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From Fresh to Weathered Electric Arc Furnace Dust: Phase Transformations, Metal Mobility, and Consequences for Hydrometallurgical and Pyrometallurgical Processing—A Critical Review

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Abstract

Electric arc furnace dust (EAFD) is a zinc-rich hazardous residue whose processing behavior depends on the distribution of zincite, zinc ferrite, iron oxides, Pb-bearing phases, chlorides, sulfates, silicates, and amorphous matter. Treating this mineralogical assemblage as static is inadequate when the dust is stored before processing. Exposure to water, oxygen, carbon dioxide, dissolved salts, and repeated wetting–drying cycles can promote dissolution, carbonation, oxidation, hydration, recrystallization, salt migration, surface coating, and agglomeration. This critical review integrates mineralogical, environmental, hydrometallurgical, pyrometallurgical, and thermodynamic evidence to distinguish primary phases inherited from furnace operation from secondary phases that can develop during natural or accelerated weathering. The strongest direct evidence indicates that reactive Zn- and Pb-bearing domains may be reorganized during storage, whereas $ZnFe_2O_4$ and related spinels can remain comparatively persistent. These changes can alter metal speciation, environmental leachability, reagent demand, solid–liquid separation, thermal response, volatilization, and downstream purification. Because direct, time-resolved fresh-to-weathered studies remain scarce, the review explicitly separates observations demonstrated in weathered EAFD from mechanisms inferred from phase-specific treatment studies and geochemical principles. A process-oriented framework treats storage history as an upstream state variable linking phase evolution to recovery performance. Controlled weathering is therefore a testable pretreatment concept rather than an established practice, with feasibility depending on coupled mineralogical, environmental, and metallurgical validation.

Keywords: electric arc furnace dust; weathering; zinc ferrite; metal mobility; leaching; resource recovery

Highlights

- Storage history is treated as an overlooked process variable for EAFD characterization and recovery.

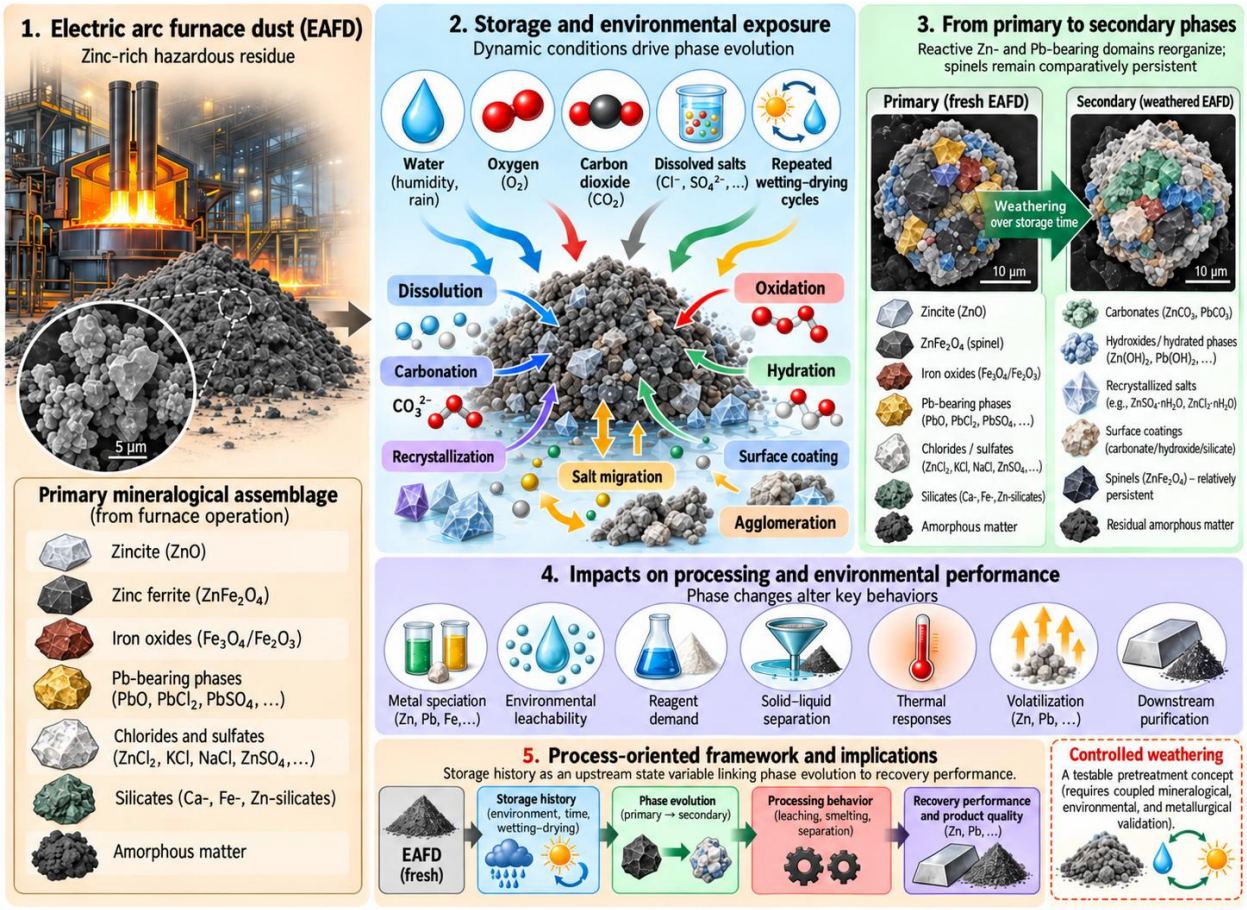
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- Weathering can remove soluble salts while converting reactive Zn and Pb phases into secondary minerals.
- Refractory $ZnFe_2O_4$ and related spinels can persist while particle surfaces and pore chemistry evolve strongly.
- A predictive framework is proposed linking aging, mineralogy, leachability, reagent demand, and process performance.

Graphical abstract



1. Introduction

1.1. Electric arc furnace dust as a dynamic metallurgical residue

Electric arc furnace dust is generated by volatilization, oxidation, condensation, and mechanical entrainment during steelmaking. Its composition varies with scrap quality, furnace practice, off-

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gas cooling, dust collection, and internal-residue recycling. Zinc and iron usually dominate the metal inventory, but Pb, Cd, Cr, Mn, Ca, Mg, Si, Cl, and S may be technologically or environmentally decisive. This heterogeneity is expressed by the coexistence of acid-reactive ZnO, refractory $ZnFe_2O_4$, Fe_3O_4, Fe_2O_3, mixed ferrites, Pb-bearing phases, soluble chlorides, sulfates, silicates, and amorphous matter (Buzin et al., 2017; Oustadakis et al., 2010; Santos et al., 2021; Trifunović et al., 2022).

The same chemistry that makes EAFD a secondary zinc resource also makes its treatment strongly dependent on mineralogy. Zinc present as zincite may dissolve rapidly, whereas Zn incorporated into ferrite or multicomponent spinel structures is substantially more resistant. Pickles (2010), Suetens et al. (2015), Wang et al. (2012), and Wang et al. (2016) collectively show why a bulk Zn assay cannot, by itself, predict recovery. Phase abundance, cation substitution within spinels, particle size, morphology, and association with iron govern the fraction of Zn accessible to direct hydrometallurgical treatment and the fraction that requires prior thermal or chemical activation.

Most process studies implicitly treat an EAFD sample as a fixed feed. In industrial practice, however, dust may remain for days, months, or years in silos, covered storage, open stockpiles, landfill cells, or blended residue inventories before recycling. Figure 1 introduces the central premise of this review: furnace operation establishes the primary phase assemblage, whereas subsequent storage can create a second, process-relevant mineralogical state through selective dissolution, redistribution, and secondary precipitation.

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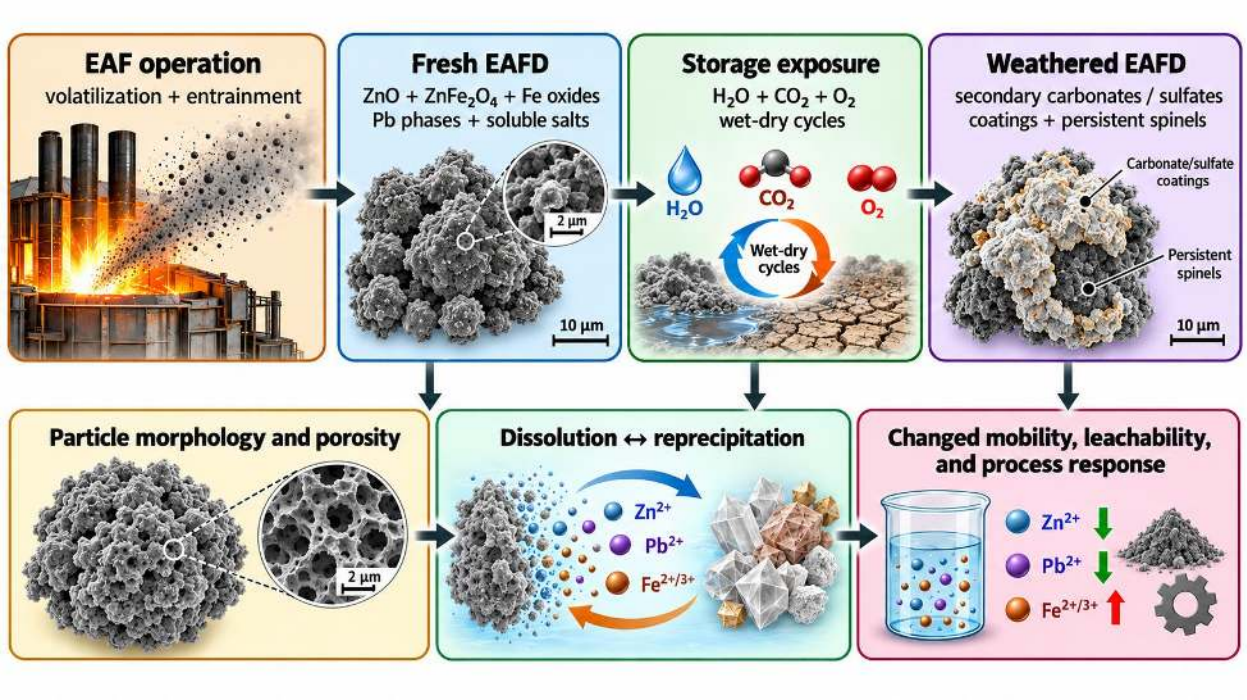


Figure 1
Formation-to-weathering pathway of electric arc furnace dust
Note. Adapted from the mineralogical and processing relationships discussed by Martins et al. (2008), Buzin et al. (2017), Lin et al. (2017), and Pereira et al. (2026).

The distinction between fresh and weathered dust is therefore substantive rather than semantic. Martins et al. (2008) directly documented mineralogical differences between recent and weathered EAFD, providing rare evidence that atmospheric alteration can modify the feed state relevant to metallurgical processing. That study anchors the central question of this review: how far can storage-induced phase evolution explain differences in leaching, thermal response, and downstream separation among EAFD samples that may otherwise appear compositionally similar?

1.2. Why aging and weathering matter

Weathering begins when reactive particles interact with H_2O, O_2, CO_2, dissolved chloride, sulfate, alkali, and alkaline-earth ions. Wetting enables dissolution and ionic transport; drying promotes supersaturation and salt recrystallization; atmospheric CO_2 shifts carbonate equilibria; and redox changes can modify Fe- and Cr-bearing surfaces. These processes are coupled rather

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than sequential. Dissolution of an outer ZnO-rich layer can expose spinel-rich cores, while secondary carbonates, sulfates, or oxyhydroxides can form coatings that reduce permeability or alter subsequent leaching kinetics.

This coupling is industrially important because chloride removal, Zn extraction, ferrite activation, and solid–liquid separation already depend on phase chemistry and particle properties (Chen et al., 2011; Halli et al., 2017; Lee et al., 2020; Lanzerstorfer & Brunner, 2023). Weathering can therefore improve one process attribute while degrading another. Natural washing may lower soluble chloride, for example, but secondary precipitation and cementation may reduce surface accessibility or impair filtration. Likewise, carbonation may lower dissolved-metal mobility under storage conditions while producing phases with different acid or alkaline leaching behavior.

1.3. Scope, objectives, and article organization

The visual and tabular architecture is signposted for traceability. Figure 1 establishes the generation-to-weathering pathway; Figures 2–5 resolve mineralogical domains and Zn/Pb transformation mechanisms; Figures 6 and 7 connect aging with mobility and hydrometallurgical response; and Figure 8 presents the predictive research framework. Table 1 defines the evidence hierarchy; Table 2 summarizes primary phases; Table 3 organizes transformation pathways; Table 4 addresses element mobility; Table 5 connects weathering with leaching; Table 6 links storage conditions with processability; and Table 7 consolidates the research agenda.

The review critically evaluates (i) the fresh mineralogical state of EAFD; (ii) the physicochemical drivers of aging; (iii) transformation pathways of Zn-, Pb-, Fe-, Ca-, Mg-, and salt-bearing phases; (iv) thermodynamic and geochemical controls; (v) consequences for metal mobility and standardized leaching tests; (vi) microstructural aging; (vii) implications for hydrometallurgical, pyrometallurgical, and hybrid processing; and (viii) storage management and future research. Table 1 summarizes the evidence classes used throughout the review. Figures 2–8 then progressively connect mineralogical transformation with geochemistry, mobility, and process response.

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Table 1
Literature classification and evidence levels for EAFD aging and weathering studies

Evidence class	Typical material state	Main methods	Strength for aging interpretation
Direct fresh-weathered comparison	Fresh vs. naturally aged	XRD, microscopy, chemistry, leaching	Strongest observational evidence; storage-related differences can be associated with storage history, but longitudinal precursor-to-product causality depends on experimental design
Time-resolved or accelerated aging	Fresh vs. artificially aged	Controlled humidity/CO_2, leaching, XRD	High when initial material and exposure are well defined
Characterization studies	Fresh or unspecified	XRD, XRF/ICP, SEM-EDS, thermal analysis	Moderate; defines plausible initial phases but not transformation kinetics
Environmental leaching/stabilization	Fresh, treated, or aged	TCLP-type tests, batch leaching, geochemical modeling	Moderate; informs mobility but mineralogical causality may be indirect
Hydrometallurgical studies	Usually unspecified storage age	Acid/alkaline/ammoniacal leaching, kinetics	Indirect but important for phase-dependent process response
Thermal/pyrometallurgical studies	Usually dried or pretreated	Roasting, reduction, chlorination, thermodynamics	Indirect; constrains persistence and conversion of refractory phases

Note. Evidence hierarchy proposed for this review. Direct fresh-to-weathered comparisons are scarce, so mechanistic interpretation also uses adjacent evidence from phase-specific leaching, thermodynamics, and treatment studies. Cross-sectional comparisons between fresh and weathered EAFD should not be interpreted as definitive time-resolved precursor-to-product transformations unless supported by longitudinal evidence.

2. Review Methodology and Literature Mapping

2.1. Search strategy and corpus boundaries

The review focused on a 2010–2026 literature window, supplemented by earlier evidence that directly addressed weathered EAFD. Search concepts combined “electric arc furnace dust,” “EAFD,” and “EAF dust” with aging/ageing, weathering, storage, stockpile, carbonation,

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hydration, oxidation, mineralogical evolution, phase transformation, leaching behavior, metal mobility, hydrozincite, hydrocerussite, chloride, and zinc ferrite. The corpus was then expanded with process studies required to interpret how altered phase assemblages could influence leaching, roasting, reduction, washing, and purification. Because this is a critical rather than a formal systematic review, the search was designed for mechanistic coverage and evidentiary triangulation rather than exhaustive systematic-review reporting.

The final bibliography contains 92 sources spanning direct weathering evidence, primary EAFD characterization, Zn speciation, chloride removal, hydrometallurgy, pyrometallurgy, stabilization, carbonation, thermodynamic modeling, and integrated recovery routes. The literature was not treated as equally diagnostic. A study reporting Zn extraction without quantitative phase information can demonstrate process performance, but it cannot, by itself, establish a weathering pathway. Conversely, a mineralogical comparison can identify secondary phases without quantifying their effect on industrial recovery. This distinction between direct evidence and mechanistic inference is maintained throughout the review.

2.2. Critical assessment criteria

Each study was interpreted against five questions: What was the dust's storage history? Was the initial mineralogy quantified? Were phase transformations observed directly or inferred from extraction behavior? Were soluble salts and pore-water chemistry considered? And was the resulting process behavior linked to specific mineral phases? These questions helped avoid conflating natural aging with treatment-induced phase reconstruction. Studies such as Chen et al. (2022, 2023, 2025), Xie et al. (2023), and Xue et al. (2025), for example, are highly informative about controlled phase conversion, but the transformations occur during deliberate thermal treatment rather than during storage.

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3. Fresh EAFD as the Initial State for Weathering

3.1. Formation mechanisms and compositional heterogeneity

Fresh EAFD forms through high-temperature volatilization-condensation and entrainment, followed by rapid cooling in the off-gas train. This origin produces submicrometric condensates, larger mechanically entrained particles, hollow or spherical particles, irregular agglomerates, and multiphase grains. Araújo and Schalch (2014), Vilela et al. (2014), Buzin et al. (2017), Almeida et al. (2023), and Zhang et al. (2024) illustrate the broad chemical and morphological variability of steelmaking dusts. Because the feedstock varies, weathering does not act on a single universal starting material.

3.2. Primary Zn-bearing and Fe-bearing phases

Zincite and zinc ferrite are the most consequential Zn-bearing end members for process interpretation. Zincite is generally accessible to acid and several alkaline or ammoniacal systems, whereas $ZnFe_2O_4$ requires stronger chemical conditions or prior phase modification. Pickles (2010) analyzed the thermodynamic formation of zinc-manganese ferrite spinel, Suetens et al. (2015) examined $ZnFe_2O_4$ formation in an off-gas treatment system, Wang et al. (2012) quantified Zn speciation using X-ray absorption spectroscopy, and Tang et al. (2023) deliberately reconstructed zinc ferrite by roasting. Together, these studies establish that ferrite abundance is a structural variable, not merely an analytical label.

Iron occurs mainly as magnetite, hematite, ferrites, and more complex spinel-like phases containing Zn, Mn, Mg, or Cr. These phases provide a relatively persistent framework during moderate atmospheric alteration. Practically, weathering may strongly alter particle surfaces and reactive minor phases while leaving a large proportion of the spinel skeleton intact. This explains how a dust can appear chemically altered yet remain refractory in subsequent zinc extraction.

3.3. Pb-, Cd-, Cr-, Ca-, and salt-bearing phases

Lead and cadmium are more likely than ferritic Zn to participate in soluble or surface-associated fractions, although their actual mineral hosts depend on furnace chemistry and off-gas

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conditions. Chlorides of Na, K, Zn, Ca, and Pb can be abundant enough to affect corrosion, washing demand, and thermal processing. Chen et al. (2011) demonstrated that chloride removal is a distinct unit-operation problem, while Al-Harahsheh, Altarawneh, et al. (2021), Al-Harahsheh, Orabi, and Al-Asheh (2021), and Al-Harahsheh et al. (2022) showed how washing and chlorine-bearing thermal treatment alter Zn and Pb behavior. Chromium is commonly associated with spinel or refractory oxide domains, so its redox state and mobility depend strongly on local chemistry rather than total Cr concentration alone.

Table 2 summarizes the primary phases that define the initial state. Figure 2 then contrasts the conceptual fresh and weathered mineralogical domains. The table deliberately distinguishes susceptibility from certainty: a phase described as weathering-prone is not assumed to transform in every stockpile, because water availability, CO_2 transport, pH, salt loading, and exposure duration differ widely.

Table 2
Major mineral phases in fresh EAFD and expected susceptibility to weathering

Phase/group	Representative formula	Main element(s)	Relative weathering susceptibility	Likely storage-related response
Zincite	ZnO	Zn	High to moderate	Dissolution; reprecipitation as carbonate/hydroxycarbonate; surface passivation
Zinc ferrite / franklinite-like spinel	$ZnFe_2O_4$	Zn, Fe	Low	Persistence; possible surface alteration; requires strong activation for major conversion
Magnetite/hematite	Fe_3O_4 / Fe_2O_3	Fe	Low to moderate	Oxidation-state adjustment; oxyhydroxide surface coatings
Mixed ferrite/spinel	(Zn,Mn,Mg,Cr)Fe_2O_4-type	Zn, Fe, Mn, Mg, Cr	Low	Persistent refractory matrix with limited surface reaction
Lead oxides/chlorides/hydroxychlorides	PbO / Pb-Cl-O-H phases	Pb	Moderate to high	Dissolution and secondary carbonate/sulfate formation
Alkali/alkaline-earth chlorides	NaCl, KCl, $CaCl_2$	Na, K, Ca, Cl	Very high	Rainwater leaching, migration, and recrystallization
Sulfates	Zn/Pb/Ca sulfates	Zn, Pb, Ca, S	Variable	Dissolution, persistence, or secondary precipitation

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				depending on pH and ionic strength
Silicates and glassy matter	Variable	Si, Ca, Fe, Al	Low to moderate	Slow alteration; possible contribution to cementation and amorphous coatings

Note. Phase behavior is a mechanistic expectation synthesized from EAFD characterization, phase-specific leaching, and thermodynamic studies. Actual transformation requires case-specific confirmation. Where phase chemistry is not independently confirmed, the terms "Zn-bearing spinel" or "franklinite-like spinel" are preferred over assignment of an exact $ZnFe_2O_4$ stoichiometry based solely on overlapping diffraction features.

Figure 2 then contrasts the conceptual fresh-domain, transition-zone, and weathered-domain assemblages, emphasizing the coexistence of reactive secondary phases with persistent spinel-rich domains.

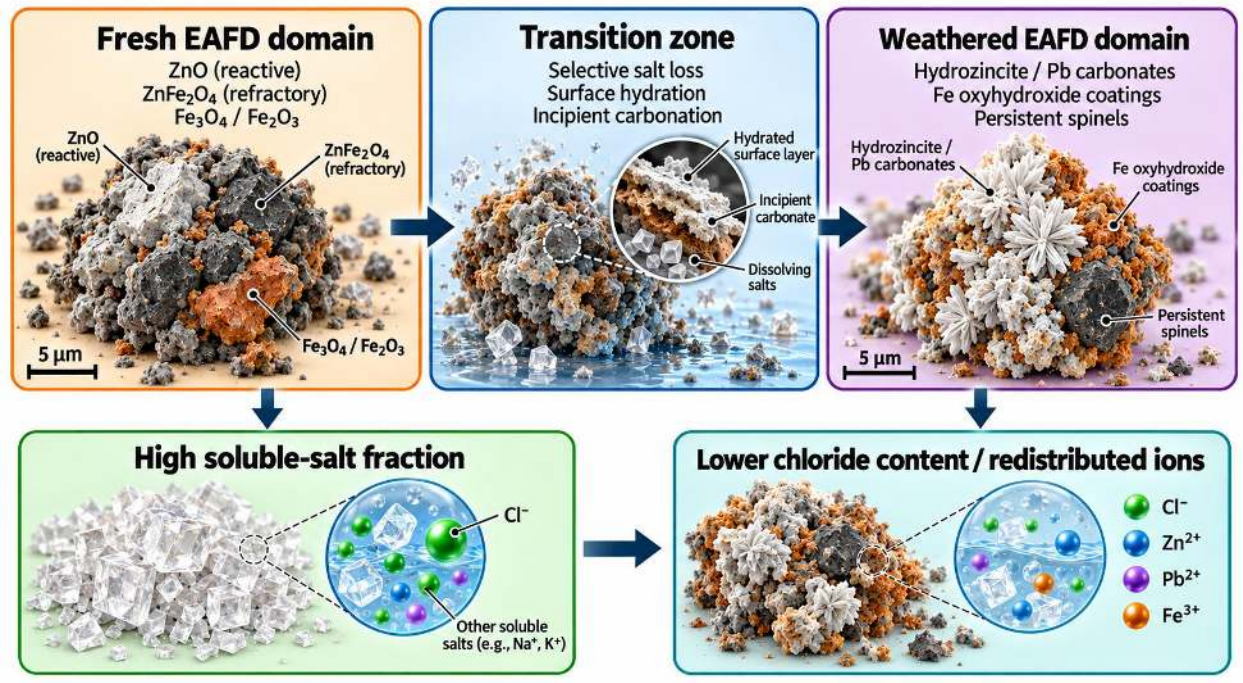


Figure 2
Conceptual mineralogical map of fresh versus weathered EAFD
Note. Adapted conceptually from Martins et al. (2008), Pickles (2010), Suetens et al. (2015), and Buzin et al. (2017). The diagram distinguishes likely reactive domains from persistent spinel-rich domains.

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4. Drivers and Mechanisms of EAFD Weathering

4.1. Water ingress, dissolution, and hydration

Water enables most low-temperature transformations. Under dry storage, atmospheric oxidation and slow surface hydration may occur, but extensive ionic redistribution is limited. Once liquid water enters a dust bed, soluble chlorides and readily leachable Zn- or Pb-bearing species enter the pore solution, increasing ionic strength and enabling interparticle transport. Repeated wetting and drying can then convert initially dispersed salts into localized efflorescent deposits or cementing bridges. Grigor'ev et al. (2026) and Chen et al. (2011) demonstrate that water washing can remove chloride efficiently from EAFD, supporting the mechanistic expectation that uncontrolled rainfall can produce analogous, although less uniform, salt migration and export.

4.2. CO_2 uptake and carbonation

Carbonation provides a direct pathway from dissolved Zn^{2+} or Pb^{2+} to secondary carbonate-bearing solids. Atmospheric CO_2 dissolves in pore water and generates HCO_3^- and CO_3^{2-} as a function of pH, alkalinity, and ionic strength. If ZnO dissolves locally, released Zn can become supersaturated with respect to zinc carbonate or hydroxycarbonate phases. Martins et al. (2008) identified hydrozincite in weathered EAFD, providing direct mineralogical evidence that this pathway can occur under natural conditions. Carbonation studies on iron- and steelmaking by-products, including Noh et al. (2025) and Puttaswamy et al. (2026), further show that CO_2 mineralization can be significant in alkaline metallurgical residues, although those systems should not be treated as direct substitutes for naturally weathered EAFD.

4.3. Oxygen, redox changes, chloride, and sulfate transformations

Oxygen can promote oxidation of Fe(II)-bearing surfaces toward Fe(III)-rich oxides or oxyhydroxides, while redox-sensitive Cr requires explicit differentiation between Cr(III) and Cr(VI). Chloride behaves differently: in many EAFD systems it acts primarily as a mobile ligand and soluble counter-ion rather than as a persistent atmospheric alteration product. Rainwater-

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driven chloride loss can therefore change both the solid inventory and the aqueous complexation environment of Zn and Pb. Sulfate may persist as $PbSO_4$ or $CaSO_4$, form during oxidation of sulfur-bearing constituents, or be introduced deliberately during sulfation roasting (Pickles & Marzoughi, 2019; Chen et al., 2022, 2023; Wu et al., 2023). Natural storage and engineered sulfation must therefore be distinguished even when both yield sulfate-bearing products.

4.4. Wetting-drying cycles, temperature, and storage duration

Wetting–drying cycles act as a reaction pump: wetting dissolves soluble phases, capillary transport redistributes ions, drying concentrates pore solutions, and supersaturation drives reprecipitation. Repeated cycles can generate hard agglomerates, surface crusts, and compositional gradients between the exterior and core of a stockpile. Temperature influences evaporation, gas diffusion, hydration, and reaction kinetics, but its effect is coupled to moisture availability. Figure 3 summarizes this coupled mechanism. Accordingly, an “age” reported only in months or years is an inadequate descriptor unless rainfall, cover, humidity, drainage, and thermal history are also documented.

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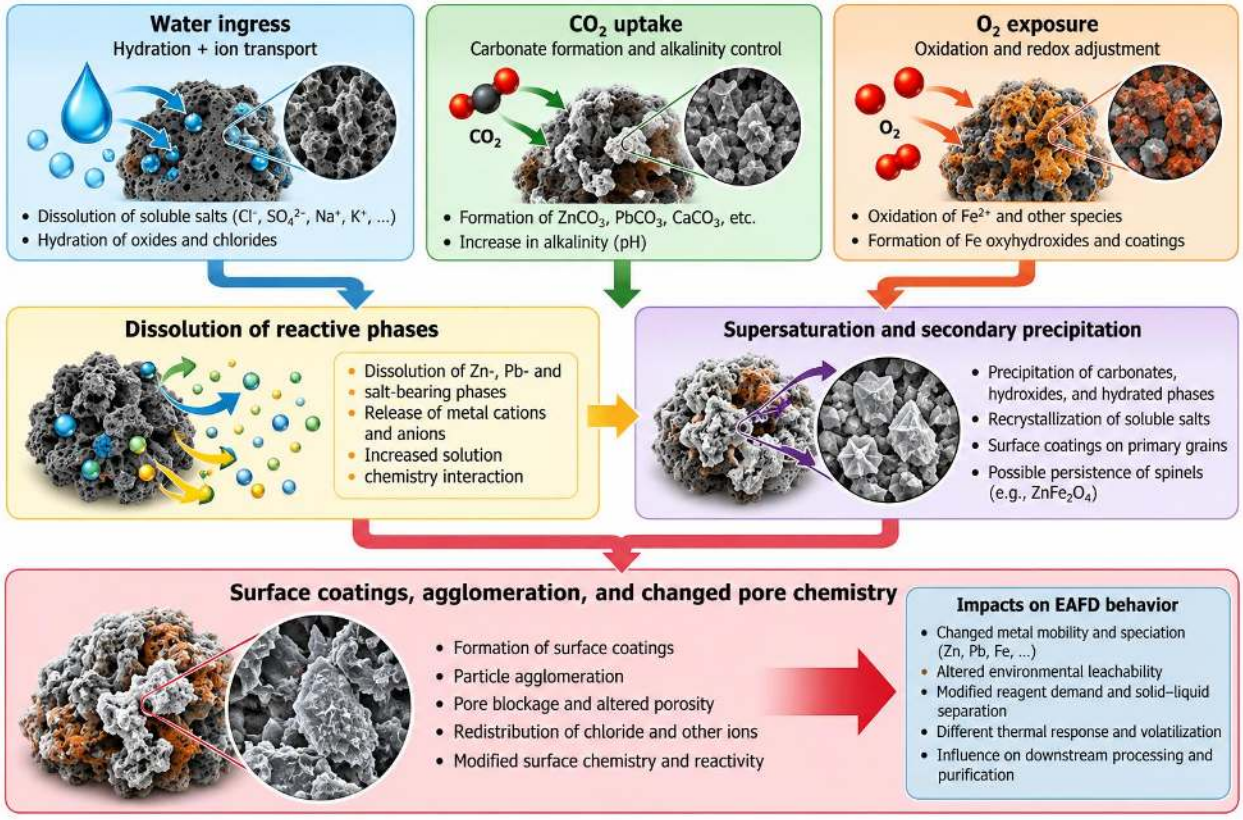


Figure 3
H_2O-CO_2-O_2-controlled weathering mechanisms
Note. Adapted conceptually from Martins et al. (2008), Chen et al. (2011), Noh et al. (2025), and Puttaswamy et al. (2026); the diagram integrates water ingress, gas exchange, dissolution, transport, secondary precipitation, and surface alteration.

5. Mineralogical Evolution from Fresh to Weathered EAFD

5.1. Persistence of refractory spinels

The strongest conclusion supported by the available evidence is not that weathering completely reconstructs EAFD, but that it selectively transforms more reactive domains around a comparatively persistent refractory framework. Martins et al. (2008) identified magnetite and franklinite as major phases in weathered material. This observation is consistent with thermodynamic and process evidence showing that $ZnFe_2O_4$ is difficult to dissolve directly and often requires CaO treatment, reduction, sulfation, chlorination, or other phase-conversion

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strategies (Chairaksa-Fujimoto et al., 2016; Miki et al., 2016; Wu et al., 2014; Ahmad et al., 2022). The key limitation is that persistence inferred from treatment resistance is not equivalent to a measured weathering rate; time-resolved kinetic data remain scarce.

5.2. Transformation of Zn-bearing phases

The weathering-sensitive Zn fraction is better represented as a pathway than as a single phase. Zincite can dissolve, the released Zn^{2+} can migrate through pore water, and subsequent evaporation or carbonation can precipitate secondary Zn phases on different particles or at different depths. Figure 4 distinguishes these reactive ZnO-derived pathways from refractory $ZnFe_2O_4$. Havlík et al. (2018), Lee et al. (2020), Zoraga et al. (2022), and Gamutan et al. (2024) show, in different leaching systems, that ZnO and ferritic Zn respond differently. Therefore, any storage-induced change in their relative abundance can plausibly change measured extraction, but the magnitude of that effect requires paired fresh/aged experiments.

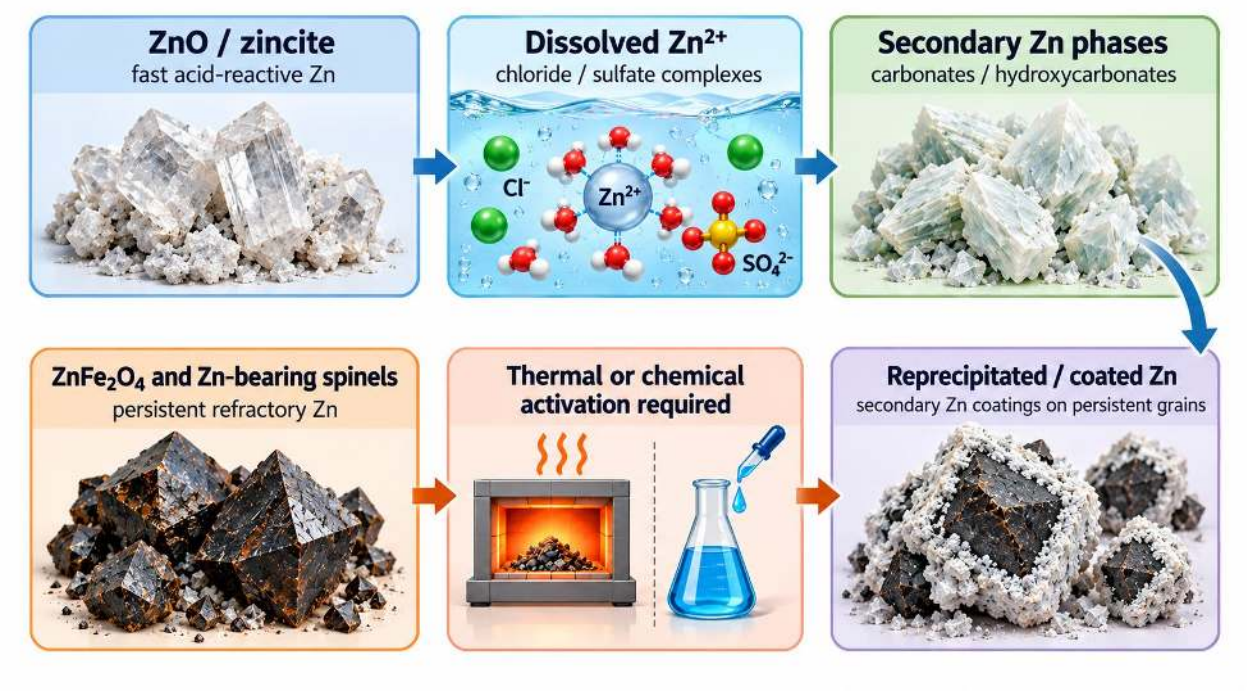


Figure 4
Zinc transformation pathways during EAFD aging

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Note. Adapted conceptually from Martins et al. (2008), Pickles (2010), Havlík et al. (2018), Lee et al. (2020), and Zoraga et al. (2022).

5.3. Transformation of Pb-bearing phases and soluble salts

Lead mineralogy is less comprehensively resolved than Zn mineralogy, making the direct weathering evidence particularly valuable. Martins et al. (2008) reported laurionite in recent dust and hydrocerussite in weathered dust, supporting a pathway in which chloride- or hydroxyl-bearing Pb phases are reorganized during atmospheric exposure. Figure 5 illustrates the competing possibilities of early solubilization and later secondary immobilization. This outcome should not be generalized as universally beneficial: chloride loss may decrease soluble Pb in one system, whereas acidic pore waters or complexing ligands may increase mobility in another.

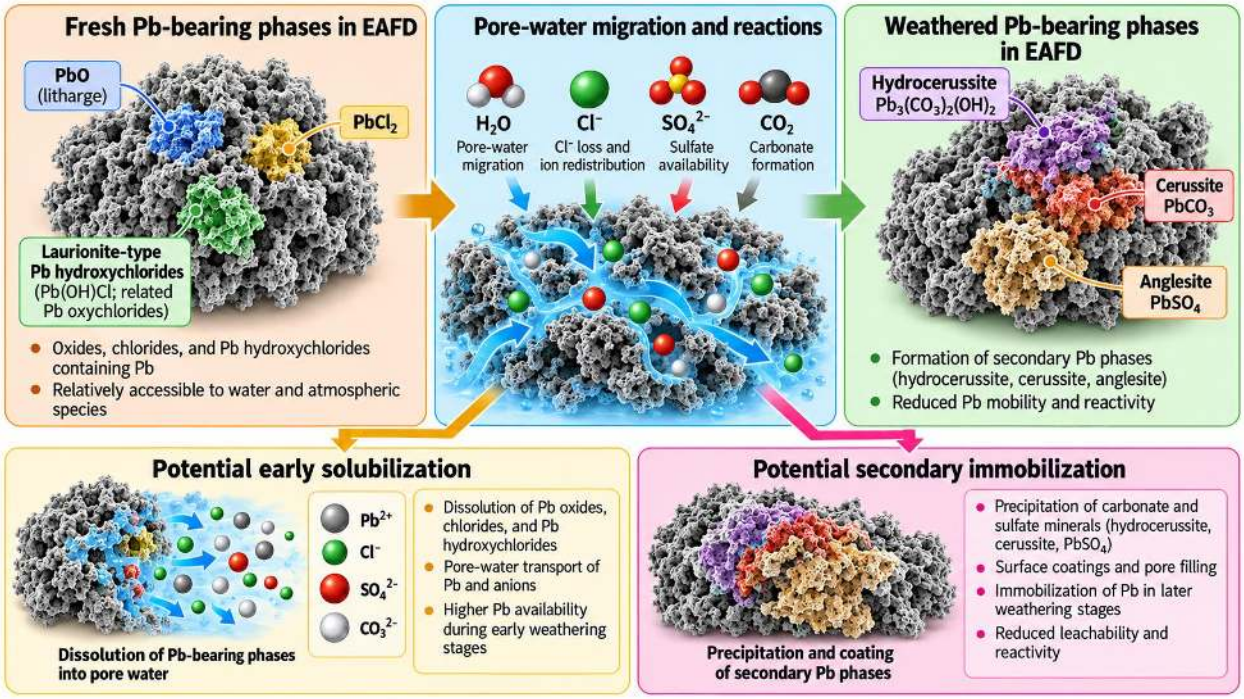


Figure 5
Conceptual Pb transformation pathways during weathering
Note. Adapted from the fresh-versus-weathered phase observations of Martins et al. (2008) and the broader Zn/Pb treatment behavior reported by Al-Harahsheh, Altarawneh, et al. (2021), Al-Harahsheh, Orabi, and Al-Asheh (2021), and Al-Harahsheh et al. (2022).

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5.4. Fe-bearing phases, Ca-Mg phases, and amorphous matter

Fe-rich phases may evolve mainly at particle surfaces through oxidation, hydration, and precipitation of poorly crystalline oxyhydroxides rather than through complete transformation of bulk magnetite or hematite. Ca- and Mg-bearing phases can buffer pH and act as carbonate or sulfate sinks, while amorphous matter may host metals that are poorly resolved by conventional XRD. Rietveld XRD alone is therefore insufficient for a rigorous weathering study. It should be combined, where feasible, with SEM-EDS or EPMA for textural association, Mössbauer spectroscopy for Fe-bearing phases, XPS for surface chemistry, and XANES/EXAFS for metal speciation. Fărcean et al. (2026) illustrate the value of tracking compositional and microstructural evolution during alkaline treatment, although natural aging requires an analogous time-resolved design. Table 3 distinguishes directly observed transformations from mechanistically plausible pathways and links each to a processing consequence.

Table 3
Observed or mechanistically plausible mineralogical transformations during EAFD weathering

Initial domain	Weathering driver	Secondary state	Evidence status	Processing consequence
ZnO-rich surface	$H_2O + CO_2$	Zn carbonate/hydroxy carbonate, including hydrozincite	Directly supported for weathered EAFD	Changes acid demand, dissolution kinetics, and Zn speciation
$ZnFe_2O_4$ / mixed spinel	$H_2O + O_2$ + time	Largely persistent spinel with altered surface	Strongly supported persistence; limited direct kinetic data	Refractory Zn fraction remains
Pb chloride/hydroxychloride	Water leaching + CO_2	Pb carbonate/hydroxy carbonate assemblage	Direct fresh-weathered evidence	May reduce chloride but alter Pb leachability
Soluble Na/K/Ca chlorides	Rainfall / pore-water flow	Partial removal or recrystallized salts	Strongly plausible and supported by washing studies	Lower Cl inventory; spatial heterogeneity
Fe(II)-bearing oxide surfaces	$O_2 + H_2O$	Fe(III)-rich oxyhydroxide coating	Mechanistically plausible; needs more direct quantification	Potential passivation and altered surface area
Ca-bearing alkaline phases	CO_2 + sulfate	Ca carbonate/sulfate	Plausible	pH buffering, cementation, and

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	altered porosity

Note. "Direct" refers to evidence from fresh-versus-weathered EAFD or explicit phase identification; "plausible" indicates a pathway consistent with geochemistry and adjacent EAFD treatment literature but requiring targeted aging experiments.

6. Thermodynamics and Geochemical Controls

6.1. pH, Eh, carbonate equilibria, and complexation

Evolving pore-solution chemistry, rather than total composition alone, governs weathering pathways. High initial alkalinity can favor Zn and Pb carbonate precipitation as CO_2 enters the pore space, while chloride-rich solutions stabilize aqueous metal-chloride complexes and delay precipitation. As soluble alkalis are washed out and carbonation proceeds, pH may decline, changing the relative stability of oxide, carbonate, sulfate, and hydroxide phases. Eh is particularly important for Fe- and Cr-bearing surfaces. A geochemical description of EAFD storage therefore requires simultaneous treatment of acid-base equilibria, gas exchange, mineral saturation, and redox constraints.

6.2. Saturation indices and reactive-transport modeling

PHREEQC-type modeling can test whether measured pore waters are saturated with $ZnCO_3$, hydrozincite, $PbCO_3$, hydrocerussite, $PbSO_4$, FeOOH, or $CaCO_3$. Saturation, however, does not demonstrate that a phase forms at an industrially relevant rate. Kinetic dissolution of ZnO and ferrites, CO_2 gas transfer, capillary transport, evaporation, nucleation barriers, and changing reactive surface area must be coupled with equilibrium calculations. Cifrian et al. (2021) demonstrate the usefulness of geochemical modeling for EAFD-bearing systems, while Kukurugya et al. (2015) provide thermodynamic and kinetic context for Zn, Fe, and Ca behavior during acid processing. The principal gap is the integration of these elements into a storage-specific reactive-transport model.

A predictive weathering model should begin with a quantified phase inventory rather than a bulk oxide analysis. It should then calculate pore-water evolution during repeated wetting and drying, including chloride and sulfate complexation, and update phase volumes as dissolution and precipitation proceed. Such a model would allow testable predictions: where in a stockpile

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hydrozincite should appear first, whether chloride is flushed faster than Zn is mobilized, and how rapidly a spinel-rich refractory residue develops at particle surfaces or within the pile.

7. Evolution of Metal Mobility and Environmental Leachability

7.1. Zinc and lead

Weathering can both mobilize and immobilize zinc. Dissolution of ZnO or soluble salts increases short-term aqueous Zn, whereas precipitation of hydrozincite or related secondary phases can reduce dissolved concentrations. Persistent $ZnFe_2O_4$ provides a third reservoir that may remain largely unaffected by moderate storage exposure. The net result depends on pH, CO_2 availability, liquid-to-solid ratio, chloride concentration, and whether water is retained or exported as drainage. Lead follows a similarly non-monotonic logic because chloride-bearing phases may dissolve while carbonates or $PbSO_4$ precipitate.

7.2. Cadmium, chromium, iron, and manganese

Cadmium commonly tracks more labile Zn-bearing or salt-associated fractions and therefore deserves targeted speciation rather than inference from Zn alone. Chromium requires explicit oxidation-state analysis because Cr(III) in spinel is fundamentally different from mobile Cr(VI). Iron and manganese can influence mobility indirectly by providing sorptive or coprecipitating surfaces. Stabilization studies such as de Souza et al. (2010), construction-related assessments such as Nair et al. (2022) and Dehnavi et al. (2024), and EAFD-containing geopolymer work such as Cifrian et al. (2021) show that matrix evolution can strongly change measured release even when total metal content remains constant.

7.3. Standard leaching tests versus field weathering

TCLP-type tests, EN 12457 procedures, SPLP, batch extraction, columns, and field lysimeters answer different questions. Batch tests accelerate contact under standardized chemistry, whereas field weathering is transport-limited and spatially heterogeneous. A low leachable concentration after prolonged storage may indicate secondary mineral stabilization, but it may also reflect prior flushing of soluble material. Figure 6 shows why storage history should be treated as a state

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variable when interpreting laboratory leaching results as environmental behavior. Table 4 summarizes the conditional mechanisms that can increase or decrease the mobility of Zn, Pb, Cd, Cr, Fe, and Mn.

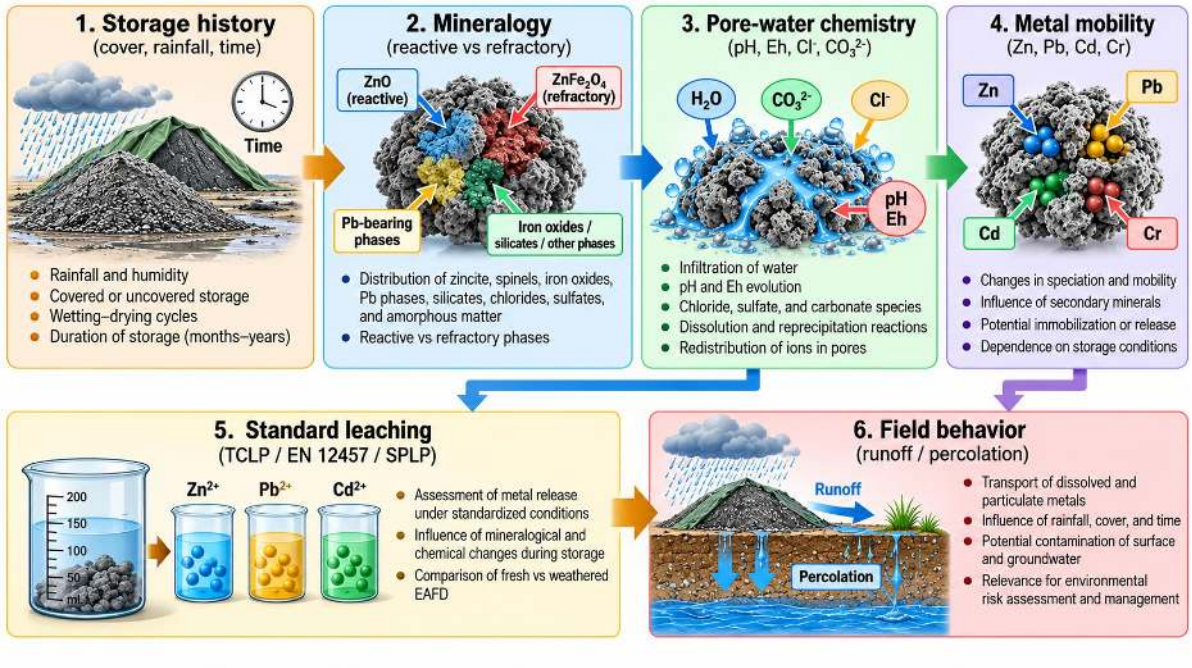


Figure 6
Coupling between weathering, metal mobility, and leachability
Note. Adapted conceptually from Martins et al. (2008), de Souza et al. (2010), and Cifrian et al. (2021). Standardized leaching results should be interpreted together with storage history, phase inventory, pore-water chemistry, and evidence of prior flushing.

Table 4 summarizes the conditional weathering mechanisms that can increase or decrease the mobility of environmentally relevant elements and identifies the measurements needed to resolve those effects.

Table 4
Expected effects of aging/weathering on the mobility of environmentally relevant elements in EAFD

Element	Primary concern	Weathering process that may increase mobility	Weathering process that may decrease mobility	Key measurement
Zn	High concentration and resource value	ZnO dissolution; chloride complexation	Carbonate/hydroxycarbonate precipitation; persistence in spinel	Sequential extraction + XAS/XRD + pore-water Zn

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Pb	Toxicity and variable chloride/carbonate hosts	Dissolution of soluble Pb-Cl phases	Hydrocerussite/cerussite or $PbSO_4$ formation	Pb speciation + pore-water Cl and carbonate
Cd	Toxicity and potentially labile association	Release with soluble Zn/salt fraction	Sorption/coprecipitation on secondary phases	Low-level dissolved Cd + host-phase identification
Cr	Oxidation-state-dependent hazard	Oxidizing/alkaline conditions if Cr(VI) forms	Retention as Cr(III) in spinel/oxide	Cr(III)/Cr(VI) speciation
Fe	Controls secondary surfaces	Acidic dissolution	Fe(III) oxyhydroxide precipitation	Fe(II)/Fe(III), mineralogy, and surface area
Mn	Redox-active and spinel-associated	Dissolution under reducing/acid conditions	Oxide or carbonate precipitation	Mn speciation and dissolved Mn

Note. Directions are conditional rather than universal. Field behavior depends on water balance, pH, redox conditions, and whether drainage exports previously mobilized species.

8. Microstructural and Physical Aging

8.1. Agglomeration, cementation, and surface coatings

Mineralogical alteration is accompanied by physical aging. Dissolved salts migrate toward drying fronts and precipitate at interparticle contacts, while carbonates, sulfates, and Fe-rich precipitates can form surface bridges or coatings. The result may be stronger agglomerates, lower dustiness, altered flowability, and reduced effective reactive surface area. Lanzerstorfer and Brunner (2023) showed that EAFD flowability is a measurable processing property; storage-induced cementation is therefore a plausible mechanism for its evolution, although dedicated aging experiments are needed to quantify the relationship.

8.2. Pore structure, permeability, and solid-liquid separation

Secondary precipitation can clog pores or, conversely, generate microcracking through crystallization stress and repeated wetting–drying cycles. Both outcomes can change water penetration through a stockpile and the uniformity with which later leaching reagents contact particles. In hydrometallurgical processing, the same physical changes can affect slurry rheology, filtration resistance, and soluble-salt entrainment. These variables are rarely reported because

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most EAFD studies characterize particle size and chemistry immediately before leaching without documenting the material's prior storage history.

The lack of physical aging data matters when comparing reported extractions. Two samples with similar total Zn and Fe can differ in agglomeration, porosity, coating thickness, and accessible ZnO surface. Such differences can appear experimentally as changes in apparent leaching kinetics even when intrinsic mineral dissolution kinetics are unchanged. Time-resolved BET surface area, mercury intrusion or gas porosimetry, particle-size distribution, micro-CT, and standardized flowability measurements should therefore accompany future aging experiments.

9. Effect of Weathering on Hydrometallurgical Processing

9.1. Acid leaching and Zn-Fe selectivity

Acid leaching is highly sensitive to the balance between reactive Zn phases and acid-consuming gangue or Fe-bearing phases. Langová and Matýsek (2010), Oustadakis et al. (2010), Shawabkeh (2010), Montenegro et al. (2013), Kul et al. (2015), Halli et al. (2017, 2018), Palimąka et al. (2018), Zoraga et al. (2020), Trifunović et al. (2024, 2026), and Miranda et al. (2026) collectively show that extraction depends on acid concentration, temperature, reductive or other pretreatment, and phase distribution. Weathering can plausibly shift this balance by converting ZnO to carbonate-bearing phases, washing out soluble salts, and forming Fe-rich coatings; however, direct quantification of these storage-induced effects is still limited.

A carbonate-rich weathered fraction can increase acid consumption through neutralization while still dissolving readily, whereas removal of soluble chloride may simplify downstream purification. Conversely, a stockpile that has preferentially lost reactive Zn phases through drainage could become relatively enriched in $ZnFe_2O_4$, reducing apparent Zn extraction at a fixed acid dose. This mechanism offers a testable explanation for part of the inter-study variability in nominally similar EAFD feeds.

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9.2. Alkaline, ammoniacal, chloride, and alternative leaching systems

Alkaline routes exploit the amphoteric behavior of Zn and can suppress Fe dissolution. Li et al. (2010), Chairaksa-Fujimoto et al. (2016), Miki et al. (2016), Zhang et al. (2019), Gamutan et al. (2024), and Fan, Du, Wang, and Gao (2026) show the importance of phase activation and alkaline chemistry. Ammonium-carbonate and ammonium-chloride systems are likewise sensitive to whether Zn occurs as ZnO, ferrite, or a secondary carbonate phase. Havlík et al. (2018) explicitly connected ZnO abundance with ammonium-carbonate leaching behavior.

Alternative systems extend this logic. Teimouri et al. (2022) explored ionic-liquid extraction, while Mousavi et al. (2026) examined EAFD as a source of rare earth elements using comparative leaching strategies. These studies reinforce a broader point: the feed is a multicomponent mineral assemblage, so any weathering-induced redistribution of major Zn, Fe, Ca, chloride, or sulfate phases can also alter the behavior of minor or valuable co-elements.

9.3. Reagent consumption, purification, filtration, and residue properties

The downstream effect of aging is not limited to percentage extraction. Halli et al. (2020) and Xanthopoulos et al. (2017) show that metal recovery from leach liquors depends on precipitation, solvent extraction, and solution composition. Remeteiová et al. (2023) demonstrate that even wastewater generated from neutral EAFD leaching requires dedicated treatment. Figure 7 therefore treats storage history as an upstream source of variation in reagent demand, impurity loading, residue mineralogy, and filtration rather than as a peripheral environmental detail. Table 5 translates the main weathering changes into testable hypotheses for acid, alkaline/ammoniacal, and downstream hydrometallurgical behavior.

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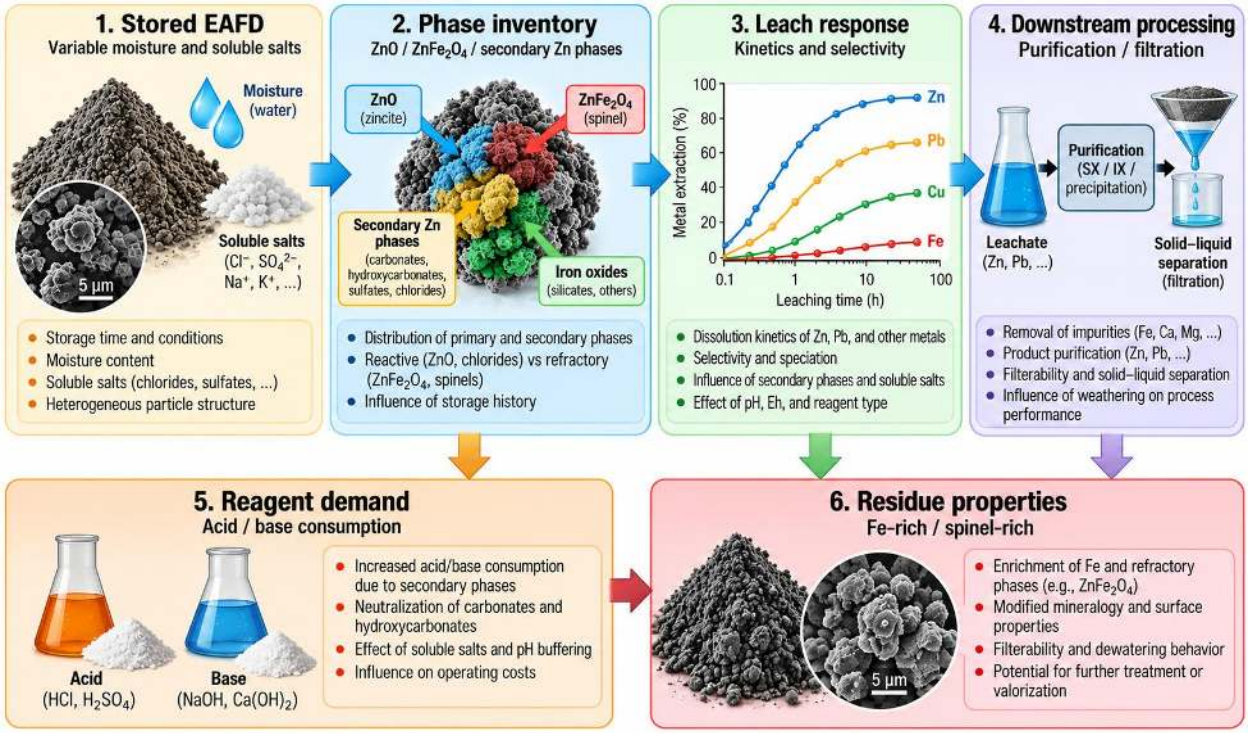


Figure 7
Effect of EAFD aging on hydrometallurgical processing
Note. Adapted conceptually from Halli et al. (2017, 2018, 2020), Havlík et al. (2018), Lee et al. (2020), and Xanthopoulos et al. (2017), emphasizing how feed-state changes can propagate into extraction, purification, residue properties, and filtration.

Table 5 summarizes the principal process hypotheses linking weathering-related feed changes to leaching behavior and downstream hydrometallurgical consequences.

Table 5
Potential effects of weathering on EAFD leaching and downstream hydrometallurgy

Weathering change	Acid leaching	Alkaline/ammoniacal leaching	Downstream consequence
ZnO -> Zn carbonate/hydroxycarbonate	Often readily soluble but with added neutralization demand	May change complexation and dissolution rate	Different reagent demand and Zn speciation
Relative enrichment in $ZnFe_2O_4$	Lower direct Zn extraction	May require CaO or other activation	More refractory residue
Loss of soluble chlorides	Lower Cl in liquor	Lower salt background	Reduced corrosion/purification burden
Fe-rich secondary coatings	Possible slower initial	Possible mass-	Filtration/rheology changes

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	kinetics	transfer limitation	
Agglomeration/cementation	Non-uniform reagent penetration	Potential diffusion limitation	Slurry preparation and filtration effects
Prior metal flushing during storage	Lower labile Zn/Pb inventory	Lower soluble fraction	Bulk assay may overpredict readily recoverable metal

Note. The table states process hypotheses that should be tested with paired fresh and aged materials. Effects can reverse depending on pH, phase abundance, and pretreatment.

10. Effect of Aging on Pyrometallurgical and Hybrid Processing

10.1. Waelz-type reduction, hydrogen reduction, and microwave treatment

Pyrometallurgical routes are sometimes assumed to be relatively insensitive to low-temperature weathering because high-temperature treatment destroys hydrates and carbonates. That assumption is incomplete. Moisture, chloride, carbonate loading, agglomeration, and feed permeability can influence drying duty, volatilization behavior, off-gas chemistry, pellet strength, and heat transfer before the feed reaches its final thermal state. Lin et al. (2017), Wang et al. (2021), Thottempudi and Roy (2022), Brandner et al. (2021), Kumar and Roy (2026), Omran et al. (2019), and Xiong et al. (2024) show the diversity of reduction and thermal routes in which feed physical and mineralogical properties matter.

10.2. Chlorination and halogen-assisted phase transformation

Chlorination deliberately converts metal-bearing phases into volatile or water-soluble chlorides. Hamann et al. (2024) demonstrated selective Zn and Pb removal by chlorination-evaporation, while Huang and Yang (2024) used magnesium chloride for oxygen-assisted zinc recovery. Al-Harahsheh et al. (2019) reviewed EAFD treatment together with halogenated plastic wastes. In this context, prior natural chloride loss may change reagent requirements, whereas residual chlorides can contribute to corrosion and off-gas management. Weathering history should therefore be reported even when the principal transformation is thermal.

10.3. Sulfation roasting and hybrid routes

Sulfation roasting converts Zn-bearing phases into water-leachable sulfates while seeking to retain Fe in less soluble forms. Pickles and Marzoughi (2019), Chen et al. (2022, 2023, 2025),

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Wu et al. (2023), and Pereira et al. (2025b) illustrate the thermodynamic and kinetic basis of this approach. Ju et al. (2025) similarly used ammonium-salt roasting followed by water leaching, and Fan, Du, Wang, and Huo (2026) developed a combined pyro-hydrometallurgical route. Weathering products such as carbonates or hydroxides decompose before or during these treatments, potentially changing early gas evolution and local reaction paths even when the final high-temperature phase assemblage converges toward a similar equilibrium state.

Low-temperature smelting and phase-reconstruction studies provide additional evidence that the phase inventory can be engineered. Li et al. (2023), Xie et al. (2023), and Xue et al. (2025) demonstrate deliberate redistribution of Zn, Fe, and other elements. These are not weathering studies, and they should not be cited as direct proof of storage reactions. Their relevance is narrower but important: they demonstrate that phase identity governs separation and, therefore, that uncontrolled low-temperature phase evolution during storage deserves direct quantification.

11. Storage, Stabilization, and Industrial Management

11.1. Open versus covered storage and water management

Open storage maximizes rainfall infiltration, gas exchange, salt migration, and runoff, whereas covered dry storage limits aqueous transport but does not necessarily eliminate slow oxidation or moisture uptake. Stockpile geometry can generate gradients in oxygen, CO_2, temperature, and water saturation. An external crust may be repeatedly washed and carbonated while the core remains closer to its fresh mineralogical state. Sampling a single location can therefore misrepresent the feed delivered to a recovery plant.

11.2. Stabilization and beneficial use versus preservation for metal recovery

Stabilization approaches intentionally reduce leachability through cementitious or geopolymeric matrices, as illustrated by de Souza et al. (2010), Cifrian et al. (2021), and construction-sector reviews or case studies such as Nair et al. (2022) and Dehnavi et al. (2024). These approaches pursue objectives that differ fundamentally from preserving EAFD as a high-grade secondary Zn resource. Management strategy should therefore begin with a decision on whether the dust is

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destined for metal recovery, safe incorporation, or disposal. Uncontrolled weathering can move the material toward a partially stabilized state while simultaneously degrading its predictability as a process feed.

11.3. Controlled weathering as pretreatment

Controlled weathering merits investigation as a deliberate pretreatment, but it should be framed as a hypothesis rather than as an established process. A staged route could combine water washing to remove chlorides, controlled carbonation to transform selected reactive phases, drainage capture to recover dissolved metals, and conditioning to avoid hard cementation. The objective would be to use low-temperature chemistry to prepare a more uniform feed without uncontrolled metal loss. Figure 8 places this concept within a predictive research framework in which storage variables are measured, modeled, and linked to process outcomes. Table 6 summarizes how contrasting storage conditions may affect phase evolution, environmental release, and downstream processing.

Table 6
Storage conditions, expected phase transformations, environmental consequences, and processing implications

Storage condition	Dominant transformation tendency	Environmental implication	Processing implication
Covered, dry, short-term	Limited hydration/oxidation	Low runoff generation	Best preservation of fresh-feed characteristics
Open, well-drained	Salt dissolution, carbonation, repeated drying	Potential metal-bearing runoff; lower soluble salt inventory over time	Lower Cl but greater mineralogical heterogeneity
Open, poorly drained	Persistent pore water, dissolution/reprecipitation	Greater potential for dissolved-metal migration	Cementation, coatings, and variable leach response
Wet slurry/ponded storage	Strong ionic redistribution	Water-treatment requirement	Potential prewashing but difficult dewatering
Controlled washing + carbonation	Targeted chloride removal and secondary phase formation	Managed effluent and potentially lower uncontrolled release	Potential pretreatment if phase and moisture targets are controlled

Note. Conceptual management matrix. Site-specific engineering requires water-balance, gas-transfer, mineralogical, and regulatory data.

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12. Critical Research Gaps and Future Research Agenda

12.1. Time-resolved natural and accelerated weathering

The first and most consequential gap is the lack of controlled time series that begin with a well-characterized fresh dust and follow the same material through weeks, months, and years. Martins et al. (2008) remains unusually valuable because it directly compares recent and weathered material. Future studies should combine natural exposure with accelerated protocols, but accelerated tests must be calibrated against field weathering rather than assumed to be equivalent.

12.2. Quantitative mineralogy, amorphous phases, and metal speciation

Second, phase identification must become quantitative. Rietveld XRD should be combined with an internal standard for amorphous content, SEM-EDS or EPMA for textural association, Mössbauer spectroscopy for Fe-bearing phases, XPS for surfaces, and XANES/EXAFS for Zn, Pb, and Cr speciation where feasible. This combination is essential because the distinction among ZnO, $ZnFe_2O_4$, amorphous Zn-bearing matter, and secondary Zn phases determines both the interpretation of weathering and the likely hydrometallurgical response.

12.3. Coupling mineralogy with kinetics, leachability, and reactive transport

Third, weathering kinetics are largely unknown. Rate laws for ZnO dissolution, ferrite persistence, carbonate nucleation, and salt flushing should be combined with pore-scale or column transport. Laboratory leaching must be conducted on the same aged specimens used for mineralogical analysis so that extraction can be correlated with phase inventory rather than with bulk composition alone.

12.4. Storage history as a mandatory feed descriptor

Fourth, EAFD recovery studies should report dust age, storage duration, cover condition, rainfall exposure, moisture content, washing history, and stockpile sampling location. Current process literature often reports reagent concentrations and temperatures in detail while identifying the

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feed only as "EAFD." That omission weakens cross-study comparison and may conceal an important source of feed variability.

12.5. Process-integrated research priorities

Fifth, aging studies should extend beyond environmental leachability. The same specimens should be tested in representative acid, alkaline, ammoniacal, sulfation, reduction, or chlorination routes so that mineralogical evolution can be related directly to process response. Recent reviews and integrated process studies by Binnemans et al. (2020), Toporkova et al. (2021), Xue et al. (2023), Rudnik (2025), Liu et al. (2026), Pereira et al. (2025, 2025a, 2026), Rinne et al. (2022), and Siame et al. (2019) provide the broader context for such integration.

Future paired fresh-versus-aged studies should also adopt a common quantitative reporting basis. At minimum, experiments should report dry-feed mass, complete elemental inventories, cumulative drainage volume and associated metal/salt losses, mass-balance closure, liquid-to-solid ratio, reagent consumption per unit mass of dry EAFD, extraction calculated from both solution and residue where possible, impurity loading, filtration performance, and final residue mineralogy. Relative enrichment after aging should not be interpreted as absolute metal accumulation unless supported by a closed mass balance.

Finally, process design should consider minor and emerging value streams. Bui et al. (2022) demonstrated conversion of EAFD-derived Zn into ZnO nanoparticles, Jia et al. (2023) used EAFD slurry in desulfurization, Yang et al. (2025) coupled wet desulfurization with valuable-metal leaching, and Mousavi et al. (2026) investigated rare-earth recovery. These examples broaden the definition of "process performance" beyond bulk Zn recovery and strengthen the need to understand how prior aging modifies feed reactivity. Figure 8 integrates these priorities into a predictive research framework, and Table 7 consolidates the principal evidence gaps and the experiments required to move from qualitative weathering concepts to predictive, process-relevant relationships.

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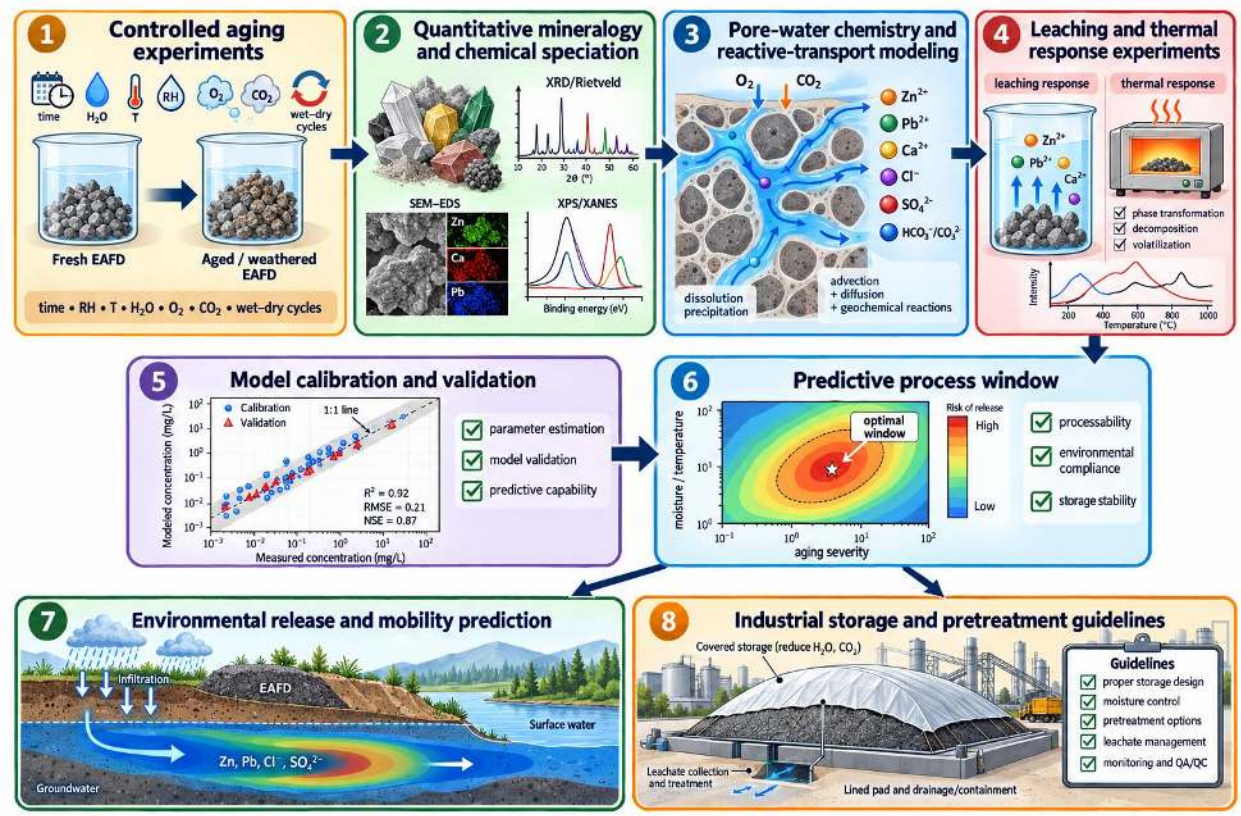


Figure 8
Integrated research framework for predictive EAFD aging
Note. Conceptual framework developed from the evidence synthesis in this review. The framework links controlled aging, quantitative mineralogy, pore-water chemistry, reactive-transport modeling, environmental release, and extractive-metallurgical response.

Table 7 summarizes the critical research gaps, preferred analytical tools, and decisions that each proposed experiment is intended to support.

Table 7
Critical research gaps and experiments required for predictive EAFD aging

Research gap	Minimum experiment	Preferred analytical tools	Decision enabled
No time-resolved phase evolution	0, 1, 3, 6, 12+ month paired exposure	Rietveld XRD, SEM-EDS, ICP/XRF	Transformation kinetics
Natural vs accelerated weathering unclear	Parallel field and chamber exposure	Humidity/CO_2 control, pore-water chemistry	Acceleration factor and validity
Amorphous/poorly crystalline phases omitted	Internal-standard XRD + spectroscopy	XPS, Mössbauer, XAS	Complete metal host inventory

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Zn/Pb speciation unresolved	Sequential phase-specific analysis	XANES/EXAFS, microprobe	Mechanistic mobility model
No reactive-transport model	Column wet-dry tests with drainage capture; cumulative drainage volume and associated metal/salt inventory	PHREEQC + kinetic/transport coupling	Stockpile release prediction
Storage history absent in process papers	Mandatory feed metadata	Moisture, age, cover, rainfall, location	Comparable process datasets
Aging not linked to recovery	Leach/roast same specimens at each age	Extraction, reagent demand, filtration	Process sensitivity to aging
Controlled aging unexplored	Washing/carbonation conditioning trials	Mass balance + phase analysis	Pretreatment feasibility

Note. The agenda prioritizes experiments that produce causal links among storage conditions, phase transformations, metal mobility, and processing response.

12.6. Coverage of the contemporary EAFD process literature

The proposed agenda is consistent with the breadth of contemporary EAFD research. Thermal and hydrometallurgical studies include Ahmad et al. (2022), Al-Harahsheh et al. (2019), Al-Harahsheh, Altarawneh, et al. (2021), Al-Harahsheh, Orabi, and Al-Asheh (2021), and Al-Harahsheh et al. (2022), Brandner et al. (2021), Chen et al. (2022, 2023, 2025), Fan, Du, Wang, and Gao (2026) and Fan, Du, Wang, and Huo (2026), Hamann et al. (2024), Huang and Yang (2024), Ju et al. (2025), Kumar and Roy (2026), Li et al. (2023), Pickles and Marzoughi (2019), Tang et al. (2023), Wu et al. (2023), and Xue et al. (2025). Hydrometallurgical selectivity and downstream recovery are represented by Chairaksa-Fujimoto et al. (2016), Halli et al. (2017, 2018, 2020), Kukurugya et al. (2015), Kul et al. (2015), Miki et al. (2016), Montenegro et al. (2013), Oustadakis et al. (2010), Raza et al. (2016), Tsakiridis et al. (2010), Xanthopoulos et al. (2017), and Zoraga et al. (2020, 2022). This diversity makes feed-state reporting increasingly important because process comparisons otherwise combine materials with unknown mineralogical histories.

Characterization, environmental behavior, and broader recycling context are represented by Almeida et al. (2023), Araújo and Schalch (2014), Buzin et al. (2017), Cifrian et al. (2021), de

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Souza et al. (2010), Dehnavi et al. (2024), Fărcean et al. (2026), Lanzerstorfer and Preitschopf (2020), Nair et al. (2022), Pereira et al. (2025, 2025a, 2026), Rinne et al. (2022), Santos et al. (2021), Toporkova et al. (2021), Trifunović et al. (2022), Vilela et al. (2014), Wang et al. (2012), and Zhang et al. (2024). Collectively, these studies support a shift from reporting bulk chemistry alone toward a common characterization package that includes quantitative phase inventory, morphology, leachable fractions, and documented storage state.

13. Conclusions and Outlook

Electric arc furnace dust is a reactive mineral assemblage rather than a chemically static waste. Its initial phase inventory is established during steelmaking and off-gas cooling, but subsequent storage can selectively dissolve, redistribute, oxidize, carbonate, hydrate, and reprecipitate the more reactive fraction while leaving a substantial spinel-rich framework comparatively persistent.

The central process implication is that storage history should be treated as an upstream state variable. Changes in soluble salts, Zn and Pb mineral hosts, surface coatings, agglomeration, pore chemistry, and moisture can alter leachability, reagent demand, filtration, thermal behavior, and impurity management. Consequently, materials with similar bulk Zn and Fe assays may respond differently because their mineralogical and physical histories differ.

The most immediate research need is a time-resolved fresh-to-weathered dataset that combines quantitative mineralogy, pore-water chemistry, metal speciation, environmental release, and representative recovery tests on the same specimens. Reactive-transport modeling should then be calibrated against those observations to translate particle- and column-scale behavior into stockpile-scale predictions.

Controlled weathering may eventually become a useful pretreatment rather than an uncontrolled degradation process, but that proposition remains to be demonstrated. Water washing, managed carbonation, selective phase transformation, and drainage recovery could be integrated to reduce chloride, manage problematic species, and prepare a more predictable feed. Its feasibility will

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depend on showing that any environmental benefit is compatible with metal retention, process selectivity, energy demand, water management, and downstream recovery.

Declarations

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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

Conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation by the author.

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