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ELECTRONIC WASTE AND SEMICONDUCTOR-RELATED RESIDUES AS SECONDARY SOURCES OF GALLIUM: OCCURRENCE, PROCESSING ROUTES, SEPARATION CHALLENGES, AND CIRCULAR SUPPLY PERSPECTIVES

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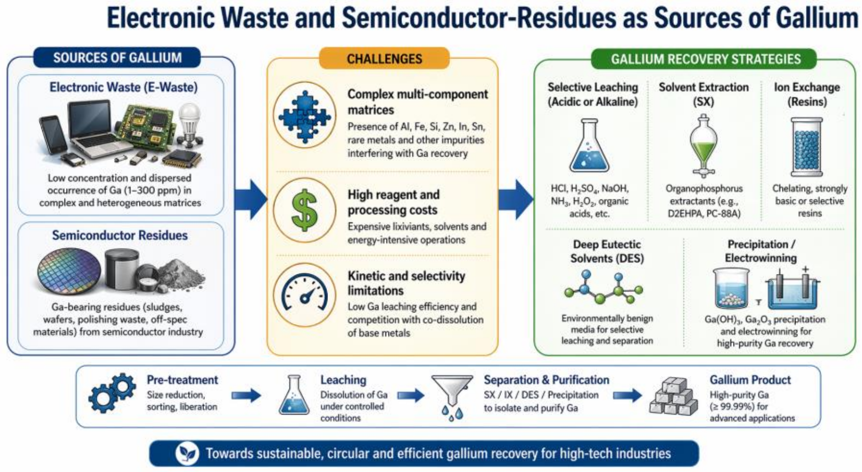
Abstract

Gallium is essential to GaAs- and GaN-based semiconductors used in LEDs, 5G devices, power electronics, and advanced photovoltaics, yet its primary supply remains structurally constrained because it is obtained mainly as a by-product of aluminum and zinc production. This critical review examines electronic waste, semiconductor-related residues, and selected industrial by-products as secondary gallium sources, with emphasis on concentration ranges, phase occurrence, leaching behavior, separation selectivity, and process integration. The review compares LED waste, GaAs/GaN scraps, CIGS photovoltaic waste, Bayer-related liquors, coal fly ash, zinc residues, and specialized process wastes. Hydrometallurgy remains the dominant route, but the key challenge is usually not dissolution itself; it is the selective separation of gallium from aluminum, iron, zinc, vanadium, and matrix-dependent impurities. The article identifies the strongest recovery opportunities in concentrated semiconductor and process wastes, while mixed e-waste remains limited by dilution, heterogeneity, and preprocessing costs. Emerging routes based on ionic liquids, membranes, biodismantling, and bioleaching improve selectivity in laboratory studies, but their scalability remains limited. The main research gaps are incomplete flowsheet integration, scarce techno-economic validation, and limited industrial evidence.

Keywords: Gallium; electronic waste; semiconductor residues; LEDs; GaAs; GaN; CIGS; hydrometallurgy; selective separation; circular supply chains.

Graphical Abstract



1. Introduction

Gallium is a critical metal for compound semiconductors such as GaAs and GaN, which support LEDs, radio-frequency components, optoelectronics, and power electronics. The strategic problem is that gallium is not mined through a dedicated primary route. Most supply still depends on indirect recovery from aluminum and zinc value chains, which makes availability sensitive to the economics and geography of those host industries rather than to gallium demand itself (Robla et al., 2024; Sverdrup & Haraldsson, 2025; Zuo et al., 2025; Bukauskaite et al., 2024; Jia et al., 2022).

This structural dependence explains why secondary sources are increasingly important. Electronic waste, LED waste, GaAs and GaN scrap, CIGS photovoltaic waste, Bayer liquors, coal by-products, zinc residues, and other industrial process streams are now discussed as relevant secondary reservoirs of gallium. However, the attractiveness of these sources varies widely because gallium may occur at trace levels, in encapsulated phases, or in chemically difficult matrices that impose strong separation penalties (Kluczka, 2024; Huang et al., 2024a; Teng et al., 2024; Zheng et al., 2023; Pereira, 2026; Patel, 2025).

The objective of this review is to compare the occurrence, recoverability, and processability of gallium in electronic waste and semiconductor-related residues, with emphasis on real process constraints rather than on nominal recovery values alone. The review focuses on source quality, liberation behavior, leaching chemistry, separation bottlenecks, industrial

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relevance, and circular supply implications. The central argument is that the future of gallium recycling will depend less on isolated laboratory extraction efficiencies and more on the selective integration of processes under realistic feed compositions, impurity loads, and economic conditions (Evans et al., 2023; Luo et al., 2025a; Ravilla et al., 2024).

2. Methodology

This critical review was conducted using a structured literature survey based on the PRISMA 2020 framework, adapted for comparative analysis rather than strict meta-analysis.

The search was performed in Scopus and Web of Science using combinations of the following keywords:

("gallium recovery" OR "gallium recycling" OR "Ga extraction") AND

("e-waste" OR "LED waste" OR "GaAs" OR "GaN" OR "CIGS" OR "Bayer liquor" OR "industrial residues").

The search covered the period from January 2020 to March 2026.

The selection process followed four steps:

(i) identification of 233 records,
(ii) removal of duplicates,
(iii) screening based on title and abstract,
(iv) eligibility assessment based on full-text review.

Inclusion criteria:

- experimental studies with defined operating conditions
- reported gallium concentration, recovery, or separation metrics
- studies addressing real or representative feed matrices

Exclusion criteria:

- purely theoretical studies
- studies without quantitative experimental data
- studies focused on unrelated metals or processes

The final dataset comprised 89 references for comparative analysis.

To improve critical consistency, the reviewed studies were qualitatively classified into:

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- synthetic solution studies
- real leach liquor studies
- integrated process studies
- pilot or industrial evidence

This classification was used to interpret recovery performance and assess technological maturity.

This article is a critical review built from a targeted survey of the 2020-2026 literature. The literature selection process is summarized in Figure 1, which outlines the identification, screening, eligibility, and inclusion stages applied in this critical review.

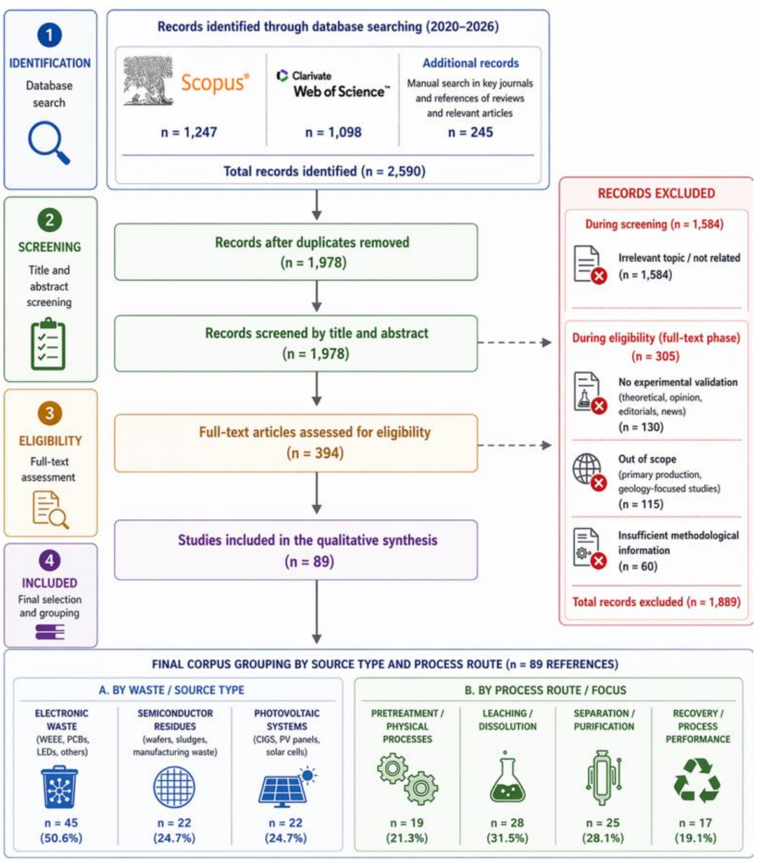

Figure 1. PRISMA-based workflow for literature selection used in this critical review. The figure should summarize database screening, eligibility criteria, exclusion logic, and final source grouping by waste type and process route. Adapted from Page et al. (2021).

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The workflow shows the reduction from a broad dataset of gallium-related studies to a focused set of 89 experimentally grounded references. This filtering ensures consistency in the comparative analysis of sources, processing routes, and recovery performance presented in this review.

3. Gallium occurrence in electronic waste and semiconductor-related residues

Mixed electronic waste is generally not an ideal feedstock for gallium recovery due to its low concentration, high heterogeneity, and complex material composition. Characterization studies on LED lamps and broader electronic waste streams show that the real challenge is not only low concentration, but also material complexity, encapsulation, and cross-contamination with plastics, glass, solders, and other metals (Evans et al., 2023; Cenci et al., 2022; Rebello et al., 2020; Annoni et al., 2020; Nikulski et al., 2021; Hadj, 2025).

This issue becomes critical when comparing different secondary sources. However, before comparing these sources, it is necessary to consider the nature of the evidence supporting the reported data.

To improve the robustness and interpretability of the comparative analysis, it is necessary to explicitly distinguish between different levels of experimental evidence reported in the literature. Gallium recovery studies vary widely in system complexity. They range from controlled synthetic solutions to real industrial liquors and integrated process demonstrations. These differences directly affect the reliability and transferability of reported performance metrics.

In particular, results obtained in simplified synthetic systems often overestimate separation efficiency and selectivity because they do not capture the high impurity loads, competing reactions, and operational variability typical of real-world process environments. Conversely, studies based on real leach liquors, integrated flowsheets, or pilot-scale operation provide more realistic indicators of process viability, although such studies remain relatively scarce.

To account for this heterogeneity, the reviewed literature was qualitatively classified by experimental system type and level of process integration, as summarized in Table 1. This

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framework provides a structured basis for interpreting reported gallium occurrence and recovery performance, preventing misleading comparisons between fundamentally different levels of experimental evidence.

Table 1. An evidence classification framework is used to interpret reported gallium occurrence and recovery potential across different secondary sources. The framework developed in this study distinguishes among different levels of experimental evidence and process realism.

Evidence Type	Description	Reliability
Synthetic solution	Controlled lab system	Low
Real leach liquor	Industrial-like conditions	Medium
Integrated flowsheet	Multi-stage process	High
Pilot/industrial	Continuous operation	Very high

The classification presented in Table 1 highlights a key limitation in the current literature: a large proportion of reported recovery efficiencies and selectivity values are derived from synthetic or simplified systems. While these studies are essential for understanding fundamental mechanisms, they often fail to capture the complexity of real feeds, in which high impurity loads, competing reactions, and process instability can significantly affect performance.

As a result, direct comparison of recovery values across studies without considering the level of evidence can lead to misleading conclusions regarding process feasibility. For example, separation efficiencies reported above 90% in controlled systems may decrease substantially when applied to real leach liquors containing high concentrations of aluminum, iron, zinc, or other competing species.

In contrast, studies based on real liquors, integrated flowsheets, or pilot-scale operation provide more reliable indicators of industrial viability, even when reported recovery values are lower. These studies better reflect operational constraints such as impurity tolerance, reagent consumption, process stability, and compatibility with industrial conditions.

Therefore, throughout this review, performance metrics are interpreted in the context of the underlying evidence type. This approach allows a more realistic assessment of gallium recovery technologies and helps bridge the gap between laboratory-scale results and industrial implementation.

LED waste is preferable to mixed e-waste because gallium is concentrated in semiconductor chips and their associated functional layers. Still, composition is highly product-

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dependent. End-of-life LEDs may contain Ga in GaN- or GaAs-related phases, often alongside In, Ag, As, rare-earth elements, glass, polymers, and metallic contacts. This makes LED waste a better secondary source than undifferentiated WEEE, but still a complex one from the standpoint of dismantling, liberation, and selective chemistry (Chen et al., 2020b; Maarefvand et al., 2020; De Oliveira et al., 2021; Mir et al., 2022; Illés & Kekesi, 2023a; Illés & Kekesi, 2023b; Yang et al., 2023).

Semiconductor-related residues are usually more attractive than consumer e-waste because gallium is present in more concentrated and less compositionally diffuse forms. These streams include etching solutions, process sludges, wafer offcuts, polishing residues, GaAs production scrap, GaN-bearing residues, and chamber wastes from semiconductor or LED manufacturing. In such cases, gallium concentrations may rise from sub-0.1% levels to the percent level, which substantially changes the recovery logic and can justify specialized flowsheets (Chen et al., 2020a; Huang et al., 2025; Liu et al., 2024a; Zhan et al., 2020a; Swain et al., 2021).

CIGS photovoltaic waste is a distinct category because gallium is concentrated in a functional absorber layer together with indium, selenium, and copper. This makes CIGS residues more valuable than most mixed electronic wastes, but separation is not straightforward because the target metals are chemically coupled in layered and multi-material systems. The literature consistently shows that CIGS waste must be understood as an integrated delamination-plus-separation problem rather than as a simple leaching feed (Hu et al., 2022; Li et al., 2022; Li et al., 2023a; Theocharis et al., 2021; Liu et al., 2022; Huang et al., 2024b).

Other secondary sources, although outside classical WEEE, are important because they reveal where industrially realistic gallium recovery may first scale. These include Bayer-related streams, coal fly ash, coal waste, zinc slags, yellow phosphorus flue dust, NdFeB-related residues, steelmaking residues, and other metallurgical process streams. Their relevance is high because some of them are already generated in large volumes and may contain gallium in chemically accessible forms, even if selectivity remains difficult (Flerus & Friedrich, 2020; Ji et

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al., 2020; Hartzell & Moats, 2023; Rudnik, 2024; Zhao et al., 2021; Qin et al., 2025; Qi et al., 2025; Pan et al., 2025).

To enable direct comparison across different secondary sources, Table 2 summarizes typical gallium concentrations, matrix characteristics, and implications for recovery.

Table 2. Comparative gallium occurrence in representative secondary sources, including indicative concentration ranges, matrix complexity, co-existing elements, and implications for recovery. Values represent typical ranges reported in the literature and are intended for comparative analysis rather than exact compositions. Adapted from Evans et al. (2023), Kluczka (2024), Teng et al. (2024), Zheng et al. (2023), Huang et al. (2024a), and Theocharis et al. (2021)

Source	Typical Ga Concentration	Matrix Complexity	Dominant Co-elements	Recovery Attractiveness
Mixed e-waste (WEEE, PCBs)	<10–50 ppm	Very high (polymers, metals, ceramics)	Cu, Sn, Pb, Fe, plastics	Very low (diluted, heterogeneous)
LED waste	50–500 ppm (local ↑)	High (encapsulation, multi-material)	In, Ag, REEs, As	Low–medium (needs dismantling)
GaAs / GaN scrap	30–70 wt.%	Low–moderate (defined phases)	As, N	Very high (high-grade feed)
CIGS PV waste	0.01–0.1 wt.%	High (layered system)	In, Cu, Se	Medium–high (complex separation)
Bayer liquors	100–300 mg/L	Low (aqueous system)	Al, V, Na	High (chemically accessible)
Coal fly ash/coal waste	10–200 ppm	High (mineral matrix)	Si, Al, Fe	Low–medium (diffuse, refractory)
Metallurgical residues (Zn, P, steel)	50–500 ppm	Moderate–high	Zn, Fe, Ca	Medium (depends on stream)

The comparison confirms that the potential for gallium recovery is primarily controlled by feed quality rather than by process choice. Semiconductor-related residues and Bayer-type liquors offer clear advantages due to higher concentration and chemical accessibility, while mixed e-waste remains unattractive without pre-concentration or selective dismantling.

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Figure 2 provides a conceptual comparison between gallium concentration and matrix complexity across different secondary sources, highlighting their relative suitability for recovery.

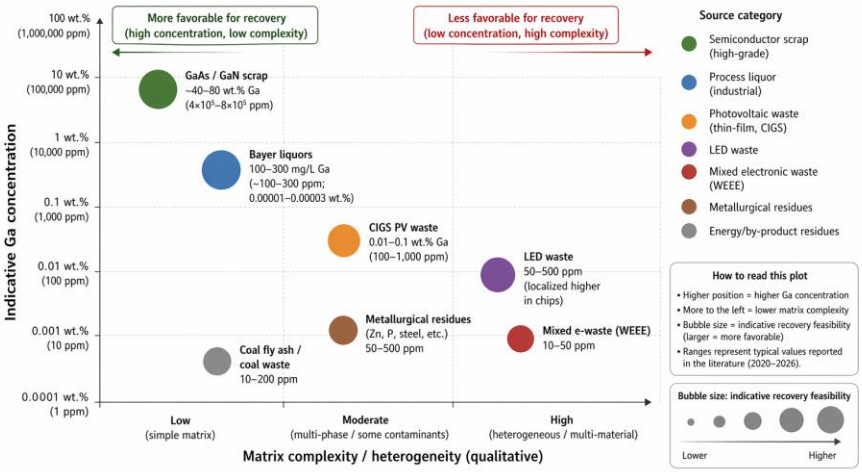

Figure 2. Conceptual comparison of gallium-bearing secondary sources as a function of concentration and matrix complexity. High-grade semiconductor residues and Bayer-type liquors exhibit higher concentrations but lower effective complexity, whereas mixed electronic waste is characterized by lower concentrations and greater heterogeneity, limiting the feasibility of recovery. Adapted from Kluczka (2024), Zheng et al. (2023), and Huang et al. (2024b).

The diagram illustrates that recovery feasibility increases with concentration but decreases with matrix complexity. This relationship explains why high-grade industrial residues are more suitable for scalable recovery, whereas conventional e-waste requires additional pre-treatment and selective concentration steps.

4. Gallium chemistry, pretreatment, and processing routes

Gallium behavior in hydrometallurgical systems is governed by its amphoteric chemistry, which strongly influences both dissolution and separation behavior. Its chemistry promotes co-dissolution with elements such as aluminum, iron, and zinc. This behavior complicates downstream processing and reduces separation selectivity. As a result, the main challenge in many systems is not the dissolution of gallium itself, but achieving selective separation from

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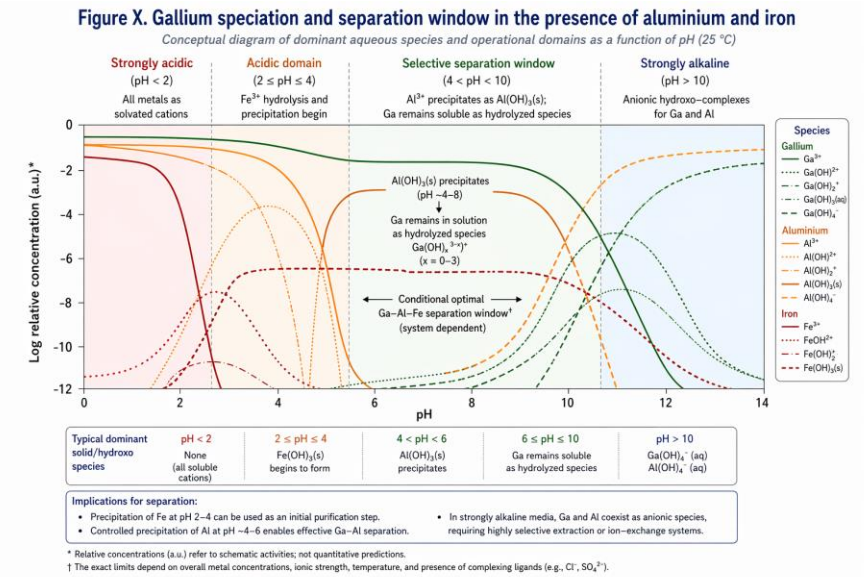
chemically similar species under realistic conditions (Robla et al., 2024; Kluczka, 2024; Qin et al., 2024; Raj et al., 2023; Zheng et al., 2021).

The separation of gallium from major co-elements such as aluminum and iron is fundamentally driven by pH-dependent speciation and hydrolysis behavior. To illustrate these constraints, Figure 3 presents a simplified speciation window highlighting the narrow pH domains in which selective separation is feasible.



Typical dominant solid/hydroxo species	pH < 2	2 ≤ pH ≤ 4	4 < pH < 6	6 ≤ pH ≤ 10	pH > 10
	None (all soluble cations)	$Fe(OH)_3(s)$ begins to form	$Al(OH)_3(s)$ precipitates	Ga remains soluble as hydrolyzed species	$Ga(OH)_4^-$ (aq) $Al(OH)_4^-$ (aq)

Implications for separation:

- Precipitation of Fe at pH 2–4 can be used as an initial purification step.
- Controlled precipitation of Al at pH ~4–6 enables effective Ga–Al separation.
- In strongly alkaline media, Ga and Al coexist as anionic species, requiring highly selective extraction or ion–exchange systems.

* Relative concentrations (a.u.) refer to schematic activities; not quantitative predictions.
† The exact limits depend on overall metal concentrations, ionic strength, temperature, and presence of complexing ligands (e.g., Cl^-, SO_4^{2-}).

Figure 3. Conceptual speciation and separation window for gallium in the presence of aluminum and iron as a function of pH. The diagram illustrates how overlapping hydrolysis and precipitation domains constrain selective recovery, defining narrow operational windows for Ga–Al–Fe separation. These relationships explain why separation performance, rather than leaching efficiency, governs industrial feasibility. Adapted from Kluczka (2024), Qin et al. (2024), Huang et al. (2025), and Raj et al. (2023).

The figure highlights that selective separation is only feasible within relatively narrow pH domains. Outside these windows, co-precipitation or co-extraction significantly reduces process efficiency, reinforcing that impurity management—rather than leaching efficiency—is the dominant challenge in gallium recovery flowsheets.

Pretreatment is therefore critical. In LED modules, chips are embedded in polymers, phosphors, and metallic contacts; in GaAs scrap, the semiconductor may be associated with SiC, packaging materials, or process residues; and in CIGS modules, the metal-bearing layer is laminated with glass, polymer, and back-contact materials. Crushing, thermal delamination, oxidative pretreatment, controlled decomposition, solvent-based dissociation, and selective dismantling are used to expose gallium-bearing phases and improve downstream processing efficiency (Annoni et al., 2020; Zhu et al., 2020; Zhan et al., 2020b; Liu et al., 2024b; Li et al., 2023b). Pretreatment is therefore not only a preparatory step, but a critical determinant of downstream process feasibility.

In CIGS modules, the gallium-bearing phase is embedded in a complex multilayer structure comprising glass, a molybdenum back contact, an absorber layer, buffer layers, and protective coatings, which complicates selective liberation and downstream processing (Mufti et al., 2020).

Hydrometallurgy is the main recovery route for most source classes, although such studies remain relatively scarce. Acidic leaching with HCl or H_2SO_4 is widely used for LEDs, GaAs waste, etching residues, and CIGS materials, whereas alkaline systems are more suitable for Bayer streams or GaN waste. In LED materials, oxidative pretreatment and phase transformation strongly influence dissolution behavior. Bayer systems benefit from chemical compatibility with alkaline media, but require high selectivity to manage the co-presence of aluminum (Flerus & Friedrich, 2020; Maarefvand et al., 2020; Illés & Kekesi, 2023b; Yang et al., 2023; Huang et al., 2025; Liu et al., 2024b).

Once gallium is in solution, solvent extraction, ion exchange, adsorption, selective precipitation, and electrowinning are the main routes for purification. Organophosphorus extractants, emulsion membranes, supported liquid membranes, hydroxamic systems, catechol-functional resins, amidoxime resins, molecularly imprinted materials, and bio-based adsorbents have all been investigated. However, their performance is highly sensitive to solution chemistry, and selectivity observed in synthetic systems often deteriorates in real liquors containing high concentrations of Al, Fe, Zn, or V (Asadian & Ahmadi, 2020; Zhou et al., 2022; Raj et al., 2023; Li et al., 2024; Qin et al., 2024; Wang et al., 2024b; Wang et al., 2025a; Luo et al., 2025b).

The adsorption literature is especially illustrative. Amidoxime, pyrogallol, hydroxamic, peptide-based, chitosan-based, and graphene-derived systems have demonstrated promising uptake or selectivity under controlled conditions. However, industrial applicability depends not

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only on equilibrium performance, but also on long-term stability, impurity tolerance, regeneration efficiency, and compatibility with complex leach liquors. Consequently, adsorption should be considered within an integrated process context rather than as an isolated material-screening problem (Li et al., 2024; Liu et al., 2024a; Lv et al., 2025; Luo et al., 2025b; Wang et al., 2024b; Wang et al., 2025b; Zhu et al., 2024). This limitation reinforces that adsorption performance must be evaluated under realistic impurity conditions rather than idealized laboratory systems.

Pyrometallurgical and thermochemical approaches remain relevant where gallium is associated with refractory or stable phases. Thermal oxidation, roasting, chlorination, vacuum decomposition, subcritical or supercritical treatments, and sulfidation–vapor transport have been proposed to convert gallium into more recoverable forms or to separate it from host matrices prior to hydrometallurgical processing. While effective in certain contexts, these routes introduce higher energy demand, potential volatilization losses, and, in arsenic-bearing systems, additional environmental and safety constraints (Hasan et al., 2022; Ji et al., 2020; Swain et al., 2021; Benderly-Kremen et al., 2025; Zhan et al., 2020a; Zhan et al., 2020b; Zhang et al., 2021). In many cases, these approaches are used to improve selectivity indirectly by modifying phase composition prior to leaching.

Emerging technologies aim to address selectivity and sustainability simultaneously. Proposed approaches include ionic liquids, deep eutectic solvents, membrane-based recovery, biodismantling, biogenic lixiviants, synthetic-biology-assisted recovery, and bioleaching-inspired systems. Despite promising laboratory results, their application remains limited due to simplified experimental conditions and short testing durations that do not capture the complexity of industrial feeds (Dhiman & Gupta, 2025; Erkmen et al., 2025; Jaiswal & Srivastava, 2024; Monneron-Enaud et al., 2020; Bai et al., 2025; Zhang et al., 2025; Zheng et al., 2024). As a result, their reported selectivity and efficiency should be interpreted cautiously when extrapolated to industrial conditions.

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To compare the main processing routes and their industrial relevance, Table 3 summarizes the typical conditions, performance, and limitations associated with the recovery of gallium from secondary sources.

Table 3. Comparative overview of gallium processing routes, including operating conditions, performance ranges, advantages, limitations, and technology readiness level (TRL). Values represent typical ranges reported for secondary resources. Adapted from De Oliveira et al. (2021), Kluczka (2024), Huang et al. (2024a), and Zheng et al. (2023)

Stage	Process	Typical Conditions	Performance	Advantages	Limitations	TRL
Pretreatment	Crushing/grinding	<100 µm	Liberation dependent	Simple, scalable	Incomplete liberation	8–9
Pretreatment	Thermal / oxidative	300–900°C	Improves leaching	Phase conversion	Energy demand, losses	5–7
Leaching	Acid (HCl, H_2SO_4)	pH < 2, 25–90°C	60–95%	Widely applicable	Co-dissolution (Al, Fe)	6–8
Leaching	Alkaline (NaOH)	pH > 10	50–90%	Selective in some systems	Al/V interference	6–8
Separation	Solvent extraction (SX)	pH 1–3	80–95%	Industrial standard	Al competition	7–9
Separation	Ion exchange / adsorption	Variable	70–90%	High selectivity (lab)	Fouling, regeneration	4–7
Recovery	Precipitation	pH control	High	Simple	Purity limitations	7–9
Recovery	Electrowinning	Controlled electrolyte	>99.9% purity	High purity	Sensitive to impurities	6–8
Advanced	Ionic liquids / DES	Lab scale	>90%	High selectivity	Low maturity	2–4
Advanced	Membranes / bioleaching	Lab scale	Variable	Low impact	Scale-up gap	2–4

The comparison shows that hydrometallurgical routes dominate industrial practice due to their flexibility, but their effectiveness is ultimately constrained by impurity interactions and the need to maintain selectivity under complex chemical conditions. In this context, downstream purification performance becomes the defining constraint for overall process viability.

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Throughout this review, performance data are interpreted according to the level of evidence defined in Table 1, recognizing that results from synthetic systems may overestimate real-world process performance.

To connect chemistry with process selection, Figure 4 presents an integrated flowsheet for the recovery of gallium from various secondary sources.

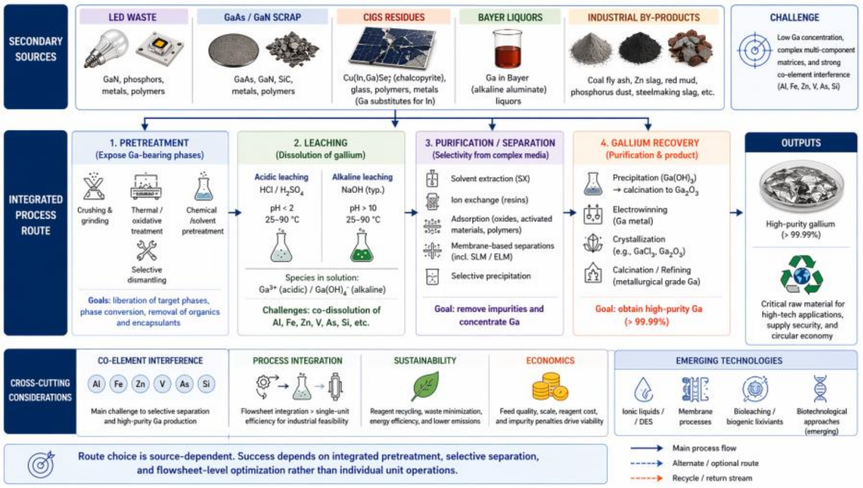

Figure 4. Integrated process map for gallium recovery from secondary resources, showing pretreatment, leaching, purification, and final recovery stages. The flowsheet highlights source-dependent pathways for LED waste, GaAs/GaN scrap, CIGS residues, Bayer liquors, and industrial by-products. Adapted from De Oliveira et al. (2021), Kluczka (2024), Huang et al. (2024b), and Zheng et al. (2023).

The flowsheet shows that gallium recovery is strongly source-dependent. Although leaching approaches may appear similar across systems, differences in pretreatment requirements and purification strategies are substantial. This reinforces that flowsheet integration and impurity management, rather than individual unit operations, determine industrial feasibility.

5. Comparative performance, bottlenecks, and industrial realism

Comparative performance cannot be discussed only in terms of headline recovery values. The most favorable laboratory recoveries are usually reported for concentrated LED-industry residues, selected GaAs/GaN scraps, specific CIGS-derived feeds, and some industrial liquors after extensive pretreatment or matrix simplification. In contrast, mixed e-waste and highly diluted consumer streams tend to suffer from preprocessing losses, complex impurity chemistry, and unfavorable economics even when the chemistry is technically feasible (Yang et al., 2023; Huang et al., 2025; Liu et al., 2024b; Ravilla et al., 2024; Evans et al., 2023).

Across the literature, three controlling factors appear repeatedly: initial gallium concentration, matrix composition, and impurity coupling. In Bayer and related alkaline systems, Ga-Al separation dominates the process challenge. In zinc and acidic metallurgical residues, interference from Fe and Zn can control downstream selectivity. In LED, GaAs, and CIGS wastes, phase accessibility and the association of gallium with As, In, Se, Cu, or encapsulating materials frequently determine whether apparently strong laboratory chemistry can be translated into a viable flowsheet (Qin et al., 2024; Qi et al., 2025; Qu et al., 2025; Hu et al., 2022; Huang et al., 2025; Theocharis et al., 2021).

To critically compare recovery performance and industrial feasibility, Table 4 summarizes the main gallium-bearing sources in terms of processing routes, impurity constraints, recovery levels, and process complexity.

Table 4. Comparative assessment of gallium recovery routes by source class, including pretreatment, leaching chemistry, purification strategy, dominant impurity constraints, recovery levels, process complexity, and technology readiness level (TRL). Adapted from Flerus and Friedrich (2020), Illés and Kékesi (2023), Yang et al. (2023), Huang et al. (2025), Qin et al. (2024), and Ravilla et al. (2024).

Source Type	Pretreatment	Leaching Chemistry	Purification Route	Main Impurity Constraint	Recovery (%)	Complexity	TRL
Mixed e-waste	Crushing, dismantling	Acidic (HCl/H_2SO_4)	SX / precipitation	Cu, Fe, plastics	40–70	Very high	4–6
LED waste	Thermal + chemical	Acidic / oxidative	SX / adsorption	In, REEs, encapsulation	60–90	High	5–7
GaAs / GaN scrap	Minimal / oxidative	Acidic / alkaline	SX / crystallization	As, stability (GaN)	80–95	Medium	6–8
CIGS PV waste	Delamination + grinding	Acidic	SX / IX	In, Cu, Se coupling	60–90	High	5–7
Bayer liquors	None (in solution)	Alkaline	IX / precipitation	Al (dominant)	70–90	Medium	7–9
Metallurgical residues	Thermal / oxidative	Acidic	SX / precipitation	Fe, Zn	50–85	Medium–High	5–7
Coal / ash / P dust	Thermal / reduction	Acidic	SX / IX	Si, Al, Fe	40–80	High	4–6

The table highlights that high recovery percentages do not necessarily reflect process maturity. In several cases, particularly for LED and semiconductor-derived materials, strong extraction or purification performance is reported only after intensive pretreatment, the use of highly selective media, or operation in simplified synthetic systems. This distinction is critical, as it separates proof-of-concept performance from industrially viable processes, consistent with the evidence classification framework presented in Table 1.

To complement the qualitative comparison presented in Table 4, a simplified techno-economic comparison of representative gallium recovery routes is provided in Table 5, highlighting the trade-offs between recovery, selectivity, reagent consumption, and industrial feasibility.

Table 5. Comparative techno-economic indicators for the recovery of gallium from secondary sources. Values represent indicative ranges based on literature data (2020–2026). Reagent consumption is expressed qualitatively (low/medium/high) relative to gallium recovery, given variability in feed composition and process configuration. Industrial potential reflects combined considerations of feed availability, process complexity, and integration feasibility. Adapted from Qin et al. (2024), Huang et al. (2025), Ravilla et al. (2024), and Ji et al. (2020).

Source Type	Typical Ga Grade	Recovery (%)	Reagent Consumption	Energy Demand	Main Bottleneck	Industrial Potential
Mixed e-waste	10–50 ppm	20–60	High (acid + oxidant)	Medium–High	Feed heterogeneity, impurities	Low
LED waste	50–500 ppm	60–85	Medium–High	Medium	Encapsulation, In/REE coupling	Medium
GaAs / GaN scrap	30–80 wt.%	80–95	Low–Medium	Low	As handling, phase stability	High
CIGS PV waste	0.01–0.1 wt.%	60–90	Medium	Medium	Cu–In–Se coupling	Medium
Bayer liquors	100–300 mg/L	70–90	Low (alkaline)	Low	Ga–Al separation	High
Metallurgical residues	50–500 ppm	50–85	Medium–High	Medium	Fe/Zn interference	Medium
Coal ash / P dust	10–200 ppm	20–70	High (thermal + acid)	High	Refractory phases	Low–Medium

The comparison confirms that high recovery values alone are insufficient to define process viability. Routes based on high-grade semiconductor scrap and Bayer liquors combine favorable recovery with lower reagent intensity and higher integration potential, whereas mixed e-waste and low-grade residues are constrained by feed variability, high reagent demand, and complex impurity chemistry. These trade-offs explain the persistent gap between laboratory performance and industrial implementation.

Beyond qualitative comparisons, industrial relevance relies on quantitative metrics that are often underreported or inconsistently defined. Recovery efficiency alone does not determine process viability; it must be considered alongside reagent use, energy, impurity rejection, and stability. For instance, acid leaching with 80–95% Ga recovery often requires high acid consumption (5–50 kg acid per kg Ga), increasing costs and complicating neutralization. Similarly, alkaline Bayer systems have lower reagent costs but require high selectivity for Ga–Al separation, often needing multiple stages or resins (Qin et al., 2024; Qu et al., 2025).

Impurity concentration is a critical scaling parameter. In many experimental studies, gallium is evaluated in simplified systems where impurity-to-gallium ratios are artificially low. In contrast, industrial liquors may exhibit Al/Ga ratios exceeding 10^3–10^4, particularly in Bayer-derived streams, or high Fe and Zn concentrations in metallurgical residues. Under such conditions, selectivity coefficients rather than absolute extraction efficiencies determine process feasibility. This explains why separation technologies that perform well in synthetic solutions often experience sharp declines in performance when applied to real feeds, due to competitive complexation, co-extraction, or sorbent fouling (Raj et al., 2023; Wang et al., 2025b; Luo et al., 2025a).

From an energy perspective, hydrometallurgical routes are generally less energy-intensive than thermochemical alternatives, with typical ranges of 1–10 kWh/kg Ga for solution-based recovery steps, excluding upstream pretreatment. However, when thermal pretreatment (300–900°C) or roasting is required to liberate gallium from refractory matrices such as coal ash or complex e-waste fractions, total energy demand may increase substantially, approaching levels comparable to pyrometallurgical processing. These additional steps often determine whether a technically feasible route remains economically viable (Hasan et al., 2022; Ji et al., 2020).

Another key parameter is process throughput and feed continuity. High-grade semiconductor scrap and Bayer liquors provide relatively stable, continuous feed conditions, enabling process optimization and scale-up. In contrast, mixed e-waste streams are characterized by variability in composition, particle size, and material distribution, thereby introducing operational instability and complicating process control. This variability directly affects the residence time distribution, reagent dosing, and separation efficiency, making scale-up more complex than laboratory data suggest.

To address these limitations, a more realistic comparison of gallium recovery routes should consider integrated performance indicators rather than isolated metrics. These include: (i) recovery yield under real feed conditions, (ii) impurity rejection efficiency (e.g., Ga/Al or Ga/Fe separation factors), (iii) reagent and energy consumption per unit of gallium recovered, (iv) process stability over extended operation cycles, and (v) compatibility with existing industrial infrastructure. When evaluated under these criteria, high-grade semiconductor residues and Bayer-type liquors remain the most promising near-term candidates for scalable recovery, while mixed e-waste and low-grade residues require substantial improvements in pretreatment and selective separation to become competitive.

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Figure 5 compares recovery efficiency with industrial realism, highlighting the gap between laboratory performance and practical implementation.

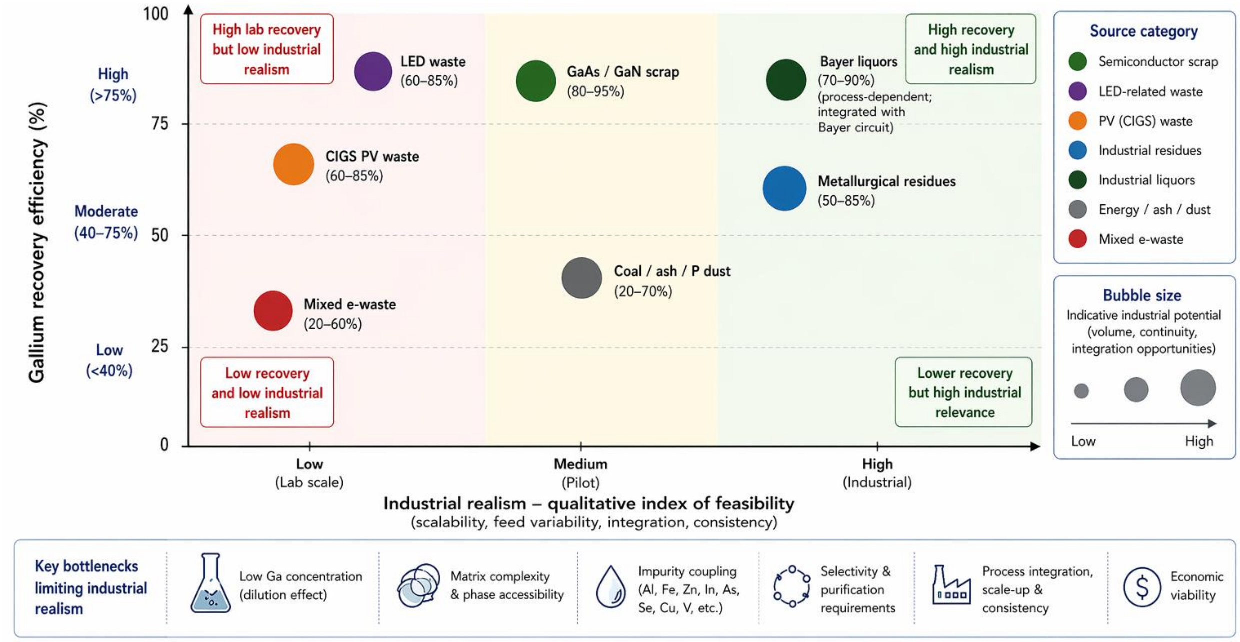

Figure 5. Simplified conceptual comparison of gallium recovery efficiency versus industrial realism. High-grade semiconductor scrap and Bayer-type liquors show better alignment between recovery and scalability, while mixed e-waste and complex residues exhibit lower feasibility despite technically achievable recovery. Adapted from Huang et al. (2025), Zheng et al. (2023), and Kluczka (2024).

The simplified comparison shows that recovery efficiency alone is not a reliable indicator of process viability. Industrial performance is influenced by feed variability, impurity control, and flowsheet integration, which explains the persistent gap between laboratory results and scalable applications (Qin et al., 2025; Pan et al., 2025).

From a techno-economic and environmental perspective, the gap between laboratory performance and industrial feasibility becomes even more evident. Although many studies report high recovery efficiencies, few provide quantitative assessments of cost, energy demand, or environmental impact under realistic operating conditions.

Available literature indicates that the cost of gallium recovery from secondary sources varies widely with feed grade, process complexity, and level of integration. For high-grade semiconductor scrap and concentrated process residues, reported estimates suggest recovery costs of 100–300 USD per kg Ga. However, these values are not directly comparable across

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studies because of differences in feed composition, scale, and system boundaries. In contrast, recovery from dilute sources such as mixed e-waste or coal ash may cost 500–2000 USD per kg Ga, primarily due to low feed grades, high reagent demand, and extensive pretreatment requirements.

Energy demand follows a similar trend. Hydrometallurgical routes typically require on the order of 1–10 kWh per kg Ga for leaching and separation stages, but total process energy can increase substantially when thermal pretreatment (300–900°C), roasting, or phase transformation steps are required. In such cases, overall energy consumption may approach or exceed that of primary production routes, particularly for refractory or low-grade materials.

From an environmental standpoint, the main contributors to process impact include reagent consumption (especially acids and alkalis), neutralization and effluent treatment, and solid residue management. While secondary recovery routes generally yield lower CO_2 emissions and waste generation than primary gallium production, these advantages depend heavily on process integration, reagent recycling, and feedstock quality. Poorly optimized flowsheets may negate environmental benefits by leading to excessive chemical use and waste generation.

A structured comparison of techno-economic and environmental indicators is therefore essential to assess process viability. Key parameters include (i) cost per kg of gallium recovered, (ii) energy consumption (kWh/kg Ga), (iii) reagent intensity (kg reagent/kg Ga), (iv) waste generation and treatment requirements, and (v) integration with existing industrial infrastructure. When evaluated under these criteria, high-grade semiconductor scrap and Bayer-type liquors remain the most economically and environmentally favorable options, while low-grade and heterogeneous feeds require significant advances in pretreatment and selective separation to become competitive.

A similar pattern holds for industrial and unconventional secondary sources. Coal fly ash, yellow phosphorus dust, steelmaking wastes, NdFeB-related residues, Bayer-derived liquors, and zinc refinery or smelting streams are often more relevant at scale than consumer e-waste, even when their separation chemistry is less selective. Their importance stems from volume, continuity, and their potential integration into existing industrial infrastructure (Ji et al., 2020; Hartzell & Moats, 2023; Rudnik, 2024; Zhao et al., 2021).

6. Environmental impacts, economic limits, and circular supply chains

Environmental performance in gallium recovery is strongly dependent on process route selection and system integration. Acidic hydrometallurgy can generate aggressive effluents and secondary residues. Thermal routes may impose higher energy demand and, in arsenic-bearing feeds, additional detoxification burdens. Photovoltaic waste management also raises questions beyond recovery, including long-term leachability, landfill behavior, and contaminant transfer to soil and water if recycling systems remain weak (Nain & Kumar, 2020, 2021; Yandem & Jablonska-Czapla, 2024; Yandem et al., 2025). These factors often represent limiting constraints in industrial implementation, particularly for arsenic- and selenium-bearing systems.

Economic feasibility is similarly uneven. High-value, concentrated residues such as wafer scrap, semiconductor process wastes, and some LED-industry streams are more likely to support specialized recovery. By contrast, diffuse consumer e-waste is penalized by the need for collection, sorting, and dismantling, as well as by low target metal content. The same logic applies to PV waste: CIGS modules are compositionally attractive, but economic performance depends on collection scale, delamination efficiency, and the value recovery of co-metals such as In, Cu, and Se (Ravilla et al., 2024; Song et al., 2023; Lin et al., 2022; Gajec et al., 2025; Wang et al., 2024b). These factors collectively determine whether technically feasible recovery routes can achieve economic viability at scale.

To systematically compare environmental and economic constraints across gallium recovery routes and feedstocks, Table 6 summarizes key trade-offs affecting industrial feasibility.

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Table 6. Environmental and economic trade-offs in the recovery of gallium from secondary sources, including process impacts, risks, cost drivers, and circularity potential. Values represent qualitative comparison based on reported industrial and experimental trends. Adapted from Nain and Kumar (2020, 2021), Yandem et al. (2024, 2025), Ravilla et al. (2024), and Sverdrup and Haraldsson (2025).

Source / Route	Environmental Impact	Main Risk	Economic Viability	Key Cost Driver	Circular Potential
Acid hydrometallurgy	High (acid effluents)	Waste treatment	Medium	Reagents + neutralization	Medium
Alkaline systems (Bayer)	Moderate	Al interference	High (existing infrastructure)	Separation complexity	High
Pyrometallurgy	High (energy, emissions)	Volatilization (Ga, As)	Low–medium	Energy	Low–medium
LED waste recycling	Moderate–high	Complex waste matrix	Medium	Dismantling + selectivity	Medium
GaAs/GaN scrap	Low–moderate	Toxic elements (As)	High	Controlled processing	High
CIGS PV recycling	Moderate	Multi-metal separation	Medium	Delamination + separation	High
Industrial residues	Variable	Impurity load	Medium–high	Integration cost	High
Mixed e-waste	Moderate	Low Ga concentration	Low	Collection + sorting	Low

The comparison highlights that circular potential is determined not solely by recoverability but by the balance among environmental burden, economic cost, and process integration. Routes with high chemical efficiency may still be unattractive if they impose excessive energy or reagent demand. This highlights that environmental and economic constraints are often coupled and cannot be evaluated independently.

Circular supply arguments are strongest where recycling can offset structural constraints on primary supply. Gallium recovery from wafers, LED residues, specialized industrial streams, and selected PV waste streams can reduce dependence on the indirect primary production of Al and Zn. Still, circularity should not be treated as automatic. If a route depends on excessive reagent intensity, unstable selectivity, or impractical preprocessing, the circular claim weakens even when recovery is chemically possible (Sverdrup & Haraldsson, 2025; Zuo et al., 2025; Jia et al., 2022; Bukauskaite et al., 2024). Circularity should therefore be understood as a conditional outcome rather than an inherent property of recovery processes.

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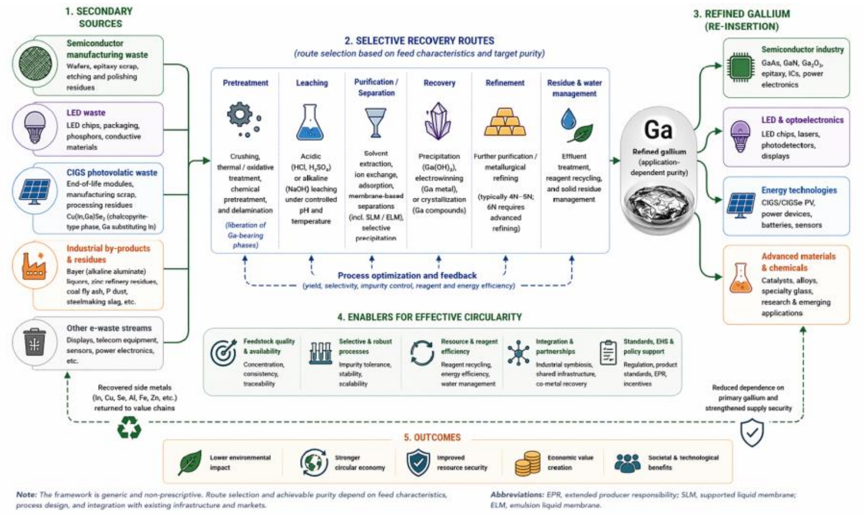
Figure 6 presents a circular supply framework for gallium that links secondary sources, recovery routes, and reintegration into high-value applications.



Note: The framework is generic and non-prescriptive. Route selection and achievable purity depend on feed characteristics, process design, and integration with existing infrastructure and markets.

Abbreviations: *EPR, extended producer responsibility; SLM, supported liquid membrane; ELM, emulsion liquid membrane.*

Figure 6. Circular supply framework for secondary gallium, linking semiconductor manufacturing waste, LED waste, photovoltaic residues, and industrial by-products to recovery processes and reintegration into semiconductor and energy technologies. The diagram highlights the dependence of circularity on feedstock quality, process selectivity, and system integration. Adapted from Jia et al. (2022), Zuo et al. (2025), and Sverdrup and Haraldsson (2025).

The framework shows that circularity is conditional rather than inherent. Effective recycling depends on aligning feedstock quality, process selectivity, and end-use requirements. Without this alignment, technically feasible recovery pathways may fail to deliver meaningful supply-chain impact.

7. Critical gaps and future directions

Three critical gaps consistently emerge across the literature. First, industrial-scale evidence is limited. Many papers show strong laboratory performance but do not test realistic impurity loads, recycle streams, long-cycle media regeneration, or integrated mass balances. Second, process integration is often incomplete. Pretreatment, leaching, purification, waste treatment, and by-product management are frequently optimized separately, even though their interactions determine viability. Third, techno-economic analysis remains underdeveloped compared to the volume of chemistry-focused research (Kluczka, 2024; Luo et al., 2025a; Zheng

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et al., 2023). These limitations systematically explain the gap between laboratory performance and industrial implementation.

To systematically structure the main limitations identified in the literature, Table 7 summarizes critical gaps, their industrial implications, and required research directions.

Table 7. Critical gaps in gallium recovery research, including current limitations, industrial implications, and priority directions for future development. Adapted from Kluczka (2024), Luo et al. (2025a), Zheng et al. (2023), and Bai et al. (2025).

Gap Category	Current Limitation	Industrial Impact	Required Action	Priority
Scale-up	Lab-scale validation only	Overestimated performance	Pilot and continuous testing	High
Impurity handling	Simplified synthetic systems	Poor selectivity in real feeds	Real-liquor testing (Al, Fe, Zn)	High
Process integration	Unit operations optimized separately	Flowsheet inefficiency	Integrated flowsheet design	High
Techno-economic data	Limited CAPEX/OPEX analysis	Uncertain viability	Full TEA + LCA studies	High
Pretreatment	Incomplete liberation	Low recovery efficiency	Controlled phase exposure	Medium
Emerging technologies	Low TRL (2–4)	Limited industrial adoption	Scale-up and stability studies	Medium
Circular integration	Weak link to supply chains	Limited impact	Industrial ecosystem integration	Medium

These gaps are consistent with the evidence hierarchy discussed in Table 7 and the performance limitations identified in Sections 4 and 5.

Future work should focus on four main directions. The first is stronger integration with semiconductor manufacturing and wafer recycling, where feed quality is high, and traceability is better. The second is selective intensification, especially for Ga-Al and Ga-Fe separation in real liquors. The third is hybrid route development combining targeted liberation, phase transformation, selective leaching, and low-loss purification. The fourth is scale-aware validation, including realistic residence times, mass transfer limits, reagent recycling, and cost sensitivity. This shift from isolated unit success to flowsheet robustness is essential if emerging concepts such as ionic liquids, mechanochemical activation, biodismantling, synthetic biology, or novel selective adsorbents are to move beyond laboratory relevance (Bai et al., 2025; Li et al., 2026; Benderly-Kremen et al., 2025; Zhang et al., 2025; Erkmen et al., 2025). These directions emphasize the transition from material-level optimization to process-level robustness.

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Figure 7 presents a simplified roadmap linking current research gaps to future development pathways for industrial gallium recovery.

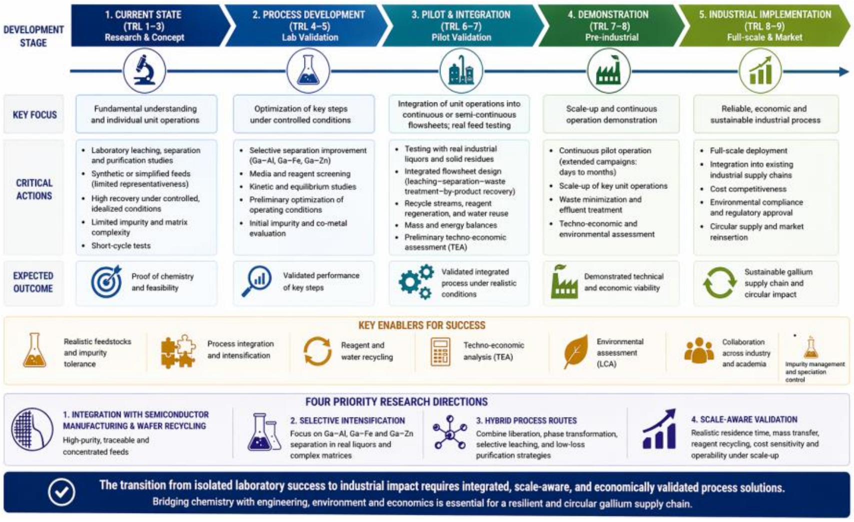

Figure 7. Simplified roadmap for gallium recovery technologies, illustrating the transition from laboratory-scale research to industrial implementation. Key pathways include process integration, impurity-tolerant separation, hybrid route development, and scale-aware validation. Adapted from Kluczka (2024), Zheng et al. (2023), and Luo et al. (2025b).

The roadmap highlights that progress depends on moving beyond isolated laboratory performance toward integrated, scale-aware systems. Bridging this gap requires combining chemical selectivity with engineering validation, process integration, and economic assessment under realistic operating conditions.

8. Conclusions

Gallium recovery from secondary resources is strategically important because primary supply remains structurally constrained by its dependence on aluminum and zinc production. The most promising secondary opportunities are not associated with mixed e-waste as a whole, but with concentrated and well-defined streams such as LED-related waste, GaAs and GaN scrap, semiconductor process residues, CIGS photovoltaic materials, and selected industrial by-products.

Hydrometallurgical routes dominate current research and development; however, process performance is not primarily limited by gallium dissolution, but by the ability to achieve selective separation from co-existing elements. Among these, Ga–Al interactions represent the most persistent challenge, particularly in alkaline systems, while Fe, Zn, V, As, In, Se, and Cu impose source-dependent constraints on downstream purification. As a result, downstream purification performance becomes the primary constraint governing overall process viability.

Emerging approaches—including ionic liquids, membrane-based separations, adsorption systems, biodismantling, and bioleaching—expand the available processing toolkit, but their industrial readiness remains limited. Progress toward scalable implementation will depend on improving selectivity under realistic impurity loads, integrating unit operations into coherent flowsheets, and aligning process design with techno-economic constraints, rather than on maximizing recovery under idealized laboratory conditions. Ultimately, advancing gallium recovery requires a transition from material-level optimization to integrated, scale-aware process design.

Declarations

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Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Author Contributions

The author confirms sole responsibility for the following: conceptualization, methodology, literature review, analysis, writing – original draft, and writing – review and editing.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethical Approval

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This article does not contain any studies with human participants or animals performed by the author.

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