential for recovering gold from electronic wastewater—a critical yet underutilized secondary resource in the circular economy. Bioleaching, biosorption, and bioreduction offer environmentally friendly alternatives to conventional methods, though challenges including slow kinetics, limited selectivity, and microbial sensitivity continue to hinder widespread adoption. Modified biomaterials and lignocellulosic matrices show promise in overcoming stability and process-control issues in complex wastewater environments. Hybrid approaches integrating biohydrometallurgy with green solvents (ionic liquids and deep eutectic solvents) and molecularly designed sorbents (covalent organic frameworks) are emerging as effective strategies to enhance recovery efficiency and selectivity. However, significant gaps remain in quantifying environmental and economic performance, as life cycle assessments and techno-economic analyses specific to gold recovery are still lacking. Future research must prioritize developing Au-selective biolixiviants and biosorbents, optimizing continuous hybrid treatment systems, and integrating comprehensive sustainability assessments to enable industrial-scale deployment of green biohydrometallurgy for urban mining.

REFERENCES

Abbas, Z., and Jung, S. M. (2024). "Green and selective recovery process of Mo, V, and Ni from spent hydrodesulfurization catalysts via novel ionic liquids and deep eutectic solvents technology," Separation and Purification Technology, 127450.

Adam, F., Piret, A., Canonne, M., Decock, R., and Nicolay, X. (2023). "Complete recycling of Printed Circuit Boards: From base metal bioleaching in a semi-continuous reactor with dual regulation to gold biosorption with brewer's yeast," Hydrometallurgy, 106190.

Adetunji, A. I., Oberholster, P., and Erasmus, M. (2023). "Bioleaching of Metals from E-Waste Using Microorganisms: A Review," Minerals, 13(6), 828.

Anastas, P. T., and Egbali, N. (2010). "Green Chemistry: Principles and Practice," Chemical Society Reviews, 39(1), 301–312.

Azizitorghabeh, A., Mahandra, H., Ramsay, J., and Ghahreman, A. (2022). "A sustainable approach for gold recovery from refractory source using novel BIOX-TC system," Journal of Industrial and Engineering Chemistry, 113, 320–330.

Baldé, C. P., Kuehr, R., Yamamoto, T., McDonald, R., D'Angelo, E., Althaf, S., Bel, G., Deubzer, O., Fernandez-Cubillo, E., Forti, V., Gray, V., Herat, S., Honda, S., Iattoni, G., Khetriwal, D. S., Luda di Cortemiglia, V., Lobuntsova, Y., Nnorom, I., Pralat, N., and Wagner, M. (2024). *Global E-waste Monitor 2024*. International Telecommunication Union (ITU) and United Nations Institute for Training and Research (UNITAR), Geneva/Bonn.

Baniasadi, M., Vakilchap, F., Bahaloo-Horeh, N., Mousavi, S., and Farnaud, S. (2019). "Advances in bioleaching as a sustainable method for metal recovery from e-waste: A review," Journal of Industrial and Engineering Chemistry, 76, 75–90.

Barbará, P. V., et al. (2025). "Recent Advances in the Use of Ionic Liquids and Deep Eutectic Solvents for Lignocellulosic Biorefineries and Biobased Chemical and Material Production," Chemical Reviews, 125, 5461–5583.

Budiarta, J., Sari, D. I. L., Betriani, R., Kunarti, E., and Roto, R. (2024). "A Novel Bio-adsorbent of CoFe2O4@SiO2 Core-Shell Nanoparticles Modified with Persimmon Tannin for Simultaneous Au(III) Ions Adsorption and Reduction," Materials Chemistry and Physics, 129419.

Bui, T., Lee, W., Jeon, S., Kim, K.-W., and Lee, Y. (2020). "Enhanced Gold(III) adsorption using glutaraldehyde-crosslinked chitosan beads: Effect of crosslinking degree on adsorption selectivity, capacity, and mechanism," Separation and Purification Technology, 248, 116989.

Chauhan, G., Jadhao, P., Pant, K., and Nigam, K. (2018). "Novel technologies and conventional processes for recovery of metals from waste electrical and electronic equipment: Challenges & opportunities – A review," Journal of Environmental Chemical Engineering, 6(1), 1288–1304.

Chen, Y., and Mu, T. (2021). "Revisiting greenness of ionic liquids and deep eutectic solvents," Green Chemical Engineering, 2(2), 115–122.

Chen, Y., and Yu, Z. (2023). "Low-melting mixture solvents: Extension of deep eutectic solvents and ionic liquids for broadening green solvents and green chemistry," Green Chemical Engineering, 4(4), 387–396.

Choudhary, B. C., Paul, D., Borse, A. U., and Garole, D. J. (2018). "Surface functionalized biomass for adsorption and recovery of gold from electronic scrap and refinery wastewater," Separation and Purification Technology, 195, 260–270.

Chowdhury, R., and Ghosh, S. (2018). "Sustainability of metal recovery from E-waste," Frontiers of Environmental Science & Engineering, 12(6), 1–12.

Dar, A., et al. (2025). "Sustainable Extraction of Critical Minerals from Waste Batteries: A Green Solvent Approach in Resource Recovery," Batteries, 11(2), 51.

Domańska, U., Wiśniewska, A., Dąbrowski, Z., Kolasa, D., Wróbel, K., and Lach, J. (2024). "Recovery of Metals from the 'Black Mass' of Waste Portable Li-Ion Batteries with Choline Chloride-Based Deep Eutectic Solvents and Bi-Functional Ionic Liquids by Solvent Extraction," Molecules, 29(13), 3142.

Dutta, D., et al. (2022). "A review on recovery processes of metals from E-waste: A green perspective," Science of the Total Environment, 859, 160391.

Ferreira-Filipe, D., Duarte, A., Hursthouse, A., Rocha-Santos, T., and Silva, A. (2025). "Biobased Strategies for E-Waste Metal Recovery: A Critical Overview of Recent Advances," Environments, 12(1), 26.

Fu, K., et al. (2024). "Utilizing cost-effective pyrocarbon for highly efficient gold retrieval from e-waste leachate," Nature Communications, 15, 6079.

Gao, X., Zhang, Y., and Zhao, Y. (2017). "Biosorption and reduction of Au (III) to gold nanoparticles by thiourea modified alginate," Carbohydrate Polymers, 159, 108–115.

Ghulam, S. T., and Abushammala, H. (2023). "Challenges and Opportunities in the Management of Electronic Waste and Its Impact on Human Health and Environment," Sustainability, 15(3), 1837.

Gomez, D. V., Whitworth, A., Vaughan, J., Sultana, U., Ledezma, P., and Parbhakar-Fox, A. (2024). "Review on Developments in Technologies for Critical Metal Recovery from Mining and Processing Wastes," Mineral Processing and Extractive Metallurgy Review, 46(5), 751–770.

Gouda, A., Merhi, N., Hmadeh, M., Cecchi, T., Santato, C., and Sain, M. (2025). "Sustainable Strategies for Converting Organic, Electronic, and Plastic Waste From Municipal Solid Waste Into Functional Materials," Global Challenges, 9(3), 2400240.

Gupta, S., Pant, K., and Corder, G. (2024). "A tandem approach for precipitant-free highly selective recovery of valuable metals from end-of-life lithium-ion batteries using a green deep eutectic solvent," Journal of Cleaner Production, 452, 142624.

Habibi, A., Kourdestani, S. S., and Hadadi, M. (2020). "Biohydrometallurgy as an environmentally friendly approach in metals recovery from electrical waste: A review," Waste Management & Research, 38(3), 232–244.

Haleem, A., et al. (2024). "A customized 3D bio-macroporous cryogels for efficient and selective gold extraction," Separation and Purification Technology, 337, 127305.

He, J., and Kappler, A. (2017). "Recovery of precious metals from waste streams," Microbial Biotechnology, 10(5), 1194–1198.

Hou, J., Gong, X.-S., Zhong, Y., Cheng, C., Liu, M., and Yang, Z. (2023). "Immobilization of tannin onto dialdehyde chitosan as a strategy for highly efficient and selective Au(III) adsorption," International Journal of Biological Macromolecules, 242, 123919.

Hubau, A., Minier, M., Chagnes, A., Joulian, C., Silvente, C., and Guézennec, A. (2020). "Recovery of metals in a double-stage continuous bioreactor for acidic bioleaching of printed circuit boards (PCBs)," Separation and Purification Technology, 238, 116481.

Huy, M., Nguyen, G. T., Thach, U. D., Lee, Y., and Bui, T. H. (2023). "Advances in hydrometallurgical approaches for gold recovery from E-waste: A comprehensive review and perspectives," Minerals Engineering, 191, 107977.

Jadhao, P. R., Ahmad, E., Pant, K., and Nigam, K. (2022). "Advancement in the Field of Electronic Waste Recycling: Critical Assessment of Chemical Route for Generation of Energy and Valuable Products Coupled with Metal Recovery," Separation and Purification Technology, 289, 120773.

James, G., Tran, D., Chaudhuri, H., Song, M.-H., and Yun, Y.-S. (2024). "Chitosan-thioglycolic acid composite cross-linked with glutaraldehyde for selective recovery of Au(III) ions from e-waste leachate via reduction-coupled adsorption and incineration," Chemosphere, 364, 143282.

Kaksonen, A., et al. (2020). "Prospective directions for biohydrometallurgy," Hydrometallurgy, 195, 105376.

Kara, T., Kremser, K., Wagland, S., and Coulon, F. (2023). "Bioleaching metal-bearing wastes and by-products for resource recovery: a review," Environmental Chemistry Letters, 21, 3329–3350.

Kudpeng, K., Bohu, T., Morris, C., Thiravetyan, P., and Kaksonen, A. (2020). "Bioleaching of Gold from Sulfidic Gold Ore Concentrate and Electronic Waste by Roseovarius tolerans and Roseovarius mucosus," Microorganisms, 8(11), 1783.

Kumar, A., Saini, H., Şengör, S., Sani, R., and Kumar, S. (2021). "Bioleaching of metals from waste printed circuit boards using bacterial isolates native to abandoned gold mine," BioMetals, 34, 1043–1058.

Kumar, S., et al. (2025). "Enhanced selective gold recovery from e-waste via synergistic hetero-atom controlled quasi-planar benzoxazine-based covalent organic frameworks," Materials Horizons, 12, 3456–3467.

Lin, G., et al. (2018). "Selective recovery of Au(III) from aqueous solutions using 2-aminothiazole functionalized corn bract as low-cost bioadsorbent," Journal of Cleaner Production, 196, 1078–1088.

Magoda, K., and Mekuto, L. (2022). "Biohydrometallurgical Recovery of Metals from Waste Electronic Equipment: Current Status and Proposed Process," Recycling, 7(5), 67.

Martin, M., García-Díaz, I., and López, F. (2023). "Properties and perspective of using deep eutectic solvents for hydrometallurgy metal recovery," Minerals Engineering, 203, 108306.

Natarajan, G., and Ting, Y. (2015). "Gold biorecovery from e-waste: An improved strategy through spent medium leaching with pH modification," Chemosphere, 136, 232–238.

Nithya, R., Sivasankari, C., and Thirunavukkarasu, A. (2020). "Electronic waste generation, regulation and metal recovery: a review," Environmental Chemistry Letters, 19, 1347–1368.

Poormoghadam, P., Bahar, S., and Naghdi, Y. (2025). "Recovery of Au(III) from electronic waste using solid phase extraction based on a magnetic nanobiocomposite, OCBs@Fe3O4@UiO-66-SH," Microchimica Acta, 192, 342.

Rai, V., Liu, D., Xia, D., Jayaraman, Y., and Gabriel, J. (2021). "Electrochemical Approaches for the Recovery of Metals from Electronic Waste: A Critical Review," Recycling, 6(3), 53.

Rana, S., Mishra, P., Wahid, Z., Thakur, S., Pant, D., and Singh, L. (2020). "Microbe-mediated sustainable bio-recovery of gold from low-grade precious solid waste: A microbiological overview," Journal of Environmental Sciences, 89, 47–64.

Ray, D., Baniasadi, M., Graves, J., Greenwood, A., and Farnaud, S. (2022). "Thiourea Leaching: An Update on a Sustainable Approach for Gold Recovery from E-waste," Journal of Sustainable Metallurgy, 8, 597–612.

Rizki, I. N., Tanaka, Y., and Okibe, N. (2019). "Thiourea bioleaching for gold recycling from e-waste," Waste Management, 84, 158–165.

Rocky, M. H., Rahman, I. M. M., Endo, M., and Hasegawa, H. (2024). "Comprehensive insights into aqua Regia-Based hybrid methods for efficient recovery of precious metals from secondary raw materials," Chemical Engineering Journal, 490, 153537.

Saha, S., Basu, H., Singh, S., and Singhal, R. K. (2024). "A biogenic hydrogel to recover Au(III) from electronic waste," Journal of Environmental Management, 363, 121384.

Sandwal, S. K., Jakhar, R., and Styszko, K. (2025). "E-Waste Challenges in India: Environmental and Human Health Impacts," Applied Sciences, 15(8), 4350.

Satriadi, T., Winarko, R., Chaerun, S., Minwal, W., and Mubarok, M. (2024). "Recycling of spent electric vehicle (EV) batteries through the biohydrometallurgy process," E3S Web of Conferences, 543, 2008.

Schwartz, E., He, H., Frost, K., Nguyen, B., Ogunseitan, O., and Schoenung, J. (2024). "Comparative life cycle assessment of copper and gold recovery from waste printed circuit boards: Pyrometallurgy, chemical leaching and bioleaching," Journal of Hazardous Materials, 473, 134545.

Sethurajan, M., et al. (2019). "Recent advances on hydrometallurgical recovery of critical and precious elements from end of life electronic wastes - a review," Critical Reviews in Environmental Science and Technology, 49(3), 212–275.

Sieber, A., et al. (2025). "Fundamentals of bio-based technologies for selective metal recovery from bio-leachates and liquid waste streams," Frontiers in Bioengineering and Biotechnology, 12, 1528992.

Smith, R., and Behdad, S. (2025). "From present to future: A review of e-waste recycling processes," Waste Management, 204, 114863.

Springthorpe, S., and Keitz, B. (2021). "Extraction of Au(III) by Microbially Reduced Metal-Organic Frameworks," Langmuir, 37(28), 8456–8466.

Srivastava, A., et al. (2025). "E-Waste Unplugged: Reviewing Impacts, Valorization Strategies and Regulatory Frontiers for Efficient E-Waste Management," Processes, 13(7), 2014.

Suffia, S., and Dutta, D. (2023). "Applications of deep eutectic solvents in metal recovery from E-wastes in a sustainable way," Journal of Molecular Liquids, 390, 123738.

Thakur, P., and Kumar, S. (2020). "Metallurgical processes unveil the unexplored 'sleeping mines' e-waste: a review," Environmental Science and Pollution Research, 27, 32359–32370.

Tran, N. T. T., Tran, D., Pham, T. P. T., and Yun, Y.-S. (2025). "Utilization of industrial by-products as nutrients for gold bioleaching from waste random access memory," Bioresource Technology, 418, 132938.

Wang, M., et al. (2023). "Integrated assessment of deep eutectic solvents questions solvometallurgy as a sustainable recycling approach for lithium-ion batteries," One Earth, 6(10), 1389–1401.

Xie, H., Li, J., and Zhang, Y. (2025). "Eco-friendly chitosan-based composite microspheres for efficient recovery of gold from electronic waste via adsorption-reduction cascade," Carbohydrate Polymers, 359, 123575.

Zhang, Y., et al. (2025). "An ionic liquid-modified PVC nanofiber facilitates gold recovery from wastewater by a light-enhancing effect," Chemical Engineering Journal, 505, 159419.

Zhao, L., et al. (2024). "Ultra-high adsorption capacity and selectivity of photo-enhanced sulfur-rich M2S3 (M Bi and Sb) for gold recovery from electronic wastewater," Journal of Water Process Engineering, 57, 104572.

Zhao, M., Huang, Z., Wang, S., Zhang, L., and Wang, C. (2020). "Experimental and DFT study on the selective adsorption mechanism of Au(III) using amidinothiourea-functionalized UiO-66-NH2," Microporous and Mesoporous Materials, 294, 109905.