JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

Indium Recovery Efficiency and Loss Mechanisms in Pyrometallurgical Processing: A Critical Metallurgical Accounting Review]

Antonio Clareti Pereira, Ph.D.
Department of Graduate Program in Materials Engineering
Federal University of Ouro Preto (UFOP)
Ouro Preto, Minas Gerais, Brazil
E-mail: claretipereira@gmail.com
ORCID: https://orcid.org/0000-0001-8115-4279

Abstract

Indium is commonly recovered as a by-product or co-product in metallurgical systems, making overall recovery highly sensitive to small losses distributed across multiple process streams. This critical review reframes indium recovery as a plant-wide metallurgical-accounting problem rather than as a single extraction percentage. The analysis distinguishes five mechanisms that can produce an apparent recovery deficit: chemical partitioning to slag, matte, or metal phases; physical entrainment of indium-bearing droplets and particles; true volatilization of indium species; incomplete condensation and off-gas capture; and analytical or accounting losses caused by sampling, assay, moisture, inventory, and recycle uncertainty. Feed variability, phase equilibria, gas–solid transformations, dust recirculation, and delayed inventory release are treated as coupled variables that can shift recovery among campaigns without changing the intrinsic chemistry. The review proposes a hierarchy for reconciling gross, stage, net, and recycle-adjusted recovery and emphasizes that indium location is more informative than the nominal recovery value alone. A diagnostic framework connects loss signatures with corrective actions in feed preparation, redox control, slag chemistry, settling, off-gas cooling, particulate capture, recycle management, and measurement practice. The central conclusion is that maximizing indium recovery requires simultaneous control of thermodynamic partitioning, physical transport, gas-path capture, and accounting closure across the full flowsheet.

Keywords: indium; pyrometallurgy; metallurgical accounting; slag partitioning; volatilization; recovery efficiency

Highlights

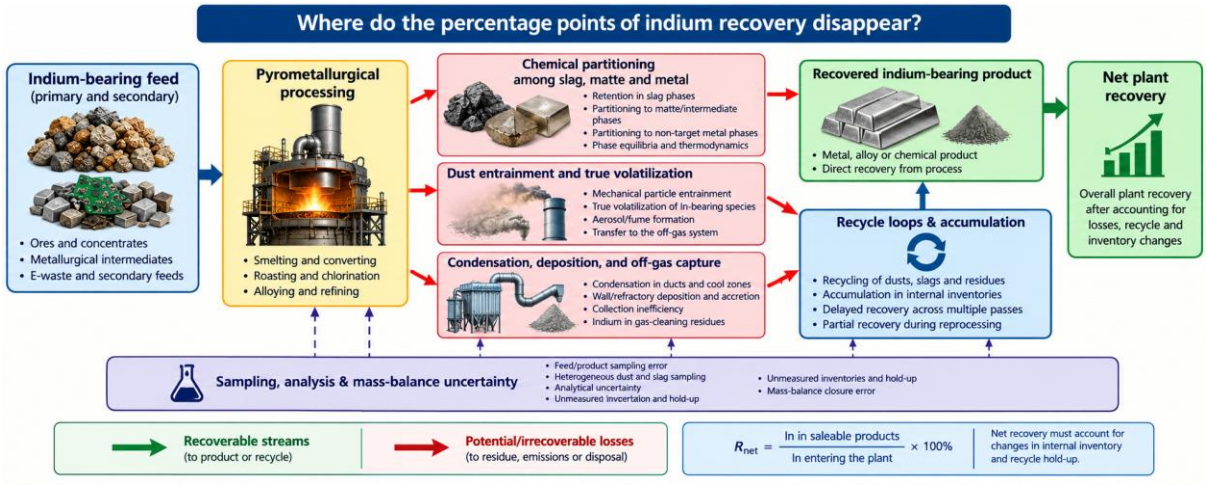
- Reframes indium recovery as a plant-wide metallurgical-accounting problem.
- Separates chemical loss, entrainment, volatilization, capture loss, and accounting loss.
- Links feed variability and recycle loops to apparent campaign-to-campaign recovery changes.
- Proposes a diagnostic framework for locating and recovering missing percentage points.

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Graphical abstract



1. Introduction

Indium occupies an unusual position in extractive metallurgy because its supply is rarely governed by a stand-alone indium ore or a dedicated primary flowsheet. Instead, it is commonly recovered from zinc-, lead-, copper-, tin-, and technology-metal value chains, as well as an increasingly diverse portfolio of secondary materials. This by-product character makes indium availability dependent not only on geological occurrence but also on the operating choices, collection efficiency, and economic incentives of host-metal processing systems (Alguacil, 2024; European Commission, 2017; European Commission, 2020; European Commission, 2023; Golev et al., 2019; Lokanc et al., 2015; Nassar et al., 2015; Reuter et al., 2019; Sverdrup et al., 2017; U.S. Geological Survey, 2023; U.S. Geological Survey, 2024; U.S. Geological Survey, 2025; U.S. Geological Survey, 2026; Werner et al., 2015).

The conventional question—"What is the indium recovery?"—is therefore insufficient. Plants can report the same headline recovery while exhibiting fundamentally different loss structures. One case may be dominated by chemical partitioning of indium to slag; another may be controlled by entrained droplets, dust carryover, or incomplete capture after volatilization; and a third may reflect sampling or inventory errors that create an apparent loss without a corresponding physical disappearance of indium. This distinction is operationally decisive because each mechanism requires a different corrective action. Experimental studies on copper smelting, WEEE pyroprocessing, trace-element partitioning, slag chemistry, and minor-

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JIRRS
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element behavior establish the basis for this mechanistic separation (Anindya et al., 2014; Avarmaa et al., 2019; Avarmaa et al., 2016; Avarmaa et al., 2018; Kandalam et al., 2023; Klemettinen et al., 2020; Klemettinen et al., 2019; Pereira, 2026f; Pereira, 2026h; Su et al., 2026; Sukhomlinov et al., 2020; Taskinen et al., 2017).

Secondary-resource studies add a second layer of complexity. LCD and ITO wastes, CIGS and heterojunction photovoltaic materials, IGZO targets, InP scrap, jarosite residues, zinc-processing residues, and smelting dusts contain indium in markedly different chemical and physical forms. Their pretreatment histories can alter particle size, oxidation state, chloride content, carbon content, and associations with Fe, Zn, Pb, Cu, Ga, Sn, As, Se, and S, all of which influence downstream thermal behavior (Cao et al., 2026; Charpentier et al., 2023; Ferella et al., 2017; Gu et al., 2026; He et al., 2026; He et al., 2014; Hong et al., 2010; Hu et al., 2022; Huang et al., 2024; Janošević et al., 2023; Kashyap & Taylor, 2022; Kaya et al., 2020; Kluczka, 2024; Li et al., 2024; Li et al., 2023; Mahiwan et al., 2026; Mejías et al., 2023; Pang et al., 2024; Parajuly & Wenzel, 2017; Peeters et al., 2013; Savvilotidou et al., 2014; Teknetzi et al., 2024; Teknetzi et al., 2023; Ueberschaar et al., 2017; van Schaik et al., 2018; Wang et al., 2024; Wang et al., 2019; Wang et al., 2023; Xu et al., 2024; Yang et al., 2023; Zeng et al., 2018; Zhang & Xu, 2016; Zhang et al., 2024; Zhang et al., 2015; Zhu et al., 2025).

The visual and tabular framework is introduced explicitly here to make the review structure traceable from the outset. Figure 1 defines the plant-wide metallurgical-accounting boundary; Figure 2 links feed variability to thermodynamic and transport responses; Figure 3 classifies the principal true and apparent loss mechanisms; Figure 4 follows indium through release, condensation, particulate capture, and recycle in the off-gas train; and Figure 5 converts the synthesis into a diagnostic recovery framework. Table 1 classifies the loss mechanisms, Table 2 defines the accounting metrics, Table 3 summarizes mass-balance closure diagnostics, and Table 4 links dominant loss mechanisms to recovery-improvement levers and their principal trade-offs. Figure 1 also makes explicit that indium leaving the reactor in a gas or dust stream is not necessarily lost: it may subsequently be condensed, captured, recycled, or recovered. Conversely, indium reporting to a nominal product phase may still be unrecoverable if it becomes diluted in a recycle loop or is ultimately bled from the circuit.

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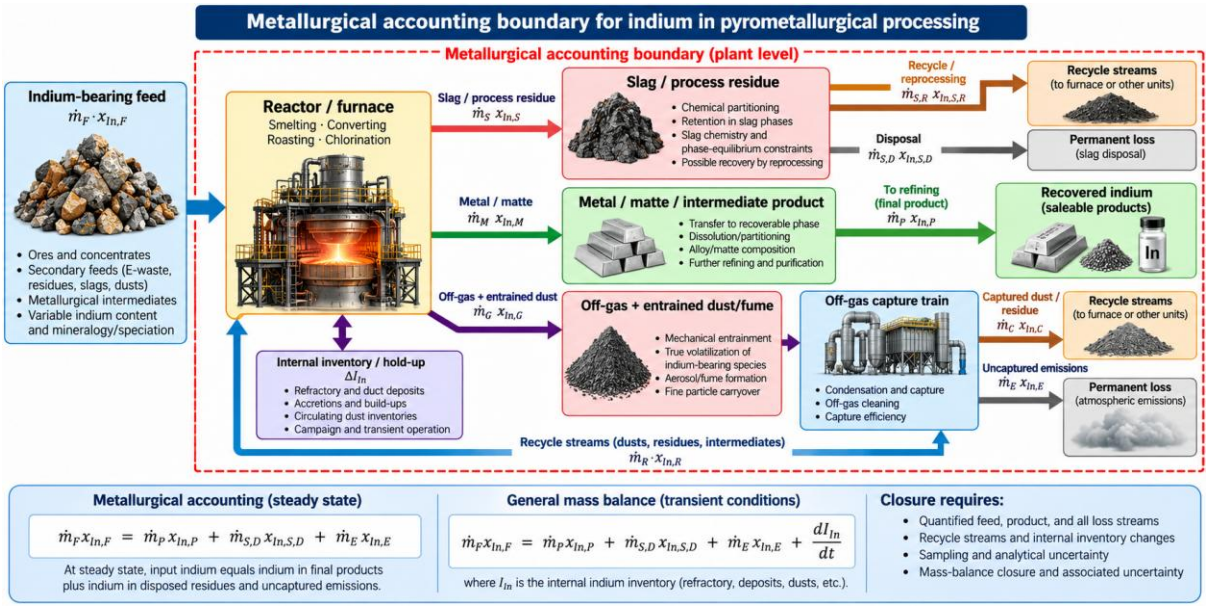


Figure 1. Metallurgical accounting boundary for indium-bearing pyrometallurgical systems.
Note. Author-developed conceptual synthesis from the metallurgical-accounting and phase-partitioning literature reviewed in this article.

As illustrated in Figure 1, a meaningful recovery calculation must identify the system boundary, the time basis, the fate of each indium-bearing stream, and whether recycle flows are treated as internal transfers or recovered output. Accordingly, this review evaluates recovery as a hierarchy of linked balances rather than as a single percentage.

Table 1 summarizes the loss classes that structure the critical analysis. The categories are deliberately mechanistic: they separate thermodynamic distribution, physical transport, gas-path behavior, and measurement effects before any attempt is made to optimize the process.

Table 1
Mechanistic classification of indium recovery deficits.

Loss class	Typical manifestation	Primary diagnostic	Main corrective lever
Chemical partitioning	Indium dissolved or chemically bound in slag, matte, metal, or residue	Phase assay + mineral/phase characterization	Redox potential, slag chemistry, temperature, fluxing, phase ratio
Physical entrainment	Indium-bearing droplets/particles mechanically carried into another phase	Microscopy, settling tests, size-resolved assays	Settling, viscosity, turbulence, residence time, tapping practice

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Loss class	Typical manifestation	Primary diagnostic	Main corrective lever
True volatilization	Indium transferred to gas as volatile species	Gas-path balance + equilibrium/speciation analysis	Temperature, oxygen/chlorine/sulfur potential, residence time
Capture loss	Volatilized/entrained indium not captured downstream	Duct-by-duct dust and condensate balance	Cooling profile, cyclone/baghouse/ESP efficiency, leak control
Accounting loss	Apparent deficit from sampling, moisture, assay, inventory, or recycle lag	Closure with uncertainty propagation	Sampling design, certified standards, inventory reconciliation

Note. Prepared by the author based on the studies cited in the surrounding text.

Table 1 also clarifies why a low overall recovery does not, by itself, identify the limiting mechanism. Optimization should begin by locating the missing indium inventory and distinguishing chemical, physical, gas-path, and accounting deficits before changing furnace chemistry, hydrodynamics, or equipment.

2. Review methodology and evidence scope

This article is a critical metallurgical narrative review, not a systematic review. The evidence base comprises 145 non-preprint sources selected to support mechanistic interpretation of indium recovery and deportment, with emphasis on phase partitioning among slag, matte, and metal; physical entrainment; volatilization and fuming; condensation and particulate capture; recycle inventories; feed variability; sampling uncertainty; and integrated plant-wide recovery. The search therefore aimed for mechanistic coverage and critical triangulation rather than exhaustive bibliometric enumeration.

We performed literature discovery primarily in Google Scholar, then checked bibliographic metadata against DOI records, publisher pages, institutional repositories, and official institutional reports when available. The final search update for this revision was 7 October 2026. Searches were conducted in English. Eligible sources included peer-reviewed journal articles, peer-reviewed conference papers directly relevant to pyrometallurgical mechanisms, books or book chapters providing fundamental thermodynamic context, and official reports from recognized institutions. We excluded preprints, duplicate records, non-

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Pages: 1-36

traceable search-result pages, and items not sufficiently relevant to indium recovery, deportment, metallurgical accounting, or downstream recoverability.

Representative Boolean strings included: (indium AND (pyrometallurgy OR smelting OR roasting) AND (recovery OR distribution OR partition*)); (indium AND (slag OR matte OR metal) AND (distribution OR partition* OR deportment)); (indium AND (volatilization OR fuming OR chlorination OR vacuum) AND (recovery OR condensation)); (indium AND (dust OR off-gas OR aerosol) AND (capture OR cyclone OR baghouse OR ESP)); (indium AND (recycle OR inventory OR bleed) AND (mass balance OR recovery)); and (indium AND (sampling OR uncertainty OR mass balance OR accounting)). Adjacent searches addressed ITO/LCD, CIGS, InP, Zn/Pb/Cu residues, Ga-In alloys, WEEE, and hydrometallurgical purification only where those routes defined feed state, downstream recoverability, or the ultimate fate of indium-bearing intermediates.

The 145-source corpus was assembled by title/abstract relevance screening followed by full-text or metadata-level verification of metallurgical relevance. Duplicate records were removed, and multiple papers from the same research group were retained only when they contributed distinct experimental systems, process conditions, or mechanistic information. No retrospective PRISMA flow count is claimed because the review was not designed prospectively as a systematic review.

For critical appraisal, this review uses an author-developed evidence hierarchy, not a validated evidence-grading instrument. Direct pyrometallurgical evidence—measured phase distributions, furnace or pilot behavior, gas-path measurements, and stream assays—receives the greatest weight for mechanistic claims. Adjacent metallurgical evidence is used to support analogous transport, separation, or recovery behavior, whereas contextual/downstream evidence is used primarily to define feed provenance, purification feasibility, circularity, criticality, and the ultimate recoverability of captured indium. When only total recovery is reported, the mechanism of the unrecovered fraction is treated as unresolved rather than inferred.

The direct thermal and pyrometallurgical evidence includes controlled partitioning, smelting, slag, roasting, vacuum, chlorination, reduction, and condensation studies (Anindya et al., 2014; Avarmaa et al., 2019; Avarmaa et al., 2016; Avarmaa et al., 2018; Gu et al., 2026;

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He et al., 2026; He et al., 2014; Huang et al., 2024; Jalkanen et al., 2003; Kandalam et al., 2023; Klemettinen et al., 2020; Klemettinen et al., 2019; Li et al., 2024; Ma & Xu, 2013; Ma et al., 2012; Mahiwan et al., 2026; Pang et al., 2024). A second group extends this evidence to process intensification, high-temperature separation, and integrated secondary-resource treatment (Pereira, 2025; Pereira, 2026a; Pereira, 2026b; Pereira, 2026c; Pereira, 2026d; Pereira, 2026e; Pereira, 2026g; Pereira, 2026i; Pereira, 2026j; Sawai et al., 2015; Su et al., 2026; Sukhomlinov et al., 2020; Taskinen et al., 2017; Wang et al., 2019; Zhang et al., 2024; Zhang et al., 2023; Zhu et al., 2025).

Hydrometallurgical studies are retained because the economic value of a pyrometallurgical capture step depends on whether the resulting dust, alloy, oxide, chloride, or residue can subsequently be upgraded and purified. This boundary evidence includes leaching, solvent extraction, ion exchange, adsorption, bioleaching, membrane separation, cementation, and electrorefining (Akama et al., 2016; Chinnam et al., 2020; De-la-Cruz-Moreno et al., 2021; Drzazga et al., 2021; Huang et al., 2023; Illés et al., 2022; Jeon et al., 2015; Jowkar et al., 2018; Kang et al., 2011; Kato et al., 2013; Kaya et al., 2020; Khezerloo et al., 2023; Lahti et al., 2020; Li et al., 2012; Li et al., 2015; Li et al., 2011; Nguyen & Lee, 2019; Nusen et al., 2016; Pereira & Silva, 2025; Pourhossein et al., 2022; Qin et al., 2021; Qin et al., 2023). Additional downstream studies define recovery pathways for high-purity indium and therefore help distinguish “captured” indium from “saleable” indium (Ruan et al., 2012; Rudnik, 2026; Sethurajan et al., 2019; Shen et al., 2013; Song et al., 2020; Souada et al., 2018; Swain et al., 2015; Tan et al., 2023; Teknetzi et al., 2023; Theocharis et al., 2021; Tian et al., 2026; Virolainen et al., 2011; Wang & Lee, 2013; Wang et al., 2025; Willner et al., 2022; Yang et al., 2013; Zeng et al., 2022; Zhang et al., 2016; Zhang et al., 2017; Zhang et al., 2020; Zhang et al., 2023; Zhang et al., 2021).

Feed and recycling studies provide evidence on the physical and chemical variability of secondary resources and on the extent to which preprocessing itself can cause indium losses before the thermal unit operation (Anindya et al., 2014; Awasthi & Li, 2017; Cao et al., 2026; Charpentier et al., 2023; Chinnam et al., 2020; Ferella et al., 2017; Hagelüken & Goldmann, 2016; He et al., 2026; He et al., 2014; Hemmati et al., 2023; Hong et al., 2010; Hu et al., 2022; Huang et al., 2024; Huang et al., 2023; Illés et al., 2022; Janošević et al., 2023; Jeon et al.,

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Pages: 1-36

2015; Kandalam et al., 2023; Kang et al., 2011; Kaya et al., 2020; Khezerloo et al., 2023; Kluczka, 2024; Lahti et al., 2020; Lee et al., 2013). The remaining recycling studies cover CIGS, LCD/ITO, IGZO, LED, InP, zinc residues, and mixed WEEE systems and are used as evidence for feed-state heterogeneity and integrated recovery chains (Li et al., 2022; Li et al., 2011; Li et al., 2024; Li et al., 2023; Lv et al., 2026; López-Yáñez et al., 2019; Ma & Xu, 2013; Ma et al., 2012; Mahiwan et al., 2026; Marra et al., 2018; Matsumoto et al., 2012; Mejías et al., 2023; Pang et al., 2024; Parajuly & Wenzel, 2017; Peeters et al., 2013; Pourhossein et al., 2022; Qin et al., 2021; Ruan et al., 2012; Savvilotidou et al., 2014; Sethurajan et al., 2019; Silveira et al., 2015; Souada et al., 2018; Su et al., 2026; Sverdrup et al., 2017; Swain et al., 2015; Tansel, 2017). A final group supports the discussion of closed-loop recovery, industrial relevance, and technology selection (Teknetzi et al., 2024; Teknetzi et al., 2023; Tesfaye et al., 2017; Theocharis et al., 2021; Tian et al., 2026; Ueberschaar et al., 2017; van Schaik et al., 2018; Wang & Lee, 2013; Wang et al., 2025; Wang et al., 2024; Wang et al., 2019; Werner et al., 2015; Willner et al., 2022; Xu et al., 2024; Yang et al., 2013; Yang et al., 2023; Ylä-Mella & Pongrácz, 2016; Zeng et al., 2018; Zhang & Xu, 2016; Zhang et al., 2017; Zhang et al., 2015; Zhang et al., 2023; Zhang et al., 2020; Zhang et al., 2021; Zheng et al., 2023).

Supply, criticality, and circular-economy sources are used to explain why modest percentage-point improvements in recovery can matter disproportionately for a by-product metal (Cao et al., 2021; Charpentier et al., 2023; European Commission, 2017; European Commission, 2020; European Commission, 2023; Golev et al., 2019; Hagelüken & Goldmann, 2016; Nassar et al., 2015; Parajuly & Wenzel, 2017; Reuter et al., 2019; Sverdrup et al., 2017; Tesfaye et al., 2017; U.S. Geological Survey, 2023; U.S. Geological Survey, 2024; U.S. Geological Survey, 2025; U.S. Geological Survey, 2026; van Schaik et al., 2018; Werner et al., 2015; Zeng et al., 2018). Fundamental and review sources support thermodynamics, electrochemistry, purification, and general indium metallurgy where those topics are not captured by the preceding evidence groups (Alguacil, 2024; Becci et al., 2024; Chen et al., 2017; Chung & Lee, 2012; Gaskell & Laughlin, 2018; Kashyap & Taylor, 2022; Koleini et al., 2010; Lokanc et al., 2015; Mizuhata & Minami, 2011; Pradhan et al., 2018; Tian et al., 2026; Tisserant & Pauliuk, 2016; Van den Bossche et al., 2019; Wang et al., 2023; Watari et al., 2020).

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Pages: 1-36

This evidence architecture is intentionally broad, but the critical ranking is narrow: direct measurements of phase distribution, furnace or pilot behavior, and stream assays are weighted more heavily than route-level reviews or sustainability assessments when mechanisms are inferred. Evidence derived from adjacent processing routes is used cautiously, and where the literature reports only total recovery, the mechanism of the unrecovered fraction remains explicitly unresolved.

3. Defining recovery, yield, enrichment factor, and partition ratio

A consistent vocabulary is essential because recovery, stage extraction, product yield, enrichment, phase distribution, and plant-wide realized recovery are metallurgically non-equivalent. All equations in this review refer to an explicitly defined plant accounting boundary and to a common accounting interval Δt. External feed and external outputs cross that boundary; internal recycle streams remain inside it and therefore cancel from the overall external balance.

For an interval Δt, the transient plant-wide indium balance is:

$$\Sigma M_{in,in} - \Sigma M_{in,out} = \Delta M_{in,inventory}$$

or, equivalently,

$$M_{in,feed} = M_{in,recovered} + M_{in,bleed} + M_{in,emitted} + \Delta M_{in,inventory}$$

where $\Delta M_{in,inventory}$ includes material accumulated or depleted in bins, silos, ducts, filters, launders, vessels, retained slag/metal, and internal recycle holdup during the accounting interval. Recycle transfers that originate and terminate inside the boundary are not counted as external recovery.

Gross recovery to a selected product p is defined as:

$$R_{gross,p} = M_{in,p} / M_{in,feed} \times 100$$

Stage recovery across unit operation k is:

$$R_{stage,k} = M_{in,k,out,target} / M_{in,k,in} \times 100$$

The preferred top-level indicator is external-boundary net recovery:

$$R_{net} = M_{in,saleable\ or\ deliberately\ stored\ recovered} / M_{in,external\ feed} \times 100$$

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A recycle-adjusted recovery for a finite interval corrects the apparent recovered fraction for inventory change:

$$R_{recycle-adjusted} = (M_{in,recovered} + M_{in,bleed} + M_{in,emitted}) / M_{in,feed} \times 100 = 100 - (\Delta M_{in,inventory} / M_{in,feed} \times 100) - \varepsilon_{bal}$$

The balance residual is defined as:

$$\varepsilon_{bal} = [M_{in,in} - M_{in,out} - \Delta M_{in,inventory}] / M_{in,in} \times 100$$

A residual close to zero is necessary but not sufficient for an accurate balance because compensating sampling, moisture, assay, and inventory errors can cancel numerically.

For two coexisting phases i and j, an operational distribution ratio can be expressed as $D_{in(i/j)} = w_{in,i} / w_{in,j}$, where w is the indium mass fraction in each phase. This value depends on temperature, oxygen potential, sulfur potential, bulk and phase composition, analytical basis, and the extent to which equilibrium has been approached. It must therefore be reported with those conditions and must not be treated as a universal material constant or transferred directly to clearly non-equilibrium plant streams (Anindya et al., 2014; Avarmaa et al., 2019; Avarmaa et al., 2016; Avarmaa et al., 2018; Gaskell & Laughlin, 2018; Kandalam et al., 2023; Klemettinen et al., 2020; Klemettinen et al., 2019; Mizuhata & Minami, 2011; Pereira, 2026f; Pereira, 2026h; Sukhomlinov et al., 2020; Taskinen et al., 2017).

An enrichment factor is conceptually different: it describes concentration relative to the feed, $EF = w_{in,product} C_t / w_{in,feed}$. A high EF can coexist with poor overall recovery if only a small fraction of the total indium mass reports to the enriched stream. Likewise, product yield is a mass ratio and should not be confused with metal recovery. These distinctions are especially important for dusts and concentrates, where strong enrichment may occur despite substantial losses elsewhere in the circuit.

Table 2 consolidates the principal accounting metrics used in this review and identifies the common interpretation error associated with each one.

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Pages: 1-36

Table 2
Accounting metrics for indium recovery and deportment.

Metric	**Generic expression**	**What it measures**	**Common misuse**
Gross recovery	mIn, product / mIn, feed	Fraction of feed indium in a selected product	Ignoring recycle accumulation or inventory change
Net recovery	Saleable or final recovered In / external feed In	Plant-wide realized recovery	Treating internal recycle as recovered product
Stage recovery	In out of one unit / In into that unit	Performance of a unit operation	Multiplying inconsistent stage recoveries
Yield	mass product/mass feed	Mass pull	Calling mass yield a metal recovery
Enrichment factor	wIn, product / wIn,feed	Concentration upgrade	Assuming high enrichment means high total recovery
Partition ratio	DIn(i/j) = wIn,i / wIn,j at stated T, pO2/pS2, composition, and equilibrium basis	Conditional relative phase preference	Treating D as a universal constant or applying equilibrium D to non-equilibrium streams
Balance closure	ΣIn,out + ΔIninventory / ΣIn,in	Accounting completeness over a defined interval	Accepting apparent 100% closure without uncertainty analysis
Recycle-adjusted recovery	(Recovered + bleed + emitted In) / external feed In	Finite-interval external disposition with inventory correction	Counting internal recycle as realized recovery
Balance residual, εbal	[Inin − Inout − ΔIninventory] / Inin × 100	Signed accounting residual	Interpreting small residual as proof that all measurements are unbiased

Note. Equations are generic definitions; specific symbols and system boundaries must be stated for each application.

The critical implication of Table 2 is that recovery should be reported with at least one deportment descriptor and one balance-quality descriptor. Without this combination, a percentage cannot distinguish a genuine process improvement from an inventory shift, a change in recycle status, or an analytical closure artifact.

4. Feed variability and initial indium deportment

Feed variability is often the hidden driver behind changes attributed to furnace performance. Indium-bearing zinc residues, jarosites, lead-smelting dusts, copper-smelting

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feeds, ITO targets, LCD glass, IGZO, CIGS, heterojunction photovoltaic materials, and InP scrap enter thermal processes with different indium grades, host phases, particle-size distributions, halogen contents, and volatile or combustible fractions (Cao et al., 2026; Ferella et al., 2017; Gu et al., 2026; He et al., 2026; Hong et al., 2010; Hu et al., 2022; Huang et al., 2024; Janošević et al., 2023; Kashyap & Taylor, 2022; Kaya et al., 2020; Li et al., 2024; Li et al., 2023; Mahiwan et al., 2026; Mejías et al., 2023; Pang et al., 2024; Parajuly & Wenzel, 2017; Peeters et al., 2013; Savvilotidou et al., 2014; Teknetzi et al., 2024; Teknetzi et al., 2023; Ueberschaar et al., 2017; Wang et al., 2024; Wang et al., 2019; Wang et al., 2023; Xu et al., 2024; Yang et al., 2023; Zhang et al., 2024; Zhu et al., 2025).

Figure 2 summarizes how compositional and physical variability acts through both thermodynamic and transport pathways. The same nominal furnace setpoint can therefore produce different indium deportment when the feed changes, even if operators observe no obvious shift in bulk throughput.

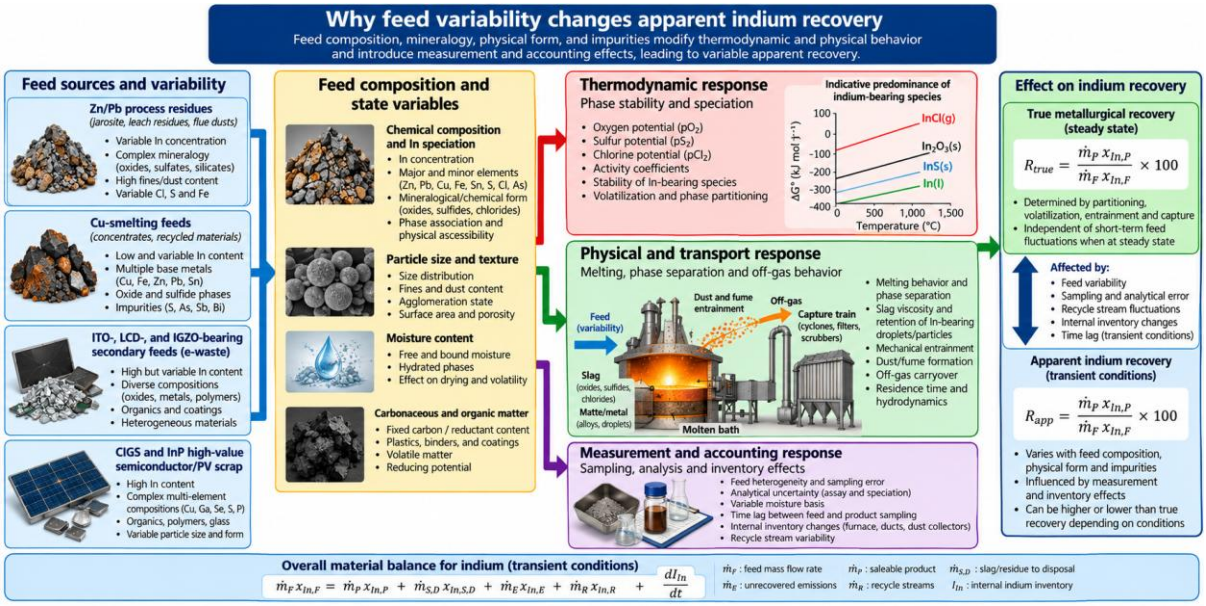


Figure 2. Coupling between indium-bearing feed variability, thermodynamic response, and physical transport behavior.

Note. Author-developed conceptual synthesis from the feed, recycling, and pyrometallurgical studies discussed in this review. Any numerical-looking inset is illustrative only and is not an empirical dataset.

As shown in Figure 2, feed characterization must include variables that govern activity and speciation, as well as variables that govern melting, viscosity, dust formation, and entrainment. A metallurgical accounting program that records only total indium grade cannot

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Pages: 1-36

explain a shift from slag loss to dust loss when chloride, sulfur, particle size, moisture, or organics change.

The pre-processing literature further demonstrates that crushing, sorting, thermal treatment, and selective disassembly can either concentrate indium or transfer it into fine fractions that are difficult to recover. This is important because a downstream furnace may appear inefficient when a meaningful part of the indium has already been lost upstream (Charpentier et al., 2023; Marra et al., 2018; Tansel, 2017; Tesfaye et al., 2017; Ueberschaar et al., 2017; van Schaik et al., 2018; Zeng et al., 2018; Zhang & Xu, 2016).

5. Losses to slag

Slag loss is the most obvious chemical-loss pathway, but it combines at least two distinct mechanisms: indium dissolved or structurally incorporated in the slag phase and indium-bearing metal or matte droplets that are physically entrained. Experimental studies on copper and WEEE smelting show that minor-element distribution depends strongly on slag composition, oxygen potential, temperature, and the identity of the coexisting condensed phase (Anindya et al., 2014; Avarmaa et al., 2016; Avarmaa et al., 2018; Jalkanen et al., 2003; Kandalam et al., 2023; Klemettinen et al., 2020; Klemettinen et al., 2019; Pereira, 2026f; Pereira, 2026h; Su et al., 2026; Sukhomlinov et al., 2020; Taskinen et al., 2017).

Chemical partitioning should be diagnosed using equilibrated or near-equilibrated phase assays together with phase-specific characterization. Whole-slag assays should be corrected, where feasible, for indium carried by entrained metal or matte droplets identified by microscopy, automated mineralogy, or other phase-resolved methods. By contrast, entrainment requires droplet-size analysis, settling behavior, residence time, tapping hydrodynamics, and explicit consideration of slag viscosity. Treating both mechanisms simply as “slag loss” can lead to an incorrect intervention: stronger reduction may lower dissolved indium while simultaneously worsening metal entrainment if phase separation deteriorates.

For industrial optimization, the critical control variables are coupled. Redox conditions alter indium activity and oxidation state; flux additions and Fe/Si/Ca/Al ratios alter slag structure and liquidus behavior; temperature changes both equilibrium and viscosity; metal/matte phase ratio affects collector capacity; and settling time and tapping hydrodynamics

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JIRRS Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

govern physical separation. Lower viscosity may improve droplet settling in one system but can also shift liquidus behavior, refractory wear, impurity partitioning, and redox response. The practical target is therefore a process-specific operating window rather than a universal minimum-viscosity or maximum-reduction condition.

6. Losses to matte and metal phases

Indium reporting to matte or metal is not inherently a loss. Whether it is beneficial depends on the downstream route, the concentration achieved, and the ability to liberate indium from the host phase. Copper-smelting studies demonstrate that minor elements can partition strongly among matte, metal, and slag as oxygen and sulfur potentials change (Avarmaa et al., 2019; Avarmaa et al., 2016; Avarmaa et al., 2018; Klemettinen et al., 2020; Klemettinen et al., 2019; Pereira, 2026f; Pereira, 2026h; Sukhomlinov et al., 2020; Taskinen et al., 2017).

A metal-rich collector can be advantageous when the subsequent refining sequence concentrates indium into a manageable intermediate. However, it becomes a hidden loss when indium is diluted into a large host-metal flow, trapped in an unrecoverable alloy, or repeatedly recycled without a defined bleed and recovery step. The literature on Pb–In–Zn enrichment, Ga–In alloys, and integrated secondary-resource processing illustrates both opportunities and constraints (Li et al., 2024; Li et al., 2023; Wang et al., 2023; Zhu et al., 2025).

This distinction supports a broader accounting rule: a stream should be classified by its ultimate fate, not by whether it is nominally a “product” at one stage. Stage recovery can therefore be high while net plant recovery remains low.

7. Dust entrainment and true volatilization

Dust formation is frequently conflated with volatilization. Mechanical dust entrainment transfers pre-existing solids or droplets into the gas path, whereas true volatilization requires transfer of indium into a gas-phase species before condensation. Both mechanisms may occur simultaneously, especially with fine, chloride-bearing, or highly reactive secondary feeds. Vacuum reduction, chlorination, roasting, and thermal-separation studies show that indium can be deliberately transferred to a volatile or condensable form under suitable conditions (Gu et al., 2026; He et al., 2026; He et al., 2014; Huang et al., 2024; Ma & Xu, 2013; Ma et al., 2012;

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JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

Mahiwan et al., 2026; Pang et al., 2024; Pereira, 2025; Pereira, 2026a; Pereira, 2026b; Pereira, 2026c; Pereira, 2026d; Pereira, 2026e; Pereira, 2026g; Pereira, 2026i; Pereira, 2026j; Sawai et al., 2015; Wang et al., 2019; Zhang et al., 2024; Zhang et al., 2023).

Figure 3 provides the diagnostic taxonomy used to separate these mechanisms from one another and from accounting artifacts. The key practical point is that the same measured high indium content in dust can arise from desirable volatilization followed by efficient capture, or from undesirable mechanical carryover of valuable condensed material.

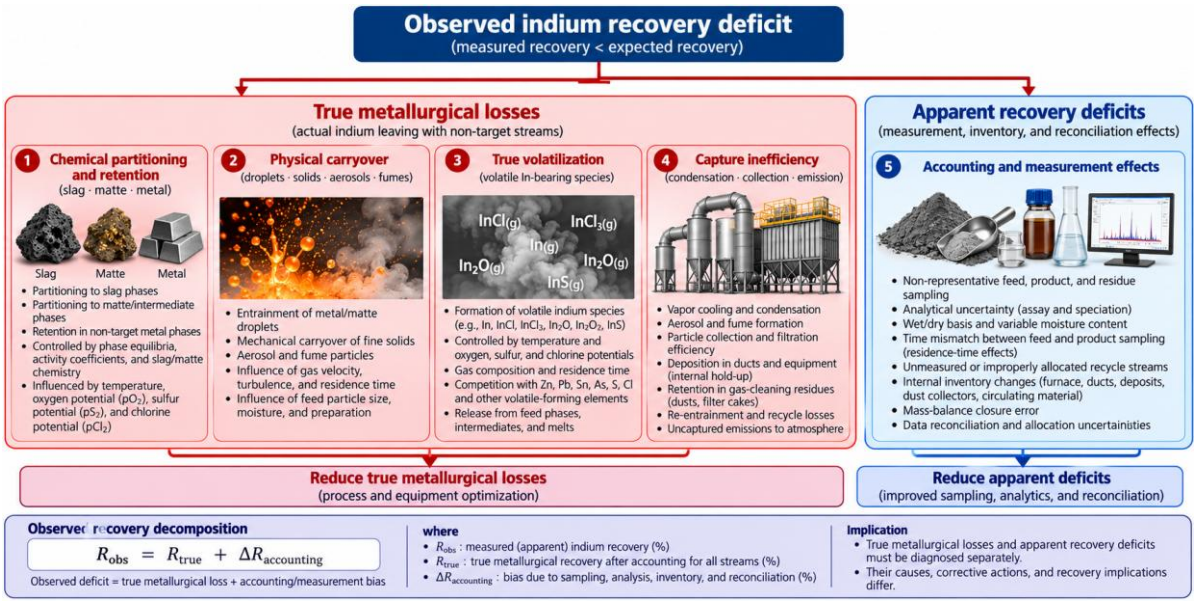


Figure 3. Mechanistic taxonomy of apparent indium recovery deficits.
Note. Author-developed conceptual synthesis from the process mechanisms and accounting distinctions synthesized in this review.

Figure 3 shows why dust assay alone cannot identify the controlling mechanism. A defensible vaporization claim should be supported, where feasible, by particle morphology and size distribution, mineralogy or phase chemistry, furnace and duct temperature history, condensation location, species/thermodynamic evidence, and size-resolved gas-path sampling. Coarse irregular particles and droplets are more consistent with mechanical carryover, whereas nucleated ultrafine aerosol or systematic downstream condensation can support a volatilization–condensation pathway. Because both mechanisms may coexist, uncertainty should be retained when evidence is insufficient. This distinction is especially important in chlorination or vacuum routes, in which deliberate volatilization may be the intended separation mechanism rather than a loss pathway.

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Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

8. Condensation and off-gas capture losses

Once indium enters the gas path, recovery becomes a sequence of transport and separation steps. Vapors may nucleate homogeneously, condense on existing particles, deposit on duct surfaces, or remain in ultrafine aerosols. Entrained solids may settle, be collected in cyclones, or pass to high-efficiency filtration. Consequently, “volatilized indium” and “lost indium” are not synonymous.

Figure 4 shows the accounting logic for the off-gas train. Each segment should be treated as a sampling domain because apparent recovery depends on where condensation occurs and where captured solids are routed.

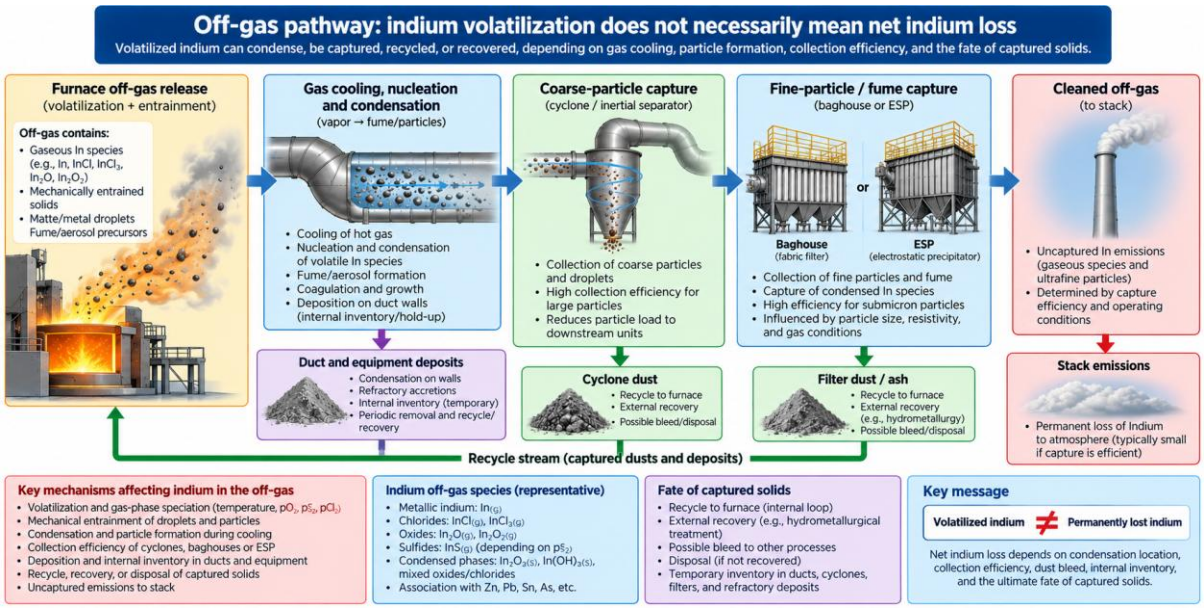


Figure 4. Off-gas pathway for indium: release, condensation, particulate capture, and recycle.
Note. Author-developed conceptual synthesis from thermal, chlorination, volatilization, dust-recovery, and recycling studies cited in the text. The figure represents sequential release–condensation–collection–product recovery conceptually; serial particulate-collector efficiency is calculated from the product of penetrations, $\eta_{overall} = 1 - \prod(1 - \eta_i)$, rather than by multiplying collector efficiencies.

As indicated in Figure 4, off-gas recovery must distinguish successive conditional steps from serial particulate collection. For a volatilization-based recovery route, a conditional recovery chain may be written $R_{gas} = \eta_{release} \times \eta_{condensation} \times \eta_{collection} \times \eta_{product}$, because each term represents a successive fraction of indium surviving to the next recovery step. By contrast, for n particulate collectors operating in series on the aerosol remaining after each device, the combined collection efficiency is $\eta_{collection,overall} = 1 - \prod_i(1 - \eta_i)$, where

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Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

ηi is the fractional collection efficiency of collector i under the relevant particle-size and gas conditions. The two formulations are not interchangeable. Leaks, bypass, re-entrainment, uncontrolled cooling, duct deposition, aerosol size, and dust bleeding must be accounted for separately.

Quantitative gas-path accounting should use representative, and where applicable isokinetic, sampling at defined domains upstream and downstream of cooling, cyclones, ESPs, baghouses, recycle take-offs, and the stack. Cyclones, ESPs, and baghouses should not be treated as equivalent devices because their performance depends differently on particle aerodynamic diameter, resistivity, gas temperature, loading, and conditioning. Duct and equipment deposits must be included as temporary inventory, periodically recovered material, or permanent loss according to the cleaning practice and accounting interval.

High-chlorine dust treatment, thermal chlorination, controlled-pressure pyrolysis–spray condensation, vacuum separation, and segmented roasting illustrate how gas-path chemistry can be engineered to convert indium into a recoverable intermediate (Gu et al., 2026; He et al., 2026; Huang et al., 2024; Ma & Xu, 2013; Ma et al., 2012; Mahiwan et al., 2026; Zhang et al., 2024). The evidence also shows that downstream purification must be considered when the target condensed phase is selected (Chen et al., 2017; Drzazga et al., 2021; Huang et al., 2024; Illés et al., 2022; Kluczka, 2024; Nguyen & Lee, 2019; Pradhan et al., 2018; Tan et al., 2023; Tian et al., 2026; Van den Bossche et al., 2019; Wang et al., 2025; Zheng et al., 2023).

9. Recycle loops, accumulation, and delayed recovery

Recycle streams can raise eventual recovery while simultaneously obscuring short-term accounting. Dust recycle, internal return of slags or residues, and repeated treatment of intermediate streams create inventories whose indium content changes over time. If a campaign is evaluated before the recycle inventory reaches steady state, apparent recovery can be artificially low or high.

Circular-economy and material-centric recycling studies reinforce the need to separate internal recirculation from external recovery (Awasthi & Li, 2017; Hagelüken & Goldmann, 2016; Parajuly & Wenzel, 2017; Sverdrup et al., 2017; Tesfaye et al., 2017; van Schaik et al., 2018; Watari et al., 2020; Ylä-Mella & Pongrácz, 2016; Zeng et al., 2018). A material can

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JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

circulate through several unit operations while remaining technically unrecovered, and repeated cycling can also concentrate deleterious impurities that eventually force a bleed stream.

For this reason, plant-wide recovery should be reconciled over a time window long enough to capture delayed recovery and campaign-to-campaign inventory effects. The external balance includes feed, saleable or deliberately stored recovered products, deliberate bleeds or purges, emissions, and the change in internal inventory; internal recycle cancels when the boundary is correctly drawn. Deliberate bleed streams must be defined and their indium content quantified rather than hidden within a generic waste term. Inventory reconciliation should include, where material, bins, silos, ducts, filters, dust hoppers, vessels, and recycle holdup. A transient circuit should not be evaluated as though it were at steady state.

10. Sampling, analytical uncertainty, and mass-balance closure

A metallurgical balance is only as reliable as its sampling and analytical system. Indium is often present at trace or minor concentrations, and the most indium-rich streams may be fine dusts, heterogeneous residues, or intermittent deposits. Such streams are especially vulnerable to segregation, moisture bias, incomplete sample recovery, and inconsistent digestion or assay methods.

The accounting literature on element-specific recycling efficiency and process distribution indicates that apparent losses can be generated when the sampling boundary does not match the physical process boundary (Pereira, 2026f; Pereira, 2026h; Sukhomlinov et al., 2020; Ueberschaar et al., 2017). For indium, this risk is amplified by recycle delays and by the possibility that a small mass of highly enriched dust contains a large fraction of the indium inventory.

All relevant mass flows should be expressed on a consistent dry basis using paired moisture and elemental assays. Replicate or duplicate sampling should be retained for heterogeneous streams, and cross-laboratory checks, certified reference materials, blanks, spikes, or other fit-for-purpose QA/QC should be used where analytical matrix effects are material. Rare, highly enriched bleed or deposit streams must be sampled and reconciled

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Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

separately because a small mass flow can carry a disproportionate share of the indium inventory.

For a derived quantity y = f(x1, x2, …, xn), first-order uncertainty propagation can be expressed as uc(y) = [Σ(∂f/∂xi)²u²(xi)]1/2 when covariance is negligible. For correlated inputs, covariance terms 2Σi<j(∂f/∂xi)(∂f/∂xj)cov(xi,xj) should be included. For a simple recovery R = 100 A/B, the approximate relative standard uncertainty is uc(R)/R ≈ [(uA/A)² + (uB/B)² − 2cov(A,B)/(AB)]1/2. Accordingly, a reported recovery change smaller than the combined sampling, moisture, analytical, and inventory uncertainty should not be interpreted as a demonstrated process improvement.

Table 3 presents a practical uncertainty checklist. It is designed to force separation between a process deficit and a measurement deficit before major operating changes are made.

Table 3
Diagnostic checklist for indium mass-balance closure.

Potential bias	**Typical symptom**	**Verification action**	**Accounting consequence**
Feed heterogeneity	Large assay scatter between increments	Incremental composite sampling; duplicate composites	Uncertain denominator
Moisture error	Dry-basis and wet-basis inconsistencies	Paired moisture and metal assays	Biased stream mass
Fine-dust loss	Poor closure despite low slag/metal In	Isokinetic or representative dust sampling; duct deposit survey	Unmeasured output
Inventory change	Recovery shifts with campaign duration	Tank/bin/duct/recycle inventory reconciliation	Time-lag artifact
Assay matrix effect	Systematic inter-laboratory difference	Certified standards, spikes, cross-lab checks	Biased grade
Rare enriched stream	Small bleed dominates In loss	High-frequency measurement of bleed streams	Underestimated true loss

Note. Prepared by the author as an accounting framework consistent with the analytical and process literature cited in this section.

Table 3 highlights that closure close to 100% is not, by itself, proof of correctness. Compensating errors can produce apparently excellent closure. Confidence therefore requires explicit balance residuals and propagated uncertainty, replicate sampling, paired

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JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

moisture/elemental assays, QA/QC checks, representative or isokinetic gas-path sampling where appropriate, and a clear statement of whether each value is measured, calculated, estimated, or inventory-derived. Recovery differences should be reported with uncertainty or confidence limits whenever the underlying data permit.

11. Process integration and downstream implications

The optimal location for indium in a pyrometallurgical flowsheet depends on the downstream recovery route. As contextual/downstream evidence rather than direct pyrometallurgical validation, hydrometallurgical literature demonstrates a broad toolbox for recovering indium from residues, leach liquors, ITO/LCD materials, and mixed critical-metal streams, including solvent extraction, ion exchange, adsorption, bioleaching, membrane separation, precipitation, cementation, and electrorefining (Akama et al., 2016; Chinnam et al., 2020; De-la-Cruz-Moreno et al., 2021; Drzazga et al., 2021; Huang et al., 2023; Illés et al., 2022; Jeon et al., 2015; Jowkar et al., 2018; Kang et al., 2011; Kato et al., 2013; Khezerloo et al., 2023; Lahti et al., 2020; Li et al., 2012; Li et al., 2015; Li et al., 2011; Nusen et al., 2016; Pereira & Silva, 2025; Pourhossein et al., 2022; Qin et al., 2021; Qin et al., 2023; Ruan et al., 2012; Rudnik, 2026; Sethurajan et al., 2019; Shen et al., 2013; Song et al., 2020; Souada et al., 2018; Swain et al., 2015; Tan et al., 2023; Theocharis et al., 2021; Virolainen et al., 2011; Wang & Lee, 2013; Wang et al., 2025; Willner et al., 2022; Yang et al., 2013; Zeng et al., 2022; Zhang et al., 2016; Zhang et al., 2017; Zhang et al., 2020; Zhang et al., 2023; Zhang et al., 2021).

These downstream routes matter to pyrometallurgical optimization because the “best” thermal product is not necessarily the one with the highest indium grade. A dust or oxide may have a lower grade but superior leachability and impurity separation, whereas an alloy may strongly enrich indium but require more difficult refining. The appropriate objective is therefore to maximize recoverable value across the integrated flowsheet, subject to impurity, energy, reagent, and recycle constraints.

Process integration also changes the interpretation of loss. For example, deliberate volatilization followed by high-efficiency capture may outperform attempts to retain indium in a metal phase, provided the condensed product is suitable for subsequent purification.

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Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

Conversely, high furnace retention can be undesirable if it sends indium to a host-metal product from which recovery is technically or economically impractical.

12. Strategies for maximizing overall recovery

The most robust improvement strategy is diagnostic rather than prescriptive. It begins with a closed balance, identifies the dominant loss class, verifies the mechanism using independent evidence, and then modifies the smallest number of variables needed to shift indium into a deliberately recoverable stream. Figure 5 converts this logic into a practical decision framework.

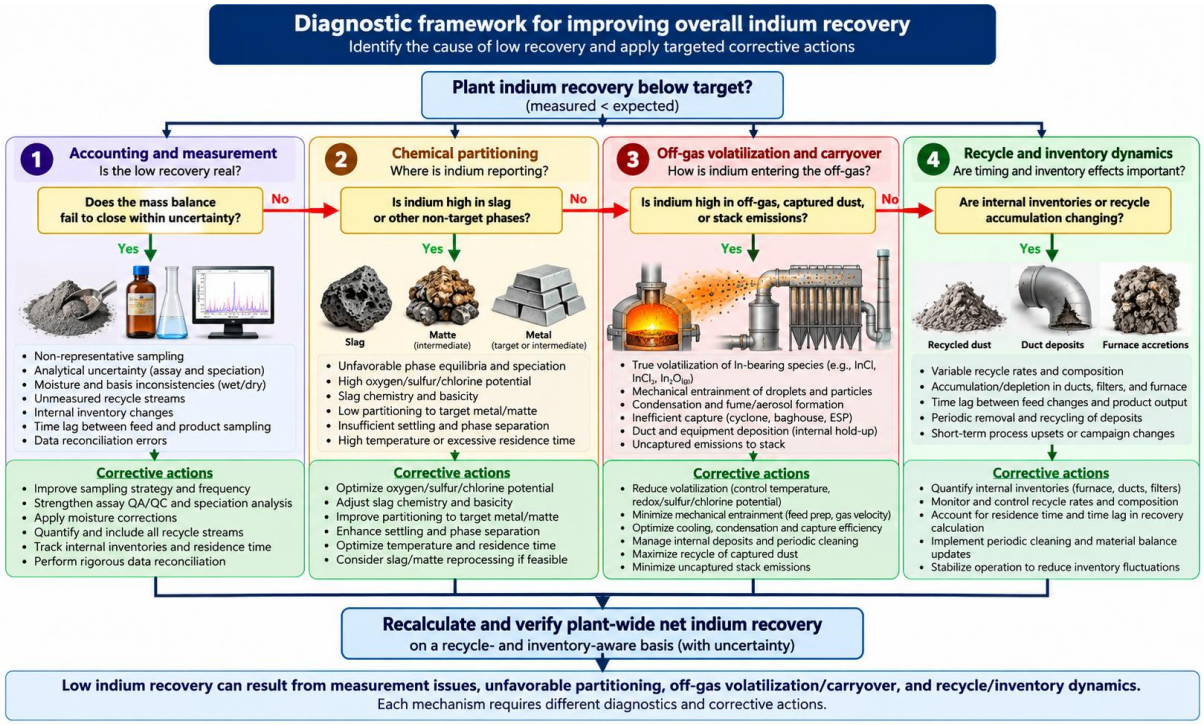


Figure 5. Diagnostic framework for locating and recovering missing percentage points of indium recovery.

Note. Author-developed diagnostic synthesis from the integrated metallurgical-accounting framework proposed in this review; the sequence is diagnostic rather than a universal prescriptive furnace recipe.

Figure 5 emphasizes that a recovery deficit should not immediately trigger more reducing conditions, higher temperature, or stronger volatilization. If the deficit is analytical, those changes may worsen the process. If the deficit is physical entrainment, chemistry changes may be secondary to settling and hydrodynamics. If the deficit is off-gas capture, the furnace may already be performing the intended separation correctly.

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Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

Table 4 translates the framework into specific interventions and identifies the main trade-offs to check before implementation.

Table 4
Recovery-improvement levers by dominant indium loss mechanism.

Dominant mechanism	**Primary levers**	**Expected benefit**	**Key trade-off/risk**
Chemical slag loss	Redox control; slag basicity/composition; temperature; phase ratio	Shift In toward collector or volatile phase	Higher co-reduction, refractory wear, impurity transfer
Entrained droplets/particles	Lower viscosity; longer settling; calmer tapping; better agglomeration	Recover mechanically trapped In	Lower throughput or larger equipment
Insufficient volatilization when desired	Temperature; chlorination potential; reductant; residence time	Increase transfer to gas-phase recovery route	Corrosion, reagent use, impurity co-volatilization
Excess dust carryover	Feed sizing; charging practice; gas velocity; pelletization/agglomeration	Reduce physical loss and filtration load	Pretreatment cost, mass-transfer changes
Poor capture	Controlled cooling; staged separation; baghouse/ESP optimization	Convert gas-path In into recoverable dust	Pressure drop, fouling, condensation/corrosion
Recycle accumulation	Define bleed and recovery step; inventory control	Convert delayed recovery into realized recovery	Impurity build-up, additional unit operations
Accounting uncertainty	Representative sampling; QA/QC; inventory reconciliation	Prevent false optimization signals	Higher analytical effort and cost

Note. Prepared by the author from the mechanistic evidence and integrated analysis presented in this review.

Across the reviewed literature, five cross-cutting principles emerge. First, optimize indium recovery on a net, plant-wide basis rather than at an isolated unit operation. Second, measure chemical and physical losses separately. Third, when volatilization is important, treat the gas path as a metallurgical separation train, with release, condensation, particulate capture, and final product recovery reported separately. Fourth, recycle streams require explicit inventory accounting and a defined route to final recovery. Fifth, report enriched dusts with both dust mass yield and indium enrichment/recovery; a high enrichment factor EFdust =

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Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

wIn,dust/wIn,feed does not imply high indium recovery, which is RIn,dust = mdust wIn,dust/(mfeed wIn,feed).

The industrial significance is amplified by indium criticality and by-product supply constraints. Improvements that recover only a few additional percentage points can be meaningful when applied to large host-metal throughput or concentrated secondary streams (Cao et al., 2021; European Commission, 2017; European Commission, 2020; European Commission, 2023; Golev et al., 2019; Lokanc et al., 2015; Nassar et al., 2015; Reuter et al., 2019; Sverdrup et al., 2017; U.S. Geological Survey, 2023; U.S. Geological Survey, 2024; U.S. Geological Survey, 2025; U.S. Geological Survey, 2026; Werner et al., 2015). However, recovery should not be maximized without regard to energy and reagent demand, emissions, corrosion, dust handling, and downstream purification. Technology selection must therefore combine metallurgical recovery with process safety, environmental performance, and economic value realization (Becci et al., 2024; Hemmati et al., 2023; Huang et al., 2024; Kluczka, 2024; Pradhan et al., 2018; Sverdrup et al., 2017; Watari et al., 2020; Ylä-Mella & Pongrácz, 2016; Zheng et al., 2023).

13. Conclusion

Indium recovery in pyrometallurgical processing is best understood as a metallurgical-accounting problem with multiple, coupled loss mechanisms. The central question is not only how much indium is recovered but also where the unrecovered fraction resides and how it reached that location. Chemical partitioning to slag, matte, or metal must be distinguished from physical entrainment, true volatilization from dust carryover, and successful volatilization from successful downstream capture. Recycle loops further separate short-term apparent recovery from long-term net recovery, while sampling, assay, moisture, and inventory uncertainty can create deficits that do not correspond to a physical loss.

The critical framework developed here therefore places mass-balance closure and mechanism identification before process optimization. Once the dominant loss class is localized, recovery can be improved through targeted control of feed state, redox conditions, slag properties, settling, temperature, gas-path chemistry, cooling, particulate capture, recycle management, and analytical practice. The most defensible performance indicator is a recycle-

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Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

aware, plant-wide net recovery accompanied by deportment data and an uncertainty statement. This framework converts a single headline percentage into a diagnostic system that identifies where recovery points are lost and which intervention is most likely to recover them.

Declarations

Funding

This review received no specific external funding.

Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. All quantitative and qualitative evidence discussed in the review is traceable to the cited literature.

Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

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Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/10/2026
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Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 13/10/2026
Vol: 1.03
DOI: 10.66104/435fmm02
Pages: 1-36

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