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Review

Recycling of Printed Circuit Boards to Recover Critical Materials

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Abstract

The printed circuit board (PCB), a central component of most electronic devices, represents a significant fraction of the electronic product waste stream. The complex composition of PCBs, consisting of metals, polymers, and fiberglass, requires specialized recovery steps to reclaim valuable and critical materials and the safe disposal of brominated compounds. In this review paper, we describe the current state of critical material recovery and traditional recycling technologies and identify key obstacles to large-scale implementation. Metals present at high concentrations, such as copper, lead, and iron, are conventionally recovered from PCBs using hydrometallurgical, pyrometallurgical, or electrometallurgical processes. Hydrometallurgical methods achieve high selectivity through chemical leaching but pose significant challenges for effluent and reagent recovery. Pyrometallurgical methods facilitate rapid metal separation through smelting but require substantial energy and may release harmful gases. Electrometallurgical techniques produce high-purity metals but are constrained by pretreatment requirements and the consumption of energy. The non-metallic fraction of PCB waste is recycled using thermochemical conversion, microwave-aided heating, and direct recycling of epoxy–fiberglass composites, enabling material or energy recovery. The recovered polymer from direct recycling may have reduced mechanical strength and poor compatibility with new polymer matrices, and the resulting products from the thermal conversion suffer from incomplete conversion, degradation of quality, and residual contamination, as compared to synthetic polymers. Recent process developments have focused on extracting rare earth and supply-critical materials present at lower concentrations in the waste stream. The literature on existing and emerging approaches for recycling PCB wastes is reviewed to identify sustainable, economically viable, and environmentally responsible strategies for the recovery and reuse of critical materials from waste streams.

Keywords: printed circuit board; circular economy; resource recovery; sustainable recycling; critical materials recovery

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1. Introduction

Electronic devices are indispensable in modern society, supporting communication, healthcare, transportation, energy management, manufacturing, and daily domestic activities. At the core of most electronic systems is the PCB, which provides mechanical support and electrical interconnection for components and integrated circuits [1]. The architecture of PCBs has evolved from early transistor-mounted layouts to highly miniaturized multilayer boards with dense surface-mounted assemblies and fine interconnect features, improving performance but increasing material coupling and recycling difficulty. Modern

PCBs typically integrate copper-rich conductive networks with alloyed metals (e.g., Sn, Pb, Zn, Al, Fe, and Ni) and precious metals, embedded within thermally robust composite substrates composed of brominated epoxy resin, glass fibers, and ceramic fillers [2]. A widely used approximation is that waste printed circuit boards (WPCBs) consist of about 40 wt.% metals, 30 wt.% polymers, and 30 wt.% ceramics, illustrating the challenge in separating and extracting individual materials, as these phases are intimately bonded and fragmented during comminution [2,3].

The rapid turnover of electronic products has driven a steep rise in electronic waste (e-waste). Global e-waste generation reached 62 million tonnes in 2022, while only 22.3% was documented as formally collected and recycled, and the total is projected to reach about 82 million tonnes by 2030 under business-as-usual trends [4–6]. Improper disposal and informal handling of PCBs can lead to persistent environmental and health hazards, including toxic metal release into soil and water, and hazardous emissions from the uncontrolled thermal treatment of halogenated polymeric materials [1,7,8]. These pressures have intensified interest in resource-efficient recycling technologies that can recover valuable metals while minimizing secondary pollution and managing the large non-metal fraction that is frequently downcycled or discarded.

Prior studies have proposed distinct, selective routes for WPCB processing, but also show why a single method rarely achieves comprehensive recovery. Wang et al. [9] reviewed WPCB recycling, with an emphasis on preparing metallic fractions and reusing non-metal fractions, noting that non-metals constitute nearly 70 wt.% of WPCBs. Historically, the non-metal fraction has been combusted or landfilled, and hence, there is a need for reuse and conversion pathways to improve the overall circularity of the WPCB processing. Mir and Dhawan [10] organized PCB recycling as an integrated sequence from pretreatment and physical upgrading to downstream pyro- and hydrometallurgy, and emphasized that recovery performance is often constrained by liberation and partitioning established during preprocessing, rather than by leaching or smelting alone. Li et al. [11] analyzed hydrometallurgical recovery and highlighted that multi-metal selectivity typically requires staged leaching and downstream purification, thereby increasing process complexity and wastewater burden when many metals must be recovered from a single heterogeneous feed. Ji et al. [12] summarized PCB bioleaching and reported that microbial dissolution can proceed under mild solvent conditions. However, the leaching rates remain limited by slow kinetics and inhibition at higher pulp density, suggesting the need for hybrid concepts in which biogenic lixiviants are generated separately and applied to PCB solids to reduce toxicity constraints. Blumbergs et al. [13] evaluated the economics of mechanical pretreatment and showed that profitability is highly sensitive to disintegration and separation choices, because concentrate grade and mass yield govern the cost and feasibility of subsequent metallurgical recovery. Taken together, these findings indicate a clear need to review PCB recycling from a combined metal and non-metal perspective, including challenges, limitations, and emerging strategies, such as selective leaching, bioleaching, deep eutectic solvents (DESs), and ionic liquids (ILs)-assisted extraction within a staged, multi-step recycling workflow.

In this article, the current recycling processes for PCBs are critically reviewed, with an emphasis on both metallic and non-metallic components. We examine established and emerging pathways for selective recovery of valuable metal fractions and discuss their operational principles and limitations. Furthermore, recent advancements in bioleaching, selective hydrometallurgy, DES systems, and IL-based extraction are summarized to highlight progress toward improved selectivity and reduced environmental burden. By integrating insights from metal and non-metal recycling studies, this review aims to clarify

current technological gaps and outline directions for more sustainable and comprehensive WPCB management strategies.

2. PCBs Recycling Process

2.1. Metal Fraction Recycling

2.1.1. Pyrometallurgical Recycling

Pyrometallurgy is an established industrial route for recovering metals from WPCBs. It relies on high-temperature operations that generate reactive liquid phases, particularly slag during lead smelting and matte during copper smelting. These phases provide an effective medium for melting and dissolving electronic scrap and for facilitating the transfer of metals between coexisting phases [13]. In many commercial smelting systems, multiple liquid phases may coexist (e.g., slag, matte, metallic melt, and, in some configurations, molten salts). This multiphase environment enables valuable metals and undesirable impurities to partition selectively, allowing subsequent recovery of target elements while directing contaminants to discardable phases [14].

Conventional pyrometallurgical PCB recycling typically begins with the mechanical size reduction of the scrap, followed by separation to concentrate the metallic fraction and remove non-metallic components [15]. The resulting metal-rich concentrate is then subjected to oxidative smelting, during which controlled oxidation converts a portion of the feed and added reagents into oxides that report to the slag phase, while collectible metals concentrate into a metallic melt or matte, depending on the process configuration. In practical operation, reducing agents and fluxing oxides are introduced to adjust oxygen potential and slag chemistry, and water-based cooling is commonly employed for off-gas handling and thermal management. The principal outputs include a metal-bearing phase (matte/metallic melt) suitable for downstream refining, alongside by-products, such as flue gases (e.g., CO, NO_x, and SO_x), wastewater from gas cleaning, and solid residues, such as slag [16,17]. The crude product is subsequently cast (e.g., as ingots) and refined to separate individual metals and remove remaining impurities to meet product specifications [15]. Figure 1 illustrates the thermal-based recycling of metal recovery from PCB waste.

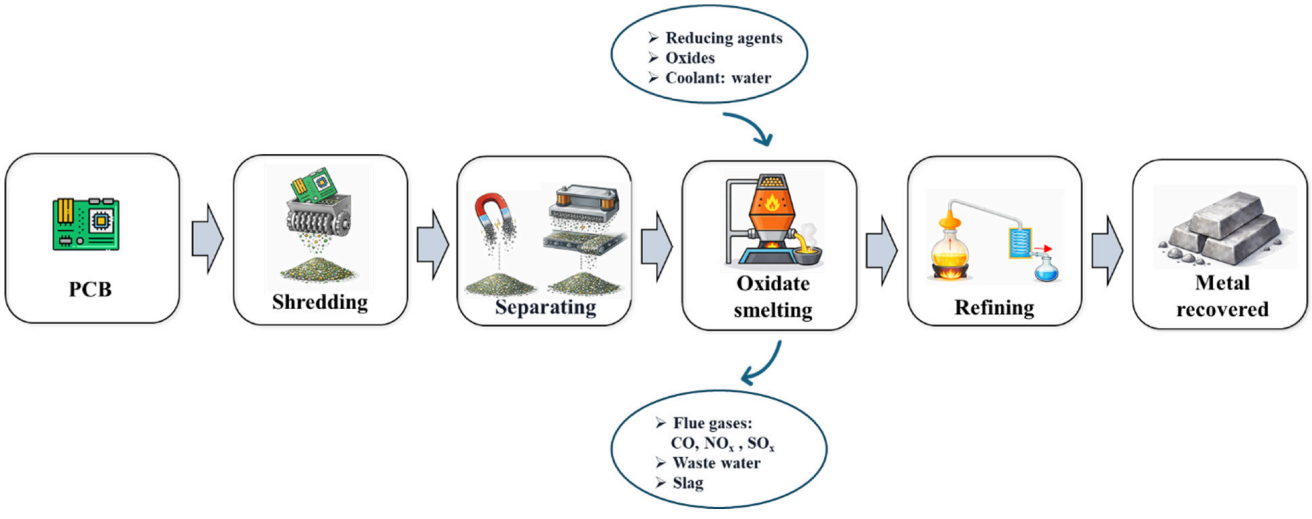

Figure 1. WPCBs recycling from the pyrometallurgical process.

Despite broad industrial adoption, pyrometallurgical recycling remains constrained by high energy demand and the generation of potentially hazardous emissions. Effective off-gas treatment is therefore essential to capture toxic species and particulates prior to atmospheric release, adding both operational complexity and cost [18].

2.1.2. Hydrometallurgical Recycling

Hydrometallurgical recycling is widely applied for recovering metals from PCBs, commonly through a leaching–solvent extraction route. In many cases, leaching is performed directly on metal-rich fractions, in which conductive components remain coated or encapsulated by resins and ceramic constituents, creating additional mass transfer and accessibility constraints [19]. Metal dissolution is typically achieved in acidic or alkaline media, using mineral acids such as nitric acid (HNO_3), hydrochloric acid (HCl), and sulfuric acid (H_2SO_4), as well as aqua regia, frequently reported for extracting metals from PCB-derived concentrates [19] Alternative lixiviants and complexing agents, such as cyanide, halide-based systems, thiosulfate, and thiourea, have also been investigated, particularly to improve the selective recovery of precious metals [20–23].

A conventional hydrometallurgical flowsheet generally begins with mechanical size reduction. WPCBs are crushed and subsequently milled (e.g., using a pulverizer) to further liberate metallic particles from the polymeric and ceramic matrix. The comminuted material is then upgraded by physical separations, such as magnetic and gravity-based methods, to obtain a metal-enriched concentrate suitable for downstream chemical processing [24]. This concentrate is leached to produce a metal-bearing pregnant leach solution. The leachate is then treated through solution purification and selective recovery steps, commonly including solvent extraction and ion-exchange operations [25]. In ion exchange, dissolved metal ions are selectively captured on functionalized resin surfaces through reversible exchange reactions, enabling separation from competing ions and impurities. The loaded resins are subsequently eluted using an appropriate stripping solution to produce a concentrated metal stream, after which the resin can be regenerated and reused. The overall sequence of crushing, concentration, leaching, solvent extraction, and electrowinning that defines the traditional hydrometallurgical approach is summarized in Figure 2.

Hydrometallurgy is particularly effective for copper recovery, but it can also extract a broader suite of metals, including Fe, Sn, Zn, Al, Ni, Pb, and others, depending on lixiviant selection, solution chemistry, and the downstream separation strategy [26]. Although the approach is often valued for its selectivity, high product purity, and comparatively lower energy demand than high-temperature routes, it also presents notable limitations. Reported challenges include long processing times, reagent hazards associated with strong acids and toxic elements, risks of heavy-metal contamination, generation of solid residues, and the production of large volumes of wastewater that require treatment prior to discharge or reuse [27].

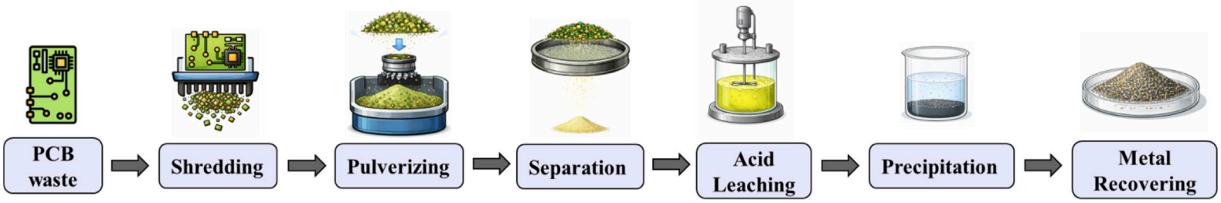

Figure 2. Hydrometallurgical process for metal recycling from WPCBs.

2.1.3. Electrometallurgical Recycling

Electrometallurgical recycling is commonly implemented as an integrated route that couples mechanical upgrading with hydrometallurgical leaching and electrochemical recovery, typically through electrowinning and/or electrorefining. This combined approach can produce high-purity metals (for example, copper purities approaching 99%) and may also enable the recovery of precious metals, such as Ag, Au, and Pd, either from the insoluble "anode slime" generated during refining or through selective electrodeposition under controlled operating conditions [28].

The process generally begins with mechanical pretreatment, including shredding and grinding, followed by physical separations, such as magnetic and electrostatic methods, to enrich the metallic fraction. Leaching becomes particularly effective once a sufficiently high metal concentrate is obtained, often reported to be in the range of 50–90% [28,29]. During leaching, metallic constituents are converted into soluble ionic species using appropriate lixiviants; commonly reported systems include H_2SO_4 with oxidants such as H_2O_2, as well as aqua regia for more aggressive dissolution of noble and base metals [29]. The resulting pregnant leach solution (PLS) is then directed to an electrochemical cell for metal recovery.

In electrorefining or electrowinning, dissolved metal ions are converted into solid products by applying a regulated electrical potential. Target ions migrate toward the cathode and are reduced to the metallic state, leading to deposition of high-purity metal on the cathode surface according to the general reaction ($M^{n+} + ne^- \rightarrow M^0$) [30–32]. In copper-focused systems, less readily soluble or less readily deposited species, including Au and Ag, do not follow copper into solution or do not electrodeposit under the same conditions. These species instead accumulate as an insoluble residue, commonly referred to as anode slime, which settles at the bottom of the cell and can be collected for subsequent precious-metal recovery. Where selective plating is pursued, electrode potential and electrolyte chemistry may be adjusted to favor the deposition of specific target metals [33]. The overall flow process of the electrometallurgical recycling is illustrated in Figure 3.

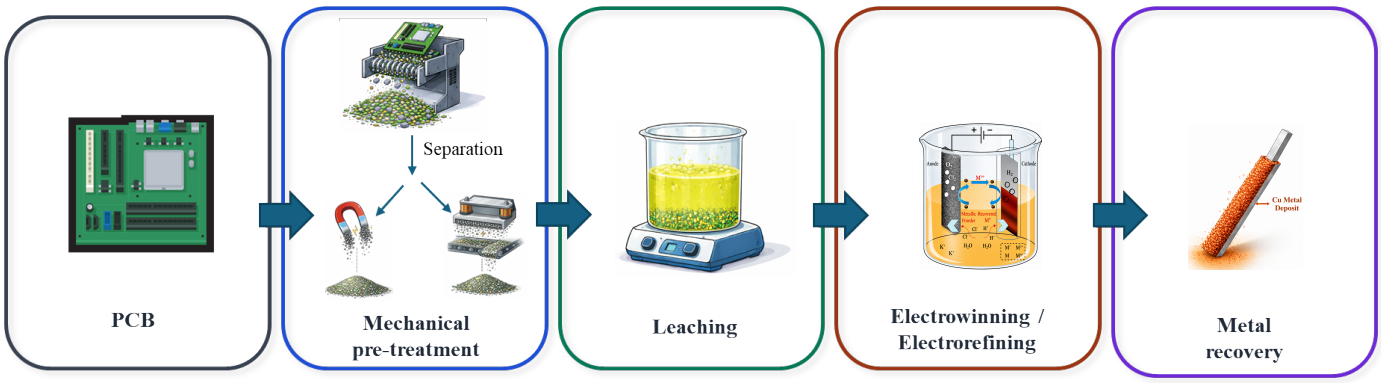

Figure 3. Electrometallurgical process for WPCB metal recycling.

A persistent challenge in electrometallurgical recycling of PCBs arises from the complex, multi-metal composition of the feed. Several metals present in PCB-derived solutions, including Cu, Sb, and Bi, can exhibit closely spaced reduction potentials under certain electrolyte conditions. This overlap complicates selective electrodeposition and increases the likelihood of co-deposition, thereby reducing product purity unless additional separation steps or tighter electrochemical control strategies are implemented [34].

2.1.4. Bio-Metallurgical Recycling

Bio-metallurgical recovery, commonly referred to as bioleaching, promotes the solubilization of metals through microbially mediated oxidation–reduction reactions. The process is most frequently associated with chemolithoautotrophic microorganisms, which derive energy from inorganic substrates such as ferrous iron (Fe^{2+}) and reduced sulfur species, while using CO_2 as the principal carbon source. In bioleaching systems, iron- and sulfur-oxidizing microorganisms play a central role in mobilizing metals from solid matrices. These organisms can oxidize Fe^{2+} to Fe^{3+}, thereby generating ferric iron as a strong oxidant capable of attacking metal-bearing phases [15]. In parallel, oxidation of elemental sulfur and reduced sulfur compounds produces leaching reagents, including sulfuric acid

and reactive sulfur oxidation intermediates, which together contribute substantially to metal dissolution and transport into the aqueous phase [35]. Although bioleaching is typically associated with sulfide materials, it has also been applied to metal recovery from non-sulfidic and low-iron sources, depending on the feed composition and microbial consortia [36].

From a flowsheet perspective shown in Figure 4, bioleaching parallels hydrometallurgical processing, with the key distinction that biological activity supplies the oxidative capacity and acidity required for leaching rather than relying solely on externally added chemical reagents. In PCB recycling applications, a sterilization step is often incorporated prior to inoculation to suppress competing or inhibitory microorganisms and to ensure that the intended strains or consortia dominate during leaching [37,38]. Relative to high-temperature smelting, bioleaching typically operates at a lower temperature and can reduce overall energy demand. However, it is frequently limited by slower kinetics compared with conventional hydrometallurgical leaching. In addition, the chemical complexity and potential toxicity of PCB-derived feeds, including flame retardants, diverse organic additives, and mixed-metal constituents, can inhibit microbial growth and activity. These effects may necessitate additional pretreatment, careful control of solution chemistry, and extended adaptation periods to establish stable and productive bioleaching performance [39–41].

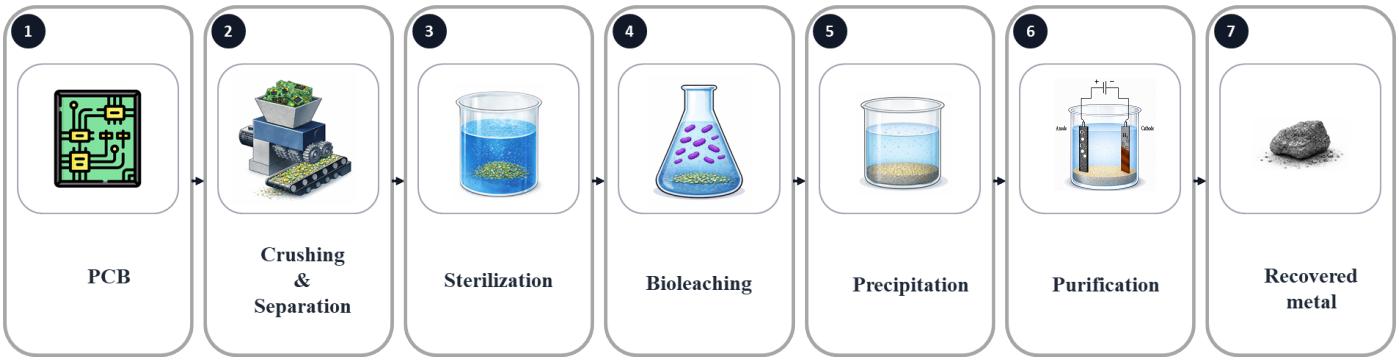

Figure 4. PCB metal recycling via a bio-metallurgical route.

2.2. Non-Metal Recycling

The non-metallic fraction of PCBs can be valorized through three primary pathways, as shown in Figure 5. The most widely implemented option is mechanical or physical recycling, in which non-metal constituents are separated using size and shape classification, along with magnetic and electrostatic separation. The recovered mixture, typically composed of thermosetting resins, glass fibers, ceramics, and other polymers, is often subjected to secondary processing such as air classification and grinding to obtain a more uniform filler material. These fillers have been reported as reinforcing additives in epoxy-based products, including adhesives, construction materials, and coatings [42,43]. Recovered polymers from these processes often suffer from reduced mechanical strength and poor compatibility with new matrices. To address these limitations, recent studies have explored coupling agents and optimized blending strategies to improve interfacial adhesion and dispersion. For example, in polypropylene (PP)-based composites, the silane coupling agent KH-550 (γ-aminopropyltriethoxysilane) was used to modify recycled non-metallic PCB fillers, resulting in improved tensile, flexural, and thermal properties [43]. Similarly, blending non-metallic PCB fractions with mixed waste plastics containing polypropylene, polyethylene, polycarbonate, and acrylonitrile–butadiene–styrene (ABS) enhanced fiber encapsulation and improved the mechanical performance of composite panels [44]. Non-metallic PCB powders have also been used in phenolic molding compounds as partial

substitutes for wood flour and lignocellulosic fillers (sawdust), improving impact resistance and heat deflection temperature, although filler loading and particle size require careful optimization to maintain processability [45–48]. Mechanical recycling is generally attractive due to its relatively low capital requirement and modest energy demand, and because it yields products that can be directed to multiple end-use applications with minimal chemical input.

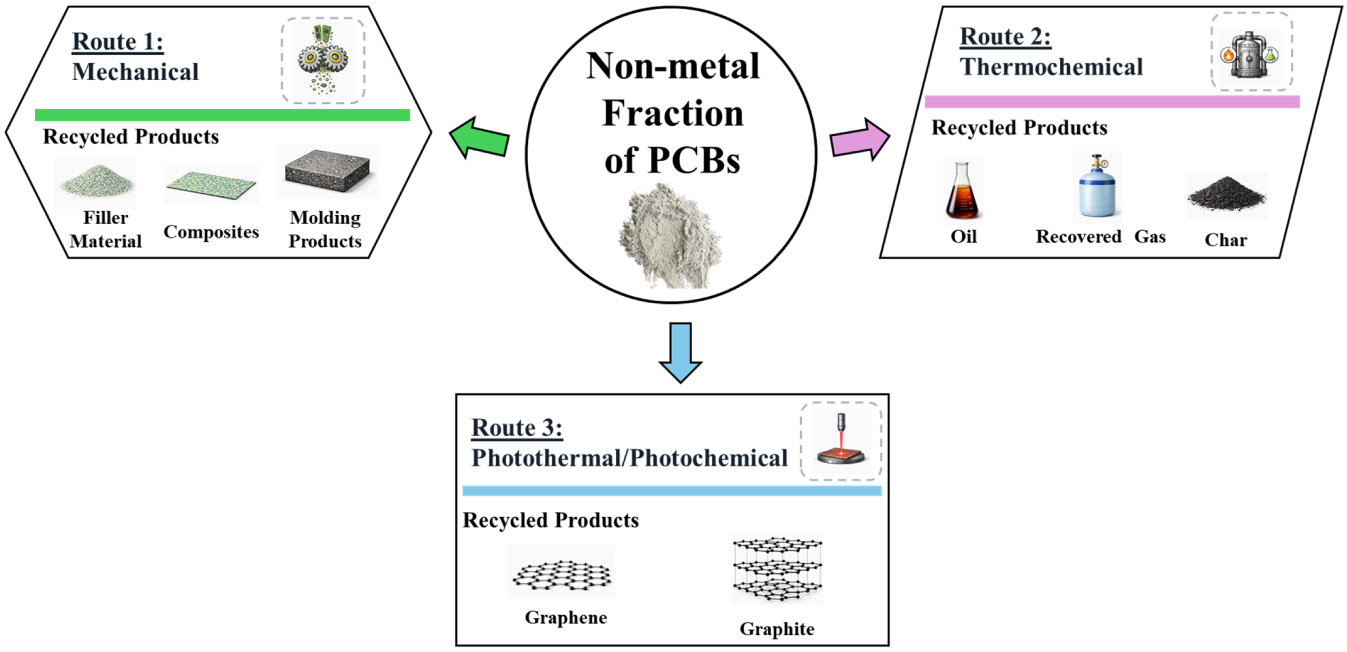

Figure 5. PCB metal recycling pathways for the non-metal fraction.

A second route involves chemical recycling through thermochemical conversion, where polymer-rich fractions are decomposed into smaller molecules or secondary products via processes such as pyrolysis, gasification, and torrefaction. In these systems, the separated polymers undergo thermal treatment under oxygen-free or oxygen-limited conditions to promote depolymerization and volatilization reactions [9]. In practice, the product distribution can be biased toward solid residues rather than liquid oil, despite oils often constituting a major fraction in the thermochemical decomposition of many polymers and lignocellulosic materials [49]. The resulting oil, char, and non-condensable gases may nevertheless be utilized as chemical feedstocks, solid fuels, or carbonaceous additives, and process energy sources, respectively, depending on their composition and required upgrading steps [50]. Recent research highlights multiple valorization pathways for glass fibers and ceramic-rich fractions, including physical separation, thermochemical processing, and material reuse. Thermochemical treatments, such as pyrolysis and thermolysis, enable the removal of the polymer matrix and recovery of glass fibers, although some degradation in mechanical properties is typically observed. Importantly, recovered glass fibers can be further valorized into high-value materials. For instance, demonstrated that glass fibers obtained from thermolysis and gasification of composite waste can be successfully converted into glass–ceramic materials for tile applications. F. López et al. [51] demonstrated that polyester fiberglass waste could be thermally treated at 550 °C to remove organics, producing a solid residue (~68 wt.%) rich in glass fibers, which was subsequently melted (≈1450 °C) and sintered (~1013 °C) to form wollastonite–plagioclase glass–ceramics suitable for architectural tiles. The resulting materials exhibited desirable properties, such as high hardness, low water absorption, and aesthetic similarity to natural stone, making them viable for wall

and floor applications. In addition, other studies have shown that NMF-derived materials can be used as fillers in polymer composites, as adsorbents, or as precursors for activated carbon and silica, further supporting the circular utilization of e-waste resources [52,53]. A key environmental and operational concern is the release of brominated species when brominated flame retardants decompose at elevated temperatures. For example, hydrogen bromide (HBr) and brominated organics, such as tetrabromobisphenol-A (TBBPA), can evolve during thermal processing, necessitating robust gas-cleaning and emission-control strategies [54].

More recently, emerging approaches have aimed to upcycle polymeric PCB residues into graphitic carbon materials. In a recent study, the epoxy-based polymer matrix was first separated from metallic components and then converted via laser scribing into graphitic structures, offering a potential route to synthetic graphite-like materials [55]. Related studies have also explored dispersing polymeric precursors in aqueous media and applying laser-based processing to generate graphene-like carbon for conductive inks, including graphene ink formulations [56]. Although these strategies remain relatively underreported compared with conventional mechanical and thermochemical routes, they highlight a promising direction for transforming polymer-rich PCB waste into higher-value carbon materials that are increasingly relevant to critical material supply chains.

3. The State of the Art in the Critical Materials Recovery Process from PCBs

3.1. Recent Advancements in Leaching

Recent studies on the selective leaching of metals from PCBs have increasingly targeted the substitution of conventional reagents, particularly aqua regia and cyanide, with lower-impact lixiviants, such as thiosulfate, thiourea, halide-based systems, and glycine. These alternatives are being pursued to improve separation selectivity while reducing the environmental and safety concerns associated with highly aggressive or toxic leaching media. A clear methodological shift is the adoption of sequential, two-stage leaching strategies. In typical implementations, dilute mineral acids or suitable complexing solutions are first applied to dissolve base metals (e.g., Cu, Pb, and Sn), followed by thiosulfate- or thiourea-based systems to target precious metals (Au, Ag, and Pd). This staged design is intended to limit interference from base–metal co-dissolution and to lower reagent demand during the precious-metal recovery step [57,58].

Within this broader framework, glycine-based leaching has drawn particular attention. Glycine can function as a selective complexant for copper under mild, near-ambient operating conditions and has also been incorporated into thiosulfate formulations for gold recovery. In such systems, Cu– or Co–glycine–thiosulfate media have been reported to achieve high Au extraction from pretreated PCB materials, with recoveries commonly exceeding ~90% under optimized conditions [59,60]. In parallel, recent work increasingly emphasizes process intensification through particle-size reduction, surface coating removal, and related pretreatment steps that improve leach accessibility and mass transfer. Integration with downstream recovery operations, including electro-recovery, cementation, and adsorption, is also frequently highlighted as a means to produce cleaner pregnant leach solutions and enhance overall flowsheet selectivity for WPCB recycling [61,62]. Table 1 summarizes recent advances in leaching-based approaches for metal recovery from PCB waste.

Table 1. Recent advancements in the selective leaching process for PCB recycling.

Year	Focus of Work	Lixiviant	Target Metals	Remarks	Ref.
2026	Two-stage leaching strategy for recovering base and precious metals from waste motherboard.	Sequential acid/lixiviant stages (optimized)	First stage (Cu, Pb), Second stage (Au, Ag, Pd)	Innovative two-stage hydrometallurgy process: >95% base metals (first stage), ~90% precious (second stage); parameters optimized via modeling/experiments.	[57]
2025	Nanoscale copper particle recovery through acid leaching and electrowinning.	Acidic leaching + nanoparticle processing	Cu	Controlled process yields selective nanoscale Cu (29,437.5 ppm) with 200 to 300 nm particle size from mobile-phone PCBs; focuses on leaching kinetics/selectivity.	[62]
2024	Au recovery from waste PCB by water-soluble organic leaching.	N-bromosuccinimide (NBS) and dimethylformamide (DMF) in water	Au	Mild WS-NBS–DMF for selective Au dissolution (94.9% efficiency); limited base metal attack, safe oxidant alternative.	[63]
2024	Sequential two stage metal recovery from waste motherboards.	Nitric acid and hydrochloric acid for first stage; thiourea and sodium thiosulfate for second stage	First stage (Cu, Pb, Sn), Second Stage (Au, Ag, Pd)	A sequential two-stage leaching route was achieved, where Cu dissolution was increased to 73.9% with HNO_3 (vs 28.7% with HCl), Sn leaching was maximized with HCl (71,584.5 µg/g), and in the second stage, Au recovery reached 6.02% with thiourea, while Pd recovery reached 30.10% with thiosulfate (Ag peaked at ~17.8%).	[58]
2023	Eco-friendly recovery of base and precious metals from WPCBs.	Glycine + H_2O_2 (for Cu leaching), glycine + $KMnO_4$ (for Au leaching)	Cu, Au	A sequential leaching process with kinetic modeling and LCA analysis was developed, where 99.96% and 96.17% recovery were achieved for Cu and Au, respectively.	[59]
2023	Gold leaching from pretreated WPCBs.	Co(II)–glycine–thiosulfate catalyst	Au	Novel Co–glycine catalyst enables efficient Au leaching (~98%) post-Cu removal; improves thiosulfate stability/selectivity.	[64]
2023	Selective leaching of base/precious metals from cellphone PCBs.	Thiourea–oxalate + inhibitors + acidic pretreatment	Au	Pretreatment removes >98% Cu, >80% Fe, Zn, and Ni; thiourea–oxalate leaches ~87% Au selectively at ambient temperature.	[61]
2021	Selective Cu leaching from pulverized WPCBs.	Alkaline glycine	Cu	92.8% Cu from ≤1 mm powder ambient; highly selective gas–liquid–solid mechanism.	[60]
2021	Selective Cu recovery from cellphone PCBs.	Citrate–phosphate system (1.0–1.2 M sodium citrate + 0.5 M ammonium phosphate + 0.2 M H_2O_2 additions, pH ≈ 4–4.5)	Cu	>30–40 g/L Cu leached with high selectivity; electrowinning gives >99% Cu and allows solution recycling	[65]
2022	Integrated glycine-based process for base and metal recovery.	Glycine at high solids (10–15%)	Cu, Au, Pd, Ag	Glycine-ammonia leaching was used to extract > 99% Cu, >80% Au, >90% Ag, and >85% Pd.	[66]
2020	Cu extraction from waste PCBs by glycine.	Glycine as Cu lixiviant (alkaline)	Cu	Glycine replaces traditional organic acids for Cu extraction; 94.8% leaching efficiency was achieved by adjusting the parametric study based on temperature, H_2O_2 volume fraction, Solid–liquid ratio, glycine concentration.	[67]
2019	Alkaline glycine leach for recovering base metals.	Glycine (alkaline)	Au, Ag, Zn, Pb, Cu	A two-stage (glycine and glycine–cyanide leaching) leaching system was utilized to recover 92.1%, 85.3%, 98.5%, 89.8%, and 99.1% for gold, silver, zinc, lead, and copper, respectively.	[68]

3.2. Recent Advancements in ILs for Metal Extraction from PCB Waste

IL approaches for WPCB metal recovery are increasingly designed around selective dissolution or extraction, coupled with efficient stripping and solvent reuse to enable closed-loop hydrometallurgical operation. Acid-functionalized IL acids, particularly hydrogen sulfate-based systems, have been reported to leach nearly 100% of Cu from waste PCBs and can outperform analogous sulfonate-based IL acids, indicating that IL acidity and anion chemistry can achieve base–metal dissolution efficiencies comparable to conventional mineral acids [69]. Acidic imidazolium ILs (e.g., [BMIM][HSO_4] and [HMIM][HSO_4]) can achieve ~100% Cu extraction and >90% Co extraction from mobile-phone PCB, while tailored phosphonium and task-specific ILs often transfer >90–99% of Cu, Ag, or Au from PCB leachates into an IL-rich phase with Au/base–metal separation factors exceeding 100 [70,71]. In optimized Cu-focused flowsheets, overall Cu recovery typically reaches 98–100% with product purity >99.9%, and many IL systems retain 90–95% of the initial extraction efficiency over multiple reuse cycles [72]. Table 2 depicts the recent advancements in the ionic leaching process.

Table 2. Recent advancements in the ionic leaching process for metal extraction from PCBs.

Year	Focus of Work	Ionic Liquid Type and Role	Target Metals	Remarks	Ref.
2025	Dual-function insoluble ILs for selective Au/Cu recovery from e-waste.	Hydrophobic imidazolium ionic liquid 1-carboxymethyl-3-dodecyl imidazolium bromide [C12C1COOHim]Br acting as dual-function phase	Au and Cu	Carboxyl-functionalized imidazolium ionic liquid enabled selective Au adsorption (≈96.7% recovery, >97% purity) from aqua regia leachate and selective Cu leaching (≈99.1%), demonstrating a single-material approach for targeted recovery of both metals from CPU-pin e-waste.	[70]
2024	Efficient and selective Au recovery from e-waste by imidazolium ionic liquid.	Imidazolium-based poly liquids (P(nDVB-mVBIMCl))	Au(III)	Imidazolium-based poly(ionic liquid) adsorbents enabled rapid and highly selective Au(III) recovery from strongly acidic CPU e-waste leachate, achieving 99.39% gold recovery (equilibrium ~15 min) with high uptake capacity (up to 820.5 mg/g) and stable reuse over at least 8 cycles.	[73]
2024	Ionic leaching of Cu, Co, Au, and Ag from WPCBs.	Didecyldimethylammonium propionate, didecylmethylammonium hydrogen sulfate, didecyldimethylammonium dihydrogen phosphate, and tetrabutylphosphonium dihydrogen phosphate	Cu, Ag, Al, Fe, Zn	Ionic-liquid extraction aided by trichloroisocyanuric acid achieved complete Ag recovery (100%) from thermally pretreated WPCB solids, while the best Cu extraction reached 68.9% using tetrabutylphosphonium chloride [P4,4,4,4][Cl] in a two-stage solid–liquid extraction.	[71]
2023	Hydrometallurgical process for Cu extraction with two task specific ionic liquid.	[Bmim]BF_4 and [Bmim]HSO_4	Au, Cu	[Bmim]BF_4 enables clean component/solder separation and [Bmim]HSO_4 leaches >99% Cu (with H_2O_2), followed by direct electrowinning to recover Cu at ~99% purity with recyclable ionic-liquid streams.	[74]
2018	Copper leaching from WPCBs using acidic Ionic leaching.	[BMIM][HSO_4]	Cu	Acid-functionalized ionic liquid [CM-MIM][HSO_4] with hydrogen peroxide achieved 98.31% Cu leaching from WPCBs under optimized conditions (80 °C, 2 h; solid/liquid 1:20), and the ionic liquid was recoverable by rotary evaporation at generally >97%.	[72]

3.3. Recent Advancements in DESs for Metal Extraction from WPCBs

DESs are liquid mixtures produced through mixing a hydrogen bond acceptor, typically a quaternary ammonium salt like choline chloride, with a hydrogen bond donor, such as organic acids, glycols, or urea, in a defined molar ratio, resulting in a homogeneous liquid with a melting point significantly lower than that of the element components. Their minimal volatility, adjustable acidity, and capacity to coordinate with metal ions give them promising substitutes for strong mineral acids in the hydrometallurgical extraction of metals from WPCBs [75]. DESs are employed in the recycling of PCBs as direct leaching media to dissolve base and/or precious metals from thermally treated or shredded boards, or as a component of hybrid schemes that include traditional separation processes like solvent extraction, precipitation, or electrowinning after DES leaching [75,76]. Choline chloride–organic acid DESs (for example, ChCl–oxalic acid, ChCl–glycolic acid, and ChCl–malonic acid), ChCl–ethylene glycol, and carboxylic acid-based DESs are all examples of common systems. In order to improve metal dissolution, various oxidants, such as hydrogen peroxide or copper chloride, are frequently coupled with these DESs [75].

In WPCB recycling, ChCl-based DESs have been utilized to dissolve metal oxides and metallic phases via a combination of proton-driven attack and complexation, facilitating the leaching of base metals (e.g., Cu, Zn, Pb, and Sn) from thermally or chemically pretreated boards under relatively mild conditions and without the use of concentrated strong acids [76,77]. Sequential DES methodologies, such as ChCl–glycolic acid followed by ChCl–oxalic acid, have been shown to fractionate metals in stages, achieving significant removals of Zn and Pb in the initial phase and facilitating the recovery of Cu as a high-purity oxalate product in the subsequent phase [77]. Additional specialized DES configurations have been reported, including DES-based emulsion liquid membranes for the treatment of WPCBs from mobile phones, which can achieve near-quantitative gold extraction following process optimization. This demonstrates that DESs can serve both as bulk leachants and as selective carriers in membrane separations [78].

Comparative studies assessing DESs in conjunction with ionic liquids demonstrate that the composition of DESs significantly influences selectivity (e.g., ChCl–malonic acid promotes Ag uptake, whereas ChCl–ethylene glycol enhances Cu extraction), although the overall metal loading and kinetics may be inferior to those attainable with specifically designed ionic liquids in certain cases [71]. Recent studies on acidic ChCl–carboxylic-acid DES (e.g., acetic, chloroacetic, and dichloroacetic acid donors) indicate the significant removal of hazardous metals, such as Pb, Zn, Cr, and Ni, establishing these systems as relatively benign alternatives for decontamination and base–metal recovery from waste printed circuit board-derived solids [79]. Furthermore, recent research has underscored the potential of DESs as a promising platform for selective and potentially recyclable WPCB hydrometallurgy by demonstrating that leaching efficiencies for targeted metals can be increased to over 90% by pairing DESs with appropriate oxidants and operating at moderate temperatures. In addition, solvent reuse is supported [76]. Current research based on DESs for PCB metal recycling is illustrated below (Table 3).

Table 3. Current research on metal extraction from PCBs using DES.

Year	Focus of Work	DES System/Solvent	Target Metals	Remarks	Ref.
2025	Acidic DESs for hazardous base metals recovery from WPCBs.	Choline chloride (ChCl)—acid DES (ChCl—acetic acid (AA), ChCl—chloroacetic acid (CAA), ChCl—dichloroacetic acid (DCA))	Pb, Cr, Zn, and Ni	Metal recovery increased with DES acidity (ChCl:DCA > ChCl:CAA > ChCl:AA); with an oxidant (H_2O_2) ChCl:DCA achieved 89.5% Pb, 55.2% Cr, 80.5% Zn, and 88.6% Ni at 50 °C for 3 h.	[79]
2025	Developed an emulsion membrane DES process to selectively recover the Au from WPCBs.	Chloride–ethylene glycol DES (ChCl: EG, 1:2 molar ratio)	Au	DES-based emulsion liquid membrane achieved near-quantitative gold separation from waste mobile-phone PCB leachate, reaching ~99.9% Au extraction under optimized conditions.	[78]
2025	Sustainable base metal leaching from WPCBs.	Carboxylic acid DES (ChCl–citric acid)	Cu, Al, Fe, Sn	DES selectively leaches >90% Cu at low T; green, selective over precious metals with solvent regeneration.	[80]
2024	Strategic metals recovery from WPCBs with DESs and IL.	ChCl + malonic acid; ChCl + ethylene glycol	Cu, Ag	DES achieves lower extraction efficiency (~15–20%) after two extraction stages, whereas ILs enable higher metal loadings and distribution.	[71]
2024	Ultra-fast metal extraction from PCBs using high-power ultrasound.	$CaCl_2{\cdot}6H_2O$: ethylene glycol DES + $CuCl_2$ (ultrasound-assisted)	Cu	High selectivity for Cu dissolution while less reactive metals (e.g., Au, Ni) remain largely on the substrate.	[81]
2024	Green DESs for metal recovery from thermally treated PCBs.	(FA-ChCl, urea-CHCl) DESs	Cu, Fe, Ni, Zn, Sn	FA–ChCl + H_2O_2 achieved >90% extraction of Cu/Fe/Ni under optimized conditions (reported Cu ~94–95% and Fe/Ni ~95% range), while urea–ChCl enabled selective Zn leaching at ~90.4 ± 2.9.	[76]
2023	Environmentally friendly metal recovery from PCBs using DESs.	ChCl-based DES (ChCl—ethylene glycol; ChCl—oxalic acid; ChCl—glycolic acid)	Sn, Zn, Cu	Two-stage choline chloride-based DES leaching flowsheet (ChCl–glycolic acid, then ChCl–oxalic acid) for calcined mixed-metal WPCBs powder, achieving 90.35% Zn and 87.47% Pb removal in stage 1 and recovering 74.93% Cu as $CuC_2O_4{\cdot}2H_2O$ with >98 wt.% purity in stage 2 (Sn recovery 51.29% via Fe-assisted precipitation).	[77]
2022	Extraction of metals from WPCBs using IL, DESs, and organophosphorous-based acid.	Choline chloride + lactic acid (1:2); choline chloride + malonic acid (1:1)	Cu, Ag	Low solid-phase extraction efficiencies, achieving only 15.8 wt.% Cu and 20.1 wt.% Ag after thermal pretreatment + DES, and 9.6 wt.% Cu and 14.2 wt.% Ag after thermal pretreatment alone.	[82]

3.4. Recent Advancements in Bioleaching Process for Metal Extraction from PCB Waste

Recent bio-based methods in WPCB recycling predominantly focus on comminuted or fragmented boards, employing acidophilic Fe/S-oxidizing consortia to regenerate ferric iron as the principal oxidant and heterotrophic fungi to produce organic acids, while distinct cyanogenic pathways are investigated for Au mobilization [83,84]. Current research is increasingly emphasizing the importance of pretreatment (e.g., size reduction and conditioning stages) to expose metal surfaces and mitigate toxicity prior to biological contact, as WPCBs contain brominated resins and multi-metal mixtures that can inhibit microbial activity [85]. The three predominant operating modes are: one-step contact, two-step operation (where microorganisms are cultivated initially before the introduction of WPCBs), and spent-medium tactics that utilize cell-free metabolites to prevent direct inhibition [85].

In terms of quantitative performance, the most effective strategies are two-step and process integration, particularly for Cu. A recent study that utilized new bacterial candidates for WPCB processing reported a maximum of 40% Cu recovery within three days (two-step, with cells), and up to 35% Au recovery within three days (spent medium). Additionally, the study demonstrated that metal release was enhanced by ball milling and ozonation pretreatments [85]. In addition, continuous or semi-continuous designs are being developed to enhance ferric–iron cycling, while separating microbial

growth from direct PCB exposure; a two-stage system that integrates a stirred-tank leaching reactor with a packed-bed bioreactor for Fe(II) re-oxidation has been shown to facilitate sustained ferric regeneration and enhance operational stability [83]. Mechanistic understanding is also advancing: a coupled kinetic model explicitly linking biological Fe(II) oxidation to chemical Cu dissolution by biogenic Fe(III) has shown strong agreement with experiments and clarified the relative rates of the biological and chemical steps [86]. Mechanistic knowledge is advancing: a coupled kinetic model that directly links biological Fe(II) oxidation to chemical Cu dissolution via biogenic Fe(III) has shown strong agreement with experimental results and confirmed the relative rates of the biological and chemical processes [86].

Cyanogenic routes for precious metals are often characterized as indirect gold mobilization through metabolite-generated complexes (complexolysis), with reported Au leaching efficiencies from WPCBs being limited to approximately 70% in optimal situations examined. Recent studies increasingly emphasize inhibition management. Progressive acclimation of an acidophilic Fe(II)-oxidizing consortium maintained Fe(II) oxidation under leachate conditions, corresponding to 6% (*w*/*v*) PCB, while sequential subculturing reduced the PCB-associated lag phase by as much as ~2.6times [87]. Table 4 depicts the recent advancement in the bioleaching process, with the type of bioleaching and target metals.

Table 4. Recent progress in metal extraction from PCBs using the bioleaching process.

Year	Focus of Work	Type of Bioleaching Used	Target Metals	Remarks	Ref.
2025	Stepwise bioleaching of Cu and Au from WPCBs.	*Bacillus thuringiensis*, *Macrococcus caseolyticus*, and *Cellulosimicrobium funkei*	Cu, Au	Demonstrates for the use of the three different strains for PCB bioleaching; best Cu extraction 40% via two-step bioleaching with *C. funkei* (cells present) and best Au dissolution 35% via spent-medium bioleaching with *B. thuringiensis*; explores ball milling and ozonation pretreatments to enhance metal release.	[85]
2024	Bioleaching of PCBs in a two-stage reactor system with an enhanced ferric iron regeneration system.	*Leptospirillum ferriphilum*	Al, Ca, Cr, CU, Mg, Ni, Pb, Sn, Zn	Two-stage operation regenerates Fe^{3+} in a packed column and uses the Fe^{3+}-rich solution in a stirred tank to leach PCBs, maintaining effective metal solubilisation up to ~18% (*w*/*v*) solids and outperforming a one-stage system for Cu extraction.	[83]
2024	Bioleaching of Au from WPCBs using cyanogenic bacteria.	*Chromobacterium violaceum*	Au	Cyanogenic–bacteria bioleaching solubilizes Au indirectly via metabolite-driven complexolysis, recovery from WPCB particles reaching at best ~70%.	[84]
2022	Bioleaching of copper from WPCBs.	*Aspergillus niger*	Cu	*Aspergillus niger*–mediated organic–acid bioleaching (citric and malic acids) enables about 100% copper extraction from PCB waste under optimized conditions (0.5% pulp density, 150-mesh, 30 °C, ~5 days).	[88]
2022	Bioleaching treatment for precious metals.	Acidophilic Fe oxidizers	Cu, Zn, Sn, Au	An acidophilic iron-oxidizing consortium was employed for leaching. High bioleaching efficiencies of 69% and 91% were observed for Cu and Zn, respectively; lower efficiencies were observed for Au (28%) and Sn (16%).	[89]
2021	Bioleaching of PCB waste using acidophilic iron-oxidizing culture.	*Leptospirillum ferriphilum*	Cu, Au	Progressive adaptation of an acidophilic Fe(II)-oxidizing consortium to PCB-containing media enabled sustained Fe(II) oxidation at leachate conditions equivalent to 6% (*w*/*v*) PCB, and sequential subculturing reduced the PCB-induced lag phase by up to ~2.6×.	[87]
2021	Kinetic analysis and mathematical modeling for bioleaching of WPCBs.	*Acidithiobacillus ferrooxidans*	Cu	Developed a kinetic model for Cu extraction from that links biological Fe(II) oxidation to chemical Cu dissolution by biogenerated Fe(III), showing similar with experiments ($R^2 > 0.97$) and showing Fe(II) bio-oxidation proceeds ~1.8–2.5× faster than the Fe(III)–Cu reaction.	[86]
2020	Selected metal recovery from WPCBs using fungs.	*Aspergillus niger*	Cu, Ag, Al	Using *Aspergillus niger* (2% *w*/*v* pulp density), the spent-medium bioleaching route delivered the highest metal mobilization, reaching approximately 20% Cu, 16% Al, and 2.2% Ag leached after 25 days.	[90]

3.5. Emerging Technologies for Rare and Critical Element Recovery (e.g., Nd, Ta, In, and Ga)

Recent work on critical dispersed metals in PCBs has concentrated more on substreams that contain Ta, Ga, and In (such as capacitors and LED modules). This is because these elements are found in specific components and may be upgraded at the component level before they are extracted. An AI-assisted sorting and "reverse leaching" strategy for tantalum achieved 98.2% Ta recovery under mild conditions and produced >99.8% Ta_2O_5. This shows that accurately identifying and separating Ta capacitors can lead to high-yield, high-purity critical-material production from PCB assemblies [91]. Complementary separation research has investigated the physical liberation of tantalum capacitors from WPCBs through molten salt or molten metal treatments, suggesting that disassembly and selective component extraction can serve as an effective preliminary step in tantalum recycling. However, encapsulation and solder/adhesive systems present challenges that must be resolved to facilitate reliable downstream refining [92]. On the contrary, gallium and indium are generally found in minimal concentrations in standard FR-4 WPCB; thus, current material on "PCB-based" Ga/In recovery incorporates design-for-recycling strategies that intentionally integrate Ga–In alloys into recoverable PCB conductor frameworks. The DissolvPCB method constructs printed circuit board assemblies (PCBA), utilizing a water-soluble polyvinyl alcohol (PVA) substrate and eutectic gallium–indium (EGaIn) conductors. Upon reaching end-of-life, immersion in water facilitates material separation and promotes reuse, achieving reported recovery rates of up to 99.4% for PVA and 98.6% for Ga–In metal, thereby quantitatively demonstrating closed-loop Ga/In reclamation in a PCB format [93].

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Table 5. Recent progress in REE recovery from PCBs.

Year	Focus of Work	Chemical/System	Target Metals	Remarks	Ref.
2025	Rare earth metals recovery from WPCBs using carboxylic acid-based DES.	Carboxylic acid	Sc	Up to ~82.6% Sc leaching under intensified conditions.	[80]
2025	Integrated leaching for REE recovery from PCB waste.	Oxalate precipitation followed by calcination	Nd, Dy, Sm, Gd, Tb, Ho	~92% REE precipitation; ~91% REO concentrate purity.	[97]
2022	REE recovery from PCBs using vacuum pyrolysis and electrostatic separation.	Multiple-stage electrostatic separation + vacuum pyrolysis (~550 °C, 10 mbar)	REE (distribution emphasized)	After separation and pyrolytic treatment, solid residue contained REEs at ppm levels, with Nd ≈ 38.72 ppm, Y ≈ 35.90 ppm, Ce ≈ 31.30 ppm, La ≈ 18.72 ppm, Sm ≈ 6.81 ppm, and Pr ≈ 5.43 ppm (with additional minor REEs such as Eu ≈ 2.84 ppm and Gd ≈ 4.22 ppm.	[96]
2022	Recovery of REEs from industrially pretreated WPCBs.	Size classification of industrially pretreated WPCBs	Y, La, Gd	Up to ~10^3 × enrichment in <0.25 mm fraction; fines can contain >60% of some REEs.	[94]

4. Mitigation of Brominated Emissions During PCB Recycling

The presence of brominated flame retardants (BFRs) in PCBs creates a major challenge during recycling, especially under thermal treatment, where hazardous species, such as hydrogen bromide (HBr), brominated phenols, and polybrominated dibenzo-p-dioxins and furans (PBDD/Fs), can form. Recent research shows that the formation and release of these brominated pollutants are strongly influenced by treatment temperature, oxygen availability, and bromine chemistry during decomposition [98–100]. Therefore, safe recycling of PCB materials requires a combination of pretreatment, in-process bromine fixation, and post-treatment emission control.

At the pretreatment stage, the main objective is to reduce brominated release before materials enter high-temperature treatment units. Mechanical separation and selective dismantling help lower the bromine load entering thermal systems, while solvent-based extraction and dissolution recycling offer direct routes for removing BFRs from polymer-rich fractions [101–103]. In particular, dissolution recycling of polystyrene-containing WEEE fractions has shown that undissolved flame retardants can be removed by >99 wt.% through filtration, while dissolved species can be reduced by 80–99 wt.%, using activated-carbon adsorption [101]. Solvent extraction studies on brominated plastics have also demonstrated that pretreatment can significantly reduce brominated content and limit later emissions during downstream thermal processing [102,103]. In addition, supercritical fluid technologies have emerged as promising debromination routes because their high diffusivity and tunable solvent properties enhance bond cleavage and bromine removal under controlled conditions [104,105].

During thermal recycling, in situ bromine fixation is essential to suppress hazardous emissions. Alkaline additives, such as CaO, $Ca(OH)_2$, and $CaCO_3$, have been widely reported to neutralize HBr and suppress the formation of brominated dioxins by converting bromine into stable inorganic salts [99,100]. Earlier studies on the thermal behavior of brominated plastics also showed that reactor temperature and process configuration strongly affect whether bromine is retained in solid residues or released into gas and oil fractions [106,107]. Transition metal oxides offer an additional control strategy. For example, Fe_2O_3 has been shown to capture bromine through dissociative adsorption and catalytic conversion, leading to about 90% reduction in HBr emission during decomposition of tetrabromobisphenol A-derived pyrolysates [108]. More recent pyrolysis studies further indicate that controlled thermal treatment can enable simultaneous debromination and

bromine recovery from WPCBs, thereby improving both environmental and economic performance [109].

Post-treatment technologies remain necessary because residual brominated compounds may still be present in flue gases after thermal conversion. Rapid quenching is commonly used to suppress the reformation of brominated dioxins, while adsorption-based systems, such as activated carbon injection and filtration units, are applied to capture brominated organic compounds and particulate-bound pollutants [98,100]. Reviews of brominated-plastic recycling also emphasize that integrated thermal–chemical systems, rather than single-unit operations, are more effective for minimizing toxic emissions while maintaining material recovery [105,110]. Till now, no single technology is sufficient on its own. Instead, environmentally sustainable PCB recycling requires an integrated strategy that combines pretreatment to lower bromine input, in-process additives or sorbents to immobilize bromine, and post-treatment systems to capture any remaining brominated emissions.

5. Challenges and Limitations of the PCB Recycling Process

Recycling WPCBs is challenging because they comprise a variety of materials, and the numerous methods used to recycle them (mechanical, pyrometallurgical, hydrometallurgical, and bio-metallurgical) can have different effects on the same multilayer feed. The integration of copper-rich metal networks with alloyed metals (Sn, Pb, Zn, Al, Fe, and Ni), precious metals, brominated epoxy resins, glass fibers, and ceramic inserts in typical PCBs results in a strong physical and chemical coupling between phases, which complicates the process of liberation and selective separation [11,111,112]. Effective recycling typically necessitates dismantling and depopulation, succeeded by comminution and pre-enrichment. However, high-energy size reduction produces fines that are challenging to separate, exacerbates dust generation, and may lead to the loss of precious and critical metals. Therefore, the overall economics are acutely sensitive to pretreatment decisions, including selective disintegration, grinding intensity, and the extent of manual or automated component removal [113,114].

Pyrometallurgical processing can handle substantial throughputs and attain effective recovery of copper and related precious metals; however, it remains highly energy-consuming and may produce hazardous off-gases (including halogenated organics) unless sophisticated gas cleaning is employed. Additionally, brominated polymers are predominantly destroyed rather than valorized, and various non-target metals segregate into slags or flue dusts, necessitating further management [11,111]. The selectivity of hydrometallurgical routes can be enhanced; however, the production of large volumes of contaminated effluents by strong acids/oxidants, and the cost of chemically complex multi-step leaching–separation flowsheets when attempting the simultaneous recovery of multiple metal groups, are both significant challenges. Recent “gentle” or gradient concepts have been developed to address selectivity and chemical intensity; however, scaling such integrated schemes remains non-trivial under realistic feed variability [11,112].

IL- and DES-based processes have demonstrated high selectivity and promising extraction performance for metals from PCBs; however, several limitations constrain their practical application. Many ionic liquids remain costly due to complex synthesis and purification requirements, while DES, although comparatively less expensive, still requires careful control of composition and regeneration [115,116]. In addition, ILs are not inherently benign, as some exhibit toxicity, persistence, and limited biodegradability, whereas the environmental profile of DESs depends strongly on the nature of the hydrogen-bond donor and acceptor [2,3]. High viscosity is another critical limitation, as it restricts mass transfer and slows reaction kinetics, particularly at higher solid loadings relevant to PCB processing [115,117]. Although solvent reuse has been reported, challenges such

as metal accumulation, contamination, and declining efficiency over repeated cycles remain [71,117]. Furthermore, most studies are still limited to laboratory-scale systems, and issues related to continuous processing, long-term solvent stability, and techno-economic feasibility hinder industrial-scale implementation [71].

Bio-metallurgical methods provide milder operating conditions; however, they are generally slower than chemical leaching and are severely restricted by pulp density and PCB toxicity (e.g., inhibition of iron oxidation and microbial activity). This necessitates precise control of pH/redox and nutrient supply, which has restricted industrial uptake to date [12,87].

Unlike base metals, such as copper (Cu: ~20–40 wt.%), iron (Fe: ~5–10 wt.%), zinc (Zn: ~5–30 wt.%), and aluminum (Al: ~1–6 wt.%), which occur at weight-percent levels in WPCBs, REEs are present at trace concentrations. Typical bulk concentrations of REEs, such as yttrium (Y), lanthanum (La), and neodymium (Nd), are generally in the range of ~1–100 ppm (0.0001–0.01 wt.%) [94,95]. However, mechanical pretreatment and size fractionation can significantly enrich REEs in finer particles (<0.5 mm), where concentrations may increase to ~100–4000 ppm (0.01–0.4 wt.%), with specific elements such as La reaching >2000 ppm and Nd exceeding 4000 ppm in certain fractions, which makes their recovery technically feasible but economically more challenging [94].

Moreover, informal recycling methods, including open burning, basic acid leaching, and manual sorting, prevail in numerous areas, resulting in significant occupational and environmental hazards, while resin-rich residues and toxic metals remain inadequately managed. Even within formal systems, an ongoing constraint is the restricted access to high-value markets for brominated epoxy and glass–fiber fractions, which are often downcycled or discarded, thereby compromising circularity [111,113,118]. Finally, process systems and techno-economic analyses highlight that much of the literature predominantly concentrates on the recovery of a single metal group (usually Cu or precious metals), while overlooking the comprehensive, sequential recovery of base, precious, and critical metals [112,119]. Table 6 illustrates the comparison of metal recycling routes from PCBs.

Table 6. Comparison of PCB metal recycling routes.

Method	Typical Efficiency	Associated Cost	Environmental Impact	Scalability	Remarks	Ref.
Pyrometallurgy	High for Cu, Au, Ag; typically ~85–98% for valuable metals	High capital and energy demand	High emissions (CO_2, dioxins, furans); requires advanced off-gas treatment	High; industrially established	Effective for large mixed streams, but poor polymer recovery and high emissions	[10,120,121]
Hydrometallurgy	High; often up to ~90–95% for targeted metals under optimized conditions	Moderate to high; depends on reagents and separation steps	Lower than pyrometallurgy but generates acidic and metal-bearing effluents	Moderate to high; pilot to industrial scale	High selectivity and purity, but chemical consumption and wastewater are concerns	[121,122]
Bioleaching	~30–90% for base metals (e.g., Cu); lower for precious metals	Low reagent cost; long residence time increases operating cost	Low emissions; mild operating conditions	Low to moderate; limited industrial implementation	Environmentally attractive, but slow kinetics and pulp density limitations	[121,123,124]
IL	Moderate to high; high selectivity for Cu, Au in lab studies	High solvent cost and recovery complexity	Low volatility; reduced emissions compared to mineral acids	Low to moderate; mostly lab-scale	Tunable and selective, but high viscosity and recycling challenges	[71,121,125]
DES	Moderate to high; metal recovery depends on composition and oxidant use	Lower than ILs but sometimes higher than conventional acids	Favorable; low volatility and reduced corrosivity	Low to moderate; emerging technology	Promising green alternative, but performance depends on system design	[71,116,117,121]

6. Conclusions

The traditional recycling of WPCBs remains constrained by the intrinsic complexity of PCB assemblies and by the selectivity limits of individual processing routes. Metal-focused pathways can recover Cu and precious metals efficiently, yet they often rely on energy-intensive pretreatment and generate secondary residues, such as slags, dusts, and contaminated solutions, with additional requirements for emissions and effluent control. These routes are typically optimized for a narrow set of targets, so co-occurring base and critical metals may be partially lost to residues or require extra purification stages that increase chemical demand, operational complexity, and cost. In parallel, the non-metal fraction constitutes a major portion of PCB mass, but thermoset epoxy, brominated additives, glass fibers, and ceramic fillers remain difficult to separate and upgrade; as a result, much of this material is still downcycled or disposed of, limiting circularity and weakening the overall environmental value proposition of recycling.

Given these constraints, no single mechanical, pyrometallurgical, hydrometallurgical, or bio-metallurgical method is sufficient to recover the full spectrum of PCB metals and non-metals with high yield, high purity, and low environmental burden. Future strategies should therefore be designed as integrated, multi-step systems that stage selectivity across unit operations: physical depopulation and pre-enrichment to create higher-grade micro-streams, sequential metal recovery to separate base, precious, and critical metals, and parallel valorization routes that convert non-metal fractions into value-added products rather than landfill-bound residues. In this context, techno-economic analysis and life-cycle assessment are essential to quantify trade-offs among recovery, purity, energy use, emissions, and waste generation, and to identify process configurations that remain viable under realistic feed variability. Ultimately, simultaneous recovery and upgrading of both metallic and non-metallic fractions is central to improving resource efficiency, reducing disposal burdens, and advancing a sustainable circular economy for PCB-derived materials.

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