JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.11
DOI: 10.66104/zxrxwx84
Pages: 1-33

Mineralogical Association of Elements in Electric Arc Furnace Dust: Elemental Deportment, Phase Hosts, and Metallurgical Implications—A Critical Review

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Abstract

Electric arc furnace dust (EAFD) is a multielement, multiphase residue whose response to mineral processing and metallurgical treatment cannot be predicted from bulk assays alone. This thematic critical review evaluates the allocation of Zn, Fe, Pb, Cd, Cr, Mn, Ni, alkaline-earth elements, silicates, halogens, and sulfur among crystalline, poorly crystalline, amorphous, and surface-associated hosts. The proposed chain of evidence distinguishes phase abundance, elemental deportment, oxidation state, particle architecture, intrinsic phase reactivity, geometric accessibility, and measured process response. Quantitative deportment, independent elemental closure, and explicitly unassigned inventory are recommended instead of forced stoichiometric assignment. Comparisons of exposed ZnO, substituted Zn-bearing spinels, and enclosed Zn-bearing grains show why intrinsic chemical resistance must be distinguished from transport limitations caused by encapsulation. Correlative diffraction, electron microscopy, microanalysis, spectroscopy, and before–after process balances support evidence-gated treatment screening without treating selective extraction as unique mineral identification. The principal limitation remains incomplete cross-feedstock validation of phase-resolved behavior.

Keywords: electric arc furnace dust; mineralogical association; elemental deportment; zinc ferrite; correlative mineralogy; process selectivity

Highlights

- Bulk chemical assays cannot establish the mineralogical hosts of EAFD elements.
- Phase abundance, elemental deportment, and particle accessibility require separate evidence.
- Correlative mineralogy is essential for discriminating spinels and surface condensates.
- Host-phase information can improve the defensibility of EAFD flowsheet screening.

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Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.11
DOI: 10.66104/zxrxwx84
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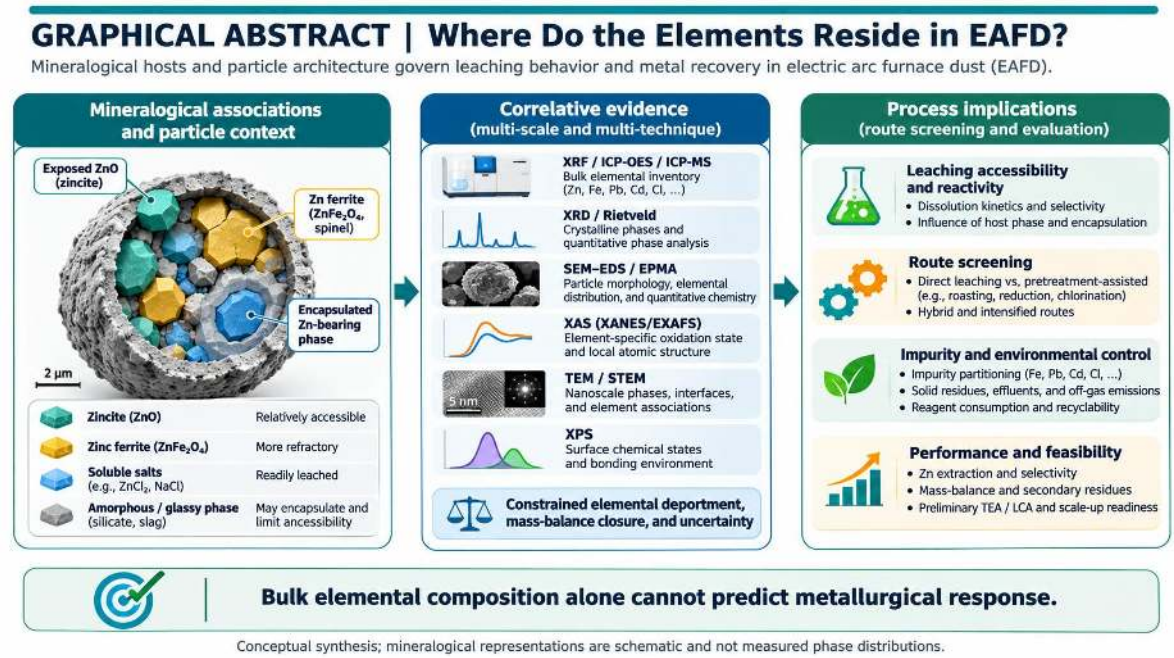
Graphical Abstract



Note. Original conceptual graphic created for this manuscript.

1. Introduction

Electric arc furnace dust (EAFD) contains zinc and iron as economically important constituents alongside minor and trace metals, gangue-forming elements, halogens, and sulfur. A bulk concentration is a weighted sum over chemically and physically dissimilar hosts; it does not specify whether a metal is present in an exposed oxide grain, a mixed spinel, a silicate inclusion, a condensed surface layer, or an amorphous component. As a result, two samples with similar global zinc concentrations may show contrasting selective dissolution, reduction, and residue behavior. The central question addressed here is where each element resides and how its host and position control process accessibility.

This review therefore distinguishes phase abundance, elemental loading, chemical valence, geometric accessibility, and actual extractability. Figure 1 sets out the governing sequence, while Table 1 contrasts candidate hosts and analytical implications. The intention is not to assert a universal EAFD mineralogy, but to specify what evidence is required before an association can be claimed and used in route selection.

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Earlier reviews by the author emphasized EAFD recovery routes, phase identification, weathering, and environmental performance. By contrast, this article focuses on how quantitatively constrained element-to-phase allocation and spatial mineralogical associations bridge characterization and route selection. The contemporary review of functional-material valorization by Liu et al. (2026) addresses a distinct downstream objective, whereas the present framework tests the evidence needed for assigning elements to hosts, reconciling unassigned inventory, and distinguishing phase transformation from actual elemental recovery.

Figure 1 summarizes the conceptual distinctions necessary to interpret this evidence without equating bulk chemistry with phase-resolved measurements.

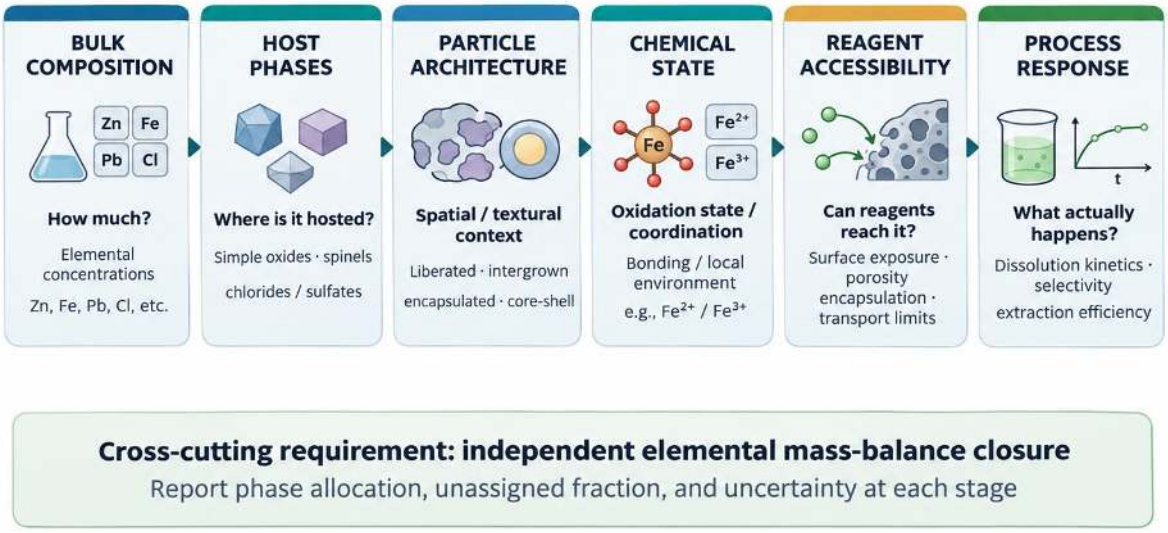

Figure 1. From bulk composition to processing response: the required chain of evidence.
Note. Original schematic created for this manuscript.

The schematic is a conceptual framework rather than a measured mineralogical map. Its proposed links require confirmation by complementary analyses and mass-balance closure.

Table 1 summarizes the relevant interpretation framework and the analytical limits that must be communicated.

Table 1. Indicative hosts and process questions

Element/group	Candidate association	Key uncertainty
Zn	ZnO; $ZnFe_2O_4$; mixed spinels; salts	Phase allocation and liberation

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Element/group	Candidate association	Key uncertainty
Fe	Oxides; spinels; metallic or amorphous hosts	Valence and matrix association
Pb/Cd	Surface condensates; oxides; salts; substitutions	Discreteness versus surface loading
Cr/Mn/Ni	Mixed spinels and solid solutions	Partitioning by EAFD origin
Ca/Mg/Al/Si	Carbonates; oxides; silicates; glass	Acid demand and encapsulation
Cl/F/S/Na/K	Soluble salts; bound or surface species	Washing and volatility

Note. Original qualitative synthesis; not a substitute for quantitative phase or deportment measurements.

Interpret these categories as screening hypotheses, not fixed signatures across furnace types, feed mixtures, or operating conditions.

2. Scope and Critical Review Methodology

2.1. Scope and evidence hierarchy

The review covers fresh and weathered EAFD, particle-size fractions, processing residues, and thermally transformed products. The initial corpus comprised 145 consolidated bibliography entries selected from an earlier literature collection focused on 2020–2026, selectively extended to 2010–2026. The manuscript and the two additions noted below were checked for relevance on 6 November 2026, which is the final update date for this revision. The existing collection is described as a thematic synthesis: its historical database-by-database retrieval and full-text screening cannot be independently reconstructed, and this article does not claim a new systematic Scopus or Web of Science search. Publisher and bibliographic records were checked for the two newly included 2026 reviews. Neither PRISMA coverage nor exhaustive retrieval is claimed.

Representative reproducible topic-based Boolean expressions are: ("electric arc furnace dust" OR EAFD) AND (mineralogy OR "phase identification" OR Rietveld); (EAFD OR "steelmaking dust") AND (ZnO OR ZnFe2O4 OR franklinite OR "zinc ferrite"); (EAFD OR "electric arc furnace dust") AND (lead OR cadmium OR Pb OR Cd) AND (association OR condensate OR surface); (EAFD OR "stainless steel dust") AND (chromium OR manganese OR nickel) AND (spinel OR speciation); (EAFD OR "steelmaking dust") AND (chloride OR fluorine OR sulfur OR sulphate) AND (washing OR mineralogy); (EAFD OR

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"electric arc furnace dust") AND ("correlative microscopy" OR EPMA OR SEM-EDS OR XAS OR Mössbauer); and (EAFD OR "steelmaking dust") AND ("process mineralogy" OR "elemental deportment" OR liberation OR accessibility). These expressions document a repeatable search strategy for subsequent updates, not an independently verified record of the original historical database queries.

Evidence is ranked operationally: direct phase identification supported by diffraction and independent chemical measurements; element–phase allocation corroborated by microanalysis; oxidation/coordination measurements; indirect chemical fractionation; and finally predictive calculations or mechanistic analogies. Selective extraction, in particular, indicates operationally defined solubility, not necessarily a unique crystalline identity. Competing assignments should remain open where methods lack spatial or structural resolution.

The cited thermal and hydrometallurgical investigations define different classes of EAFD treatment, but their reporting metrics cannot be combined without distinguishing feed mineralogy, reaction conditions, and residue composition. For a phase-host review, the relevant evidence is whether each treatment study measured the starting and transformed solids rather than merely reporting bulk recovery. (Al-Harahsheh et al., 2017; Al-Harahsheh et al., 2014; Borda et al., 2022; Brandner et al., 2021). Further comparative studies addressing these constraints include Pereira et al., 2026; Puttaswamy et al., 2026; Suárez-Macías et al., 2022; Trifunović et al., 2022.

Methodological and applications-oriented reports expand the sampling and process boundary, but do not, by themselves, determine which elements occupy individual phases. Their value is primarily in identifying analytical or downstream endpoints that require mineralogical corroboration. (Khanmohammadi Hazaveh et al., 2020; Lanzerstorfer et al., 2023; Lin et al., 2017; Omran et al., 2017). Further comparative studies addressing these constraints include Xue et al., 2023.

3. Mineralogical Association Versus Bulk Composition

Let f_i denote the mass fraction of phase i and $C_{j,i}$ the mass fraction of element j within that phase. The bulk concentration C_j is $C_j = \Sigma_i f_i C_{j,i}$. This accounting identity is useful for

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deportment only when the phase inventory is sufficiently complete, and the elemental compositions are independently constrained. Ignoring unresolved amorphous material or forcing phases to ideal stoichiometry can give an apparently closed mineralogical balance that is structurally wrong.

A zinc-bearing phase comprising a small mass of dust may nevertheless contain a large fraction of the zinc inventory. Conversely, a common iron-rich phase can host only a small fraction of the zinc inventory. Reporting only bulk Zn or total crystalline fractions conflates these separate denominators. A defensible balance therefore reports measured phase proportions, element concentrations by phase, total element closure, residual unassigned material, and uncertainty.

For a phase i and element j, elemental deportment is $D_{j,i} = (f_i\ C_{j,i})/C_j,F$, where the phase and feed compositions are evaluated on the same dry-mass basis. For a finite process stream, elemental closure (%) = $100 \times [\Sigma_i(m_i\ C_{j,i})]/(mF\ C_j,F)$. Both numerator and denominator must use measured stream masses and element concentrations; closure should be reported separately for Zn, Fe, Pb, Cd, Cr, Mn, Ni, and Cl wherever analytically relevant. Report any unresolved/amorphous inventory and unassigned elemental fraction rather than assigning it to an assumed ideal spinel. Propagate uncertainty from phase abundance, spot chemistry, sampling, and bulk assays; crystalline-phase closure is not equivalent to elemental mass closure.

Evidence derived from phase analysis and selective dissolution illustrates a fundamental identification problem: chemical extraction is a response variable, whereas crystalline-phase attribution is a structural claim. A valid deportment argument requires quantitative reconciliation of the two rather than assuming one measures the other. (Al-Harahsheh et al., 2021; Fărcean et al., 2026; Gualtieri et al., 2019; He et al., 2026). Further comparative studies addressing these constraints include Pereira, 2026; Simonyan et al., 2019; Toraya, 2019; Xue et al., 2025.

Treating all zinc as a single chemical inventory conceals differences between directly accessible oxides, substituted spinels, and material released only after phase transformation. The comparative question is therefore not simply which route extracts more zinc, but which

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host fractions are demonstrably depleted. (Lanzerstorfer et al., 2020; León-Reina et al., 2016; Leuchtenmüller et al., 2025; Pereira, 2026a).

4. Zinc Mineralogical Associations

4.1. Zincite and zinc-bearing spinels

Zincite (ZnO) and zinc ferrite ($ZnFe_2O_4$) represent contrasting structural environments and, often, contrasting dissolution behavior. However, the label “franklinite” should not imply end-member stoichiometry when manganese, iron, zinc, and other metals occupy substituted spinel sites. Any claim that a given process selectively removes ZnO while preserving zinc ferrite requires direct before–after phase evidence rather than total zinc recovery alone.

The $ZnFe_2O_4$ fraction should not be treated as a fixed feed property. Otero Olmos et al. (2026) review zinc-ferrite formation through solid–solid and Zn-vapor/iron-oxide gas–solid interactions in steelmaking off-gas systems, demonstrating the relevance of reaction mechanism, temperature, gas composition, and kinetics. Direct EAFD process-mineralogy and electronic-structure evidence from He et al. (2026) further supports characterization of individual Zn hosts rather than inference from total Zn. Substitutions, crystal defects, particle dimensions, thermal history, and accessibility can modify ferrite reactivity, so no universal leaching severity should be assigned to the $ZnFe_2O_4$ label alone.

4.2. Secondary and surface hosts

Potential supplementary zinc hosts include silicates, sulfates, chlorides, glassy domains, and surface-associated material. Their prevalence can change with furnace conditions, quench history, particle size, aging, and washing. A low-intensity diffraction signal does not rule out a significant dissolved or amorphous zinc inventory. This uncertainty motivates paired quantitative diffraction, particle-scale mapping, and chemical accounting.

Secondary Zn-bearing salts and surface condensates may dissolve rapidly while glassy or silicate-bound Zn may respond slowly for reasons independent of ferrite crystal stability. A practical differentiation is to compare mild leaching, targeted liberation or attrition, and phase-transforming pretreatment against the same measured feed mineralogy.

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Miranda et al. (2026) provide a contemporary leaching context; Xue et al. (2025) illustrate the need to trace phase transformation together with elemental migration in products and residues. These studies are informative but cannot substitute for sample-specific phase inventories.

Figure 2 summarizes the conceptual distinctions necessary to interpret this evidence without equating bulk chemistry with phase-resolved measurements.

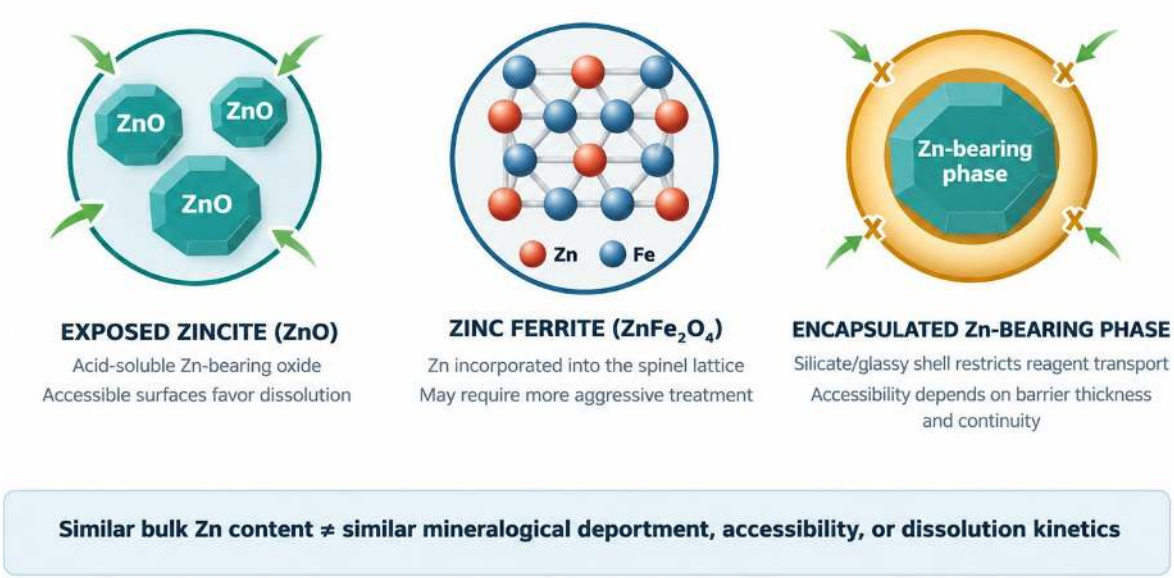

Figure 2. Candidate zinc host classes and the distinct accessibility questions they raise.
Note. Original schematic created for this manuscript.

The schematic is a conceptual framework rather than a measured mineralogical map. Its proposed links require confirmation by complementary analyses and mass-balance closure.

Studies involving zinc ferrite and secondary zinc-bearing residues offer mechanistic comparisons but are not automatically transferable to EAFD. Differences in solid-solution chemistry, encapsulation, and coexisting salts can change the rate-controlling step. (Al-Harahsheh et al., 2022; Bayoumi et al., 2022; Carranza et al., 2016; Fan et al., 2021). Further comparative studies addressing these constraints include Pickles, 2011; Prasetyo et al., 2020; Tang et al., 2023; Tang et al., 2022.

The cited zinc-recovery pathways span alkaline dissolution, ferrite transformation, and reductive or thermochemical approaches. These route classes target different chemical

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constraints; reported extraction alone is insufficient to attribute a result to zincite or ferrite without pre- and post-treatment mineralogy. (Huang et al., 2024; Kashyap et al., 2021; Li et al., 2010; Lucheva et al., 2026). Further comparative studies addressing these constraints include Wang et al., 2016; Xie et al., 2023; Yang et al., 2026.

5. Iron Mineralogical Associations and Oxidation State

Iron may occur in hematite, magnetite, maghemite, wüstite, metallic iron, substituted ferrites, and amorphous material. The distinction between Fe^{2+} and Fe^{3+} matters for redox chemistry, but bulk valence does not identify the host crystal structure. In particular, check overlapping diffraction features among iron oxides and mixed spinels against independent, phase-sensitive evidence.

Mössbauer spectroscopy, phase-resolved electron microprobe data, and local-structure measurements can reduce ambiguity when interpreted together. The practical question for process design is whether iron is a separately accessible impurity, a structural component of the zinc host, or an enclosing matrix that controls mass transfer.

Comparisons between reduction and leaching should track iron-bearing residual phases and secondary solid products as well as dissolved zinc. Otherwise, a favorable zinc recovery figure may obscure iron mobility or transformation into a difficult residue. (Chang et al., 2022; Chen et al., 2022; Grudinsky et al., 2022; Kinnunen et al., 2025). Further comparative studies addressing these constraints include Pereira et al., 2026; Rinne et al., 2022; Wu et al., 2023; Wu et al., 2025.

The iron-related studies distinguish zinc–iron separation in thermal conversion from selective iron rejection during wet extraction. The mineralogical mechanism remains underdetermined whenever iron valence, oxide identity, and substituted spinel composition are not jointly established. (Lee et al., 2020; Li et al., 2023; Lumongsod et al., 2023; Matsukevich et al., 2022). Further comparative studies addressing these constraints include Yang et al., 2024; Zhang et al., 2021.

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6. Lead, Cadmium, and Other Volatile Metals

Lead- and cadmium-bearing material can be concentrated in fine particles or surface deposits, but surface enrichment does not establish a unique salt, oxide, or substitutional structure. The proposed distinction is between discrete crystalline grains, non-crystalline condensates, adsorbed species, and trace constituents of dominant phases. This can influence volatilization, washability, residue classification, and downstream impurity control.

A defensible analysis couples size-resolved total elemental inventories to spatially resolved chemistry and structural identification. When concentrations are near detection thresholds, consider analytical uncertainty and potential beam-induced changes before making process claims about specific cadmium hosts.

For thermal treatment of volatile metals M (notably Pb and Cd), a complete balance is $mM,F = mM,S + mM,C + mM,G + mM,L$, where F is the feed, S the processed solid, C the captured condensate or dust, G the measured gas-phase discharge, and L separately recorded loss or unaccounted inventory. Reports should discriminate size enrichment, surface enrichment, crystalline hosts, water-soluble fractions, and volatile fractions; a high volatilization percentage without collector and off-gas accounting does not establish selective recovery.

Volatile-metal behavior depends on species, particle-scale location, thermal conditions, and collection performance. Claims about a specific Pb or Cd host therefore require direct phase or local chemical evidence rather than inference from volatility alone. (Al-Harahsheh et al., 2021; Borda et al., 2021; Halli et al., 2017; Hamann et al., 2024). Further comparative studies addressing these constraints include Suetens et al., 2014; Wang et al., 2021; Ye et al., 2021; Zhang et al., 2014.

The referenced treatments place Pb and Zn in competing dissolution and volatilization pathways, emphasizing the need to measure where the impurities report. A selective operation cannot be evaluated solely from a dust-to-product recovery figure when condensates, fines, and off-gas residues are not included. (Huang et al., 2023; Miranda et al., 2026; Pereira et al., 2025; Raza et al., 2016).

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7. Manganese, Chromium, and Nickel Associations

Manganese, chromium, and nickel may enter substituted oxide and spinel structures, particularly in dusts derived from alloyed or stainless steel production. Idealized powder patterns alone cannot reliably assign such solid solutions. Interpret apparent differences between carbon-steel and stainless-steel EAFD through feed metallurgy, furnace practice, and verified host compositions rather than universal labels.

A chromium-bearing spinel may behave differently from a readily soluble surface species even at identical total chromium content. The same reasoning applies to nickel and manganese. Species assignment and redox state must be distinguished, especially where environmental claims require evidence of oxidation state rather than total elemental presence.

Total Cr and Cr(VI) must be reported as different measurements when potential environmental hazards are assessed. Oxidative thermal treatment or alkaline roasting can change Cr speciation; validated oxidation-state or selective speciation data are required before asserting Cr(VI) formation or absence. For substituted Mn/Cr/Ni spinels, powder peak matching alone does not specify cation occupancy. Carbon-steel EAFD and stainless/alloy-steel EAFD should be interpreted as distinct feed classes unless host compositions have been demonstrated comparable.

Mixed ferrite formation, reductive treatment, and secondary-metal recovery are relevant to Mn, Ni, and Cr association, although they do not establish a common structure for all furnace dusts. Substitutional chemistry should be measured directly before associating low leachability with a specific spinel end member. (Coleti et al., 2022; Galal et al., 2021; Huang et al., 2025; Kul et al., 2015). Further comparative studies addressing these constraints include Thottempudi et al., 2022; Wang et al., 2020; Xia et al., 2010; Zoraga et al., 2020.

The cited processing studies encompass different dust compositions and treatment routes. Group their results by carbon-steel versus alloy-steel origin where known, rather than interpreting them as universally representative of Cr- or Ni-bearing hosts. (Liu et al., 2026; Montenegro et al., 2013; Mousavi et al., 2025; Sajal et al., 2025).

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8. Calcium, Magnesium, Aluminum, and Silicon Associations

Calcium-containing oxides, hydroxides, carbonates, and silicates may contribute to neutralization demand, while magnesium and aluminum can be associated with oxides and mixed spinels. Silicate or glassy domains may embed metal-bearing inclusions and impede reagent access. Therefore, estimating acid demand from total calcium and magnesium is insufficient without distinguishing reactive from structurally bound fractions.

An apparently refractory zinc response may result from the intrinsic dissolution rate of zinc ferrite or from silicate encapsulation around an otherwise reactive zinc oxide inclusion. Cross-sectional mapping and selective liberation tests can distinguish these competing interpretations, though reagent-induced transformations must also be considered.

For comparable hydrometallurgical tests, report an acid-use index Iacid = nacid,consumed/mZn,recovered (mol acid per kg Zn recovered), specifying acid-equivalent conventions and including co-dissolution. The index is not a substitute for the quantitative reactivity of Ca-, Mg-, and Al-bearing phases: total Ca is not the same as reactive acid-consuming Ca, and an encapsulating silicate may limit transport without itself accounting for major reagent consumption.

Studies on converted residues and mixed gangue products inform understanding of encapsulation, but they require an explicit before–after phase balance to transfer to untreated EAFD. The central distinction is between chemical resistance of a host and restricted reagent transport through an enclosing matrix. (Chairaksa-Fujimoto et al., 2016; Gamutan et al., 2024; Grudinsky et al., 2026; Grudinsky et al., 2024). Further comparative studies addressing these constraints include Toporkova et al., 2021; Xie et al., 2022; Yakornov et al., 2017; Yakornov et al., 2018.

Calcium-assisted pretreatment and mineral transformation can alter the accessibility of Zn-bearing phases, while the corresponding by-products may consume reagents or immobilize other elements. Consequently, the calcium budget must distinguish reactive oxides and hydroxides from silicates and carbonate-like hosts. (Ma et al., 2011; Mousavi et al., 2024; Pereira et al., 2025a; Shawabkeh, 2010).

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9. Chlorine, Fluorine, Sulfur, and Alkali Associations

Halogens, sulfur, sodium, and potassium may occur as soluble surface salts, thermally condensed species, or structurally bound constituents. Chloride mass fraction is not equal to the fraction removed by water washing: accessibility, phase chemistry, and dissolution equilibrium all matter. Washing changes the chemistry and can also redistribute fine particles and soluble metal species.

Distinguishing soluble salts from structurally associated ions matters for corrosion, volatilization, electrolyte quality, and effluent management. A before–after washing experiment should reconcile the aqueous composition, retained solids, solution volume, and any fines losses before interpreting the apparent removal efficiency as a host-phase property.

A complete wash test should reconcile the initial dry-solid mass, initial elemental Cl inventory, liquid volume, dissolved Cl and co-dissolved metals, final dry-solid Cl inventory, and fines lost in handling. The measured chlorine removal is R_{Cl} (%) = 100 × ($m_{Cl,F}$ − $m_{Cl,S}$)/$m_{Cl,F}$, with the appropriate account for particulate and aqueous sinks. This removal metric establishes transfer, not mineralogical identity or a universal water-soluble Cl fraction.

Washing and halide-assisted conversion address different fractions of the chlorine inventory: freely soluble deposits and chemically or physically retained chlorine. Interpret chloride removal with a water–solid balance rather than assuming it represents a unique mineral phase. (Al-Harahsheh et al., 2015; Chen et al., 2011; Chen et al., 2025; Freitas et al., 2015). Further comparative studies addressing these constraints include Pickles & Marzoughi, 2019a; Toporkova et al., 2020; Wang et al., 2024; Yang et al., 2026a.

Sulphation and chloride-based processes can change both targeted metal speciation and surface-salt composition. A valid comparison requires measured residual solids, dissolved ions, and any condensed volatile constituents, not just overall zinc yield. (Grigor'ev et al., 2026; Havlík et al., 2019; Ledesma et al., 2018; Pereira et al., 2025b). Further comparative studies addressing these constraints include Zhang et al., 2016.

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10. Spatial Association and Particle-Level Deportment

A single EAFD particle can contain an Fe-rich core, a Zn-bearing intergrowth, and an alkali- or Pb-enriched exterior. Identical crystalline host phases can react at different rates when exposed, enclosed, coated, or shielded by another phase. Consequently, spatial association cannot be reduced to the diffraction-derived phase list.

Polished cross-sections and serial chemical maps can reveal whether surface signals correspond to a continuous coating or isolated deposits. However, a two-dimensional section cannot always establish three-dimensional connectivity. Interpretation should consider particle-size stratification, the representativeness of analyzed particles, and the possibility of sample-preparation artifacts.

Where accessibility controls the route, document coating thickness, exposed host surface fraction, inclusion depth, connectivity, liberation class, and particle-size dependence across representative numbers of particles. Two-dimensional polished sections can misrepresent three-dimensional phase connectivity; serial sectioning, FIB–SEM, or tomography can resolve critical ambiguities where justified, but are not mandatory for all feeds.

Thermal and wet-process investigations show the practical importance of heterogeneous particles, but most bulk conversion measurements do not resolve internal architecture. Discriminating evidence comes from cross-sectional or three-dimensional mapping that identifies exposed grains, intergrowths, and coatings. (Fan et al., 2026; Grudinsky et al., 2023; Kabogo et al., 2024; Kumar et al., 2026). Further comparative studies addressing these constraints include Tsakiridis et al., 2010; Xiong et al., 2024; Yu et al., 2011; Zoraga et al., 2022.

Particle-scale claims must separate the intrinsic reaction rate of a host phase from geometric accessibility. Before interpreting incomplete extraction as an equilibrium limitation, compare size fractions, liberated particles, and protected inclusions. (Ma et al., 2022; Najera Ibarra et al., 2024; Pickles et al., 2019; Siame et al., 2019).

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11. Analytical Determination of Element–Phase Associations

Quantitative X-ray diffraction with Rietveld refinement constrains crystalline mass fractions but can under-represent nanocrystalline and amorphous hosts. Scanning electron microscopy with energy-dispersive spectroscopy provides spatial co-localization, while wavelength-dispersive microanalysis can supply more precise local composition under suitable conditions. Neither a chemical map nor a diffractogram alone uniquely establishes elemental deportment.

Mössbauer spectroscopy and X-ray absorption measurements can constrain local iron environments or element-specific coordination, and X-ray photoelectron spectroscopy probes near-surface chemical states. Transmission electron microscopy may be necessary for nanoscale mixtures. The most credible phase–element allocation relies on convergence across techniques and independently checked elemental closure.

Technique-specific evidentiary limits are complementary rather than interchangeable: XRD/Rietveld estimates identified crystalline phases but not unique cation partitioning within substituted spinels; standard-assisted diffraction can constrain amorphous content. SEM–EDS supports spatial association and approximate local chemistry but neither valence nor crystal structure. EPMA/WDS improves local quantification. XAS probes local coordination and oxidation state, while Mössbauer is informative for iron environments. XPS is near-surface sensitive, TEM/STEM can resolve nanoscale structures, and selective leaching measures operational accessibility, not unique host identity. Unindexed reflections, analytical limits, measurement uncertainty, and independent elemental balances should be documented.

Figure 3 summarizes the conceptual distinctions necessary to interpret this evidence without equating bulk chemistry with phase-resolved measurements.

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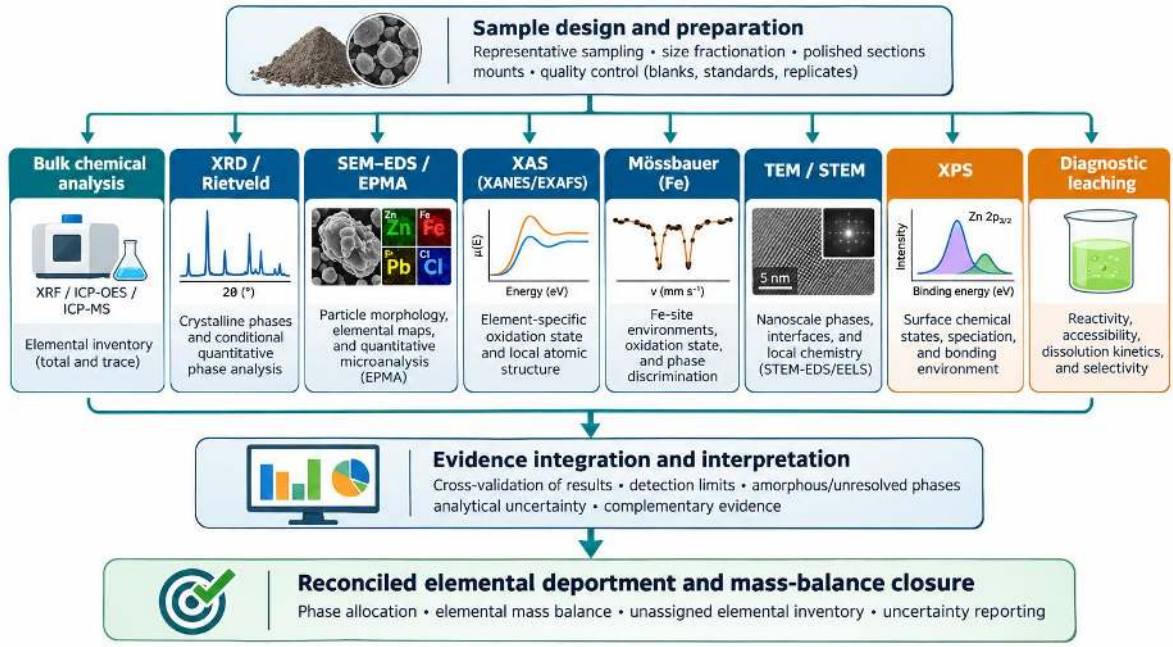

Figure 3. Correlative characterization workflow for phase identity, elemental association, and balance reconciliation.

Note. Original schematic created for this manuscript.

The schematic is a conceptual framework rather than a measured mineralogical map. Its proposed links require confirmation by complementary analyses and mass-balance closure.

Method studies using materials other than EAFD can justify analytical protocols, but not identify the phases present in the dust under review. A defensible assignment therefore combines structural identification, representative sampling, element-specific mapping, and balance closure. (Christidis et al., 2020; Halli et al., 2018; Havlík et al., 2018; Hiraga et al., 2021). Further comparative studies addressing these constraints include Wang et al., 2016; Wang et al., 2013; Zhang et al., 2019.

The analytical literature provides complementary constraints: diffraction estimates crystalline phases, microanalysis maps element associations, and local spectroscopy probes coordination and valence. None alone provides a unique and complete mass-weighted elemental deportment for a heterogeneous EAFD sample. (Ma et al., 2021; Pereira, 2026a; Pereira, 2026c; Rowles, 2021).

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12. Mineralogical Association as a Predictor of Process Behavior

12.1. From host characterization to flowsheet choice

An association-based flowsheet begins with measured elemental inventory and a ranked list of host phases, then separates intrinsic chemical resistance from geometric inaccessibility. For a ZnO-rich feed, mild dissolution may merit initial testing; for a spinel-rich feed, phase-transforming pretreatment may be required. This statement is a conceptual route-screening distinction, not a universal recommendation or evidence of commercial readiness.

Lead and cadmium distribution guides gas-cleaning and product-purification questions; calcium hosts affect acid consumption; soluble chlorides influence washing requirements; and encapsulation determines whether comminution can improve accessibility. The correct balance must extend through treatment residues and secondary streams, because high extraction of a target metal can coexist with uncontrolled impurity mobilization.

To compare transformations and recovery, define T_p (%) = 100 × (m_p,F − m_p,R)/m_p,F for a specified measured host phase p, with m_p expressed as phase mass in feed and residue. This measures phase depletion, not necessarily the specific reaction mechanism or recovery of its constituent metal. Metal recovery is R_j (%) = 100 × m_j,collected product/(m_j,feed); extraction to solution and final product recovery should be identified separately. Selectivity for target M relative to impurity I is SM/I = RM/RI for consistently defined yields, with an explicit impurity and denominator and appropriate treatment when RI approaches zero. Compare host depletion, target yield, co-element migration, and residues before claiming a selective route.

Figure 4 summarizes the conceptual distinctions necessary to interpret this evidence without equating bulk chemistry with phase-resolved measurements.

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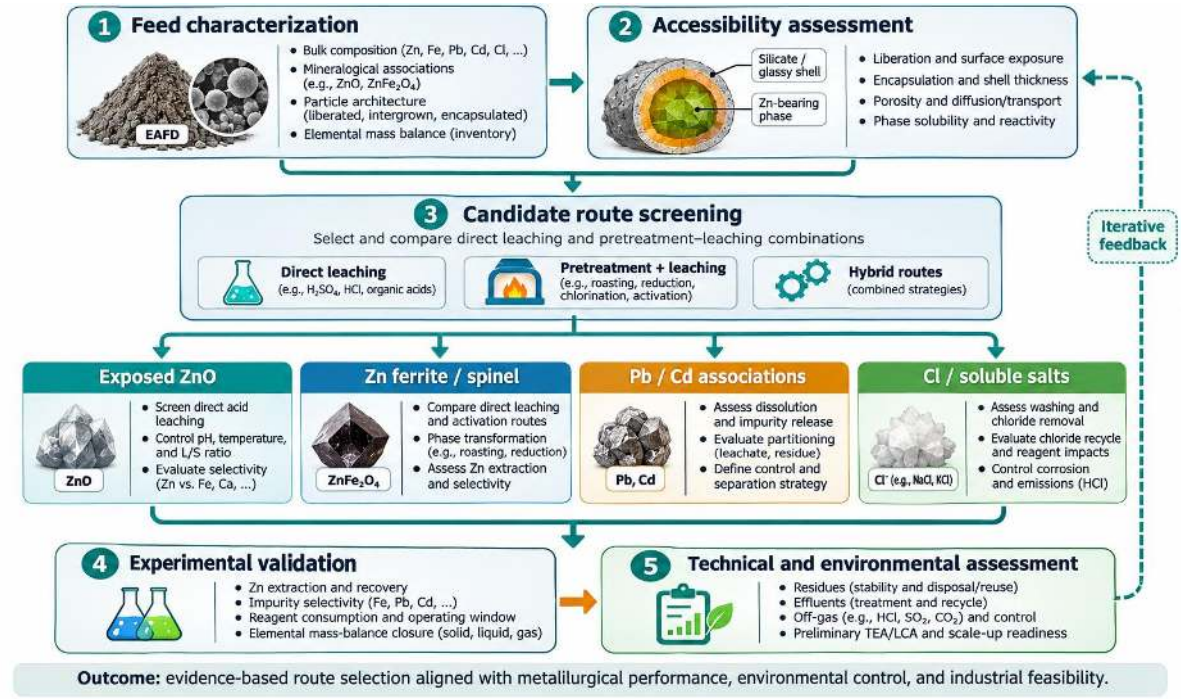

Figure 4. Association-based decision framework from feed characterization to process and residue assessment.

Note. Original schematic created for this manuscript.

The schematic is a conceptual framework rather than a measured mineralogical map. Its proposed links require confirmation by complementary analyses and mass-balance closure.

Table 2 summarizes the relevant interpretation framework and the analytical limits that must be communicated.

Table 2. Evidence needed before process implications are asserted

Proposed inference	Minimum corroboration	Principal failure mode
ZnO can be leached selectively.	Phase-specific before/after accounting	Confounding ferrite dissolution
Spinel requires pretreatment	Phase identification and comparative kinetic tests	Mistaking encapsulation for intrinsic resistance
Chloride washing is sufficient.	Water/solid chloride mass balance	Ignoring insoluble or inaccessible chlorine
Ca drives acid use	Reactive Ca phase inventory plus titration	Equating total Ca with neutralization demand
Pb/Cd can be volatilized selectively.	Species, volatility, and gas/solid balances	Unaccounted fugitive metals

Note. Original qualitative synthesis; not a substitute for quantitative phase or deportment measurements.

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Interpret these categories as screening hypotheses, not fixed signatures across furnace types, feed mixtures, or operating conditions.

12.2. Critical gaps and research priorities

The most consequential gaps are quantified element–phase deportment, three-dimensional particle accessibility, uncertainty-aware mineralogical balance closure, standardized characterization of amorphous phases, and cross-feedstock validation. Comparable datasets should disclose particle preparation, detection limits, uncertainty propagation, phase-identification criteria, and the fraction of each element remaining unassigned.

Research priorities include a common nomenclature for compositionally substituted spinels, interlaboratory round-robin tests, representative particle counts and sampling uncertainty, quantitative propagation of phase-fraction uncertainty to element deportment, tracking weathering and storage transformations, and cross-feedstock replication. Route-ranking studies should report initial and final phase masses, amorphous inventory, reagent consumption, impurity co-extraction, and destination-specific residue quality.

The processing literature covers multiple lixiviants and thermal transformations; a direct ranking is not defensible without normalizing feed mineralogy, reagent dose, temperature, duration, and product-quality constraints. Route screening should explicitly disclose which host phases are demonstrably transformed and which remain unassigned. (Ahmad et al., 2022; Ahn et al., 2015; Al-Harahsheh, 2018; Al-Harahsheh et al., 2018). Further comparative studies addressing these constraints include Ju et al., 2025; Kalpakli et al., 2021; Luo et al., 2025; Oustadakis et al., 2010.

Technology concepts, kinetic investigations, and residue-treatment studies supply candidate mechanisms rather than an experimentally reconciled universal flowsheet. The next validation step is a mineralogical inventory spanning feed, products, off-gas collection, and residual solids under matched operating conditions. (Al-Harahsheh et al., 2017; Anzulevich et al., 2021; Chen et al., 2023; Huo et al., 2025). Further comparative studies addressing these constraints include Teimouri et al., 2022; Trifunović et al., 2024; Trifunović et al., 2026; Tu et al., 2026.

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13. Conclusion

Bulk composition defines the recoverable elemental inventory but neither establishes phase identity nor predicts reagent accessibility or selectivity. Defensible EAFD route selection requires a linked sequence of crystalline and amorphous host quantification, element-specific deportment, oxidation state, particle-scale architecture, intrinsic phase reactivity, geometric accessibility, and independently reconciled process balances. In particular, intrinsically resistant substituted zinc-bearing spinels and otherwise reactive Zn-bearing phases isolated by encapsulation require different intervention strategies; an incomplete leach curve alone cannot distinguish these mechanisms. Diagnostic extraction identifies operational accessibility, not uniquely the mineralogical source of the extracted metal. An explicitly unassigned elemental fraction is preferable to a falsely exact mineralogical closure. Because steel grade, scrap, operating practice, off-gas cooling, dust recycling, and storage control phase occurrence and morphology, a single sample must not be generalized to all EAFD. Future validation should combine representative sampling, compositional uncertainty propagation, standardized spinel nomenclature, three-dimensional accessibility where needed, and independent phase/element balance closure across feedstocks and treatment residues.

Declarations

Funding

No specific external funding was reported for the preparation of this critical review.

Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

Author Contributions

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

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