

Controlled Jarosite Formation as a Multifunctional Hydrometallurgical Circuit-Integration Tool: Fundamentals, Applications, Benefits, and Limitations—A Critical Review

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DOI: <https://doi.org/10.68050/JAMS.2026.811>

Received: 10 Oct 2026; Accepted: 17 Oct 2026; Published: 19 October 2026

ABSTRACT

Jarosite precipitation is typically treated as an iron-removal operation that produces a bulky residue. This critical narrative review evaluates controlled jarosite formation as a multifunctional tool for integrating hydrometallurgical circuits and asks when it also meets stricter process-intensification criteria. The evidence base combines recent literature from 2020–August 2026 with seminal studies on phase stability, precipitation kinetics, impurity incorporation, continuous operation, and seed recycling. Direct evidence is strongest for ferric-iron removal and zinc-liquor purification; benefits for ion exchange, membranes, high-purity crystallization, and some battery circuits remain largely inferential. Ideal alkali jarosites generate approximately 2.86–2.99 kg of solid, fix about 1.15 kg of sulfate, and produce about 1.76 kg of H₂SO₄ equivalent per kilogram of Fe precipitated. These stoichiometric penalties make residue mass and acid balance intrinsic design variables. Controlled precipitation can remove Fe(III), transfer sulfate to a separable solid, capture selected hazardous elements, and potentially reduce downstream impurity loads. Conversely, excessive supersaturation, uncontrolled neutralization, poor seed management, or deposition on mineral and equipment surfaces can cause ultrafines, scaling, passivation, losses of valuable metals, and unstable residues. Route selection must therefore consider residual Fe, target-metal retention, particle and cake properties, water and reagent balances, evidence maturity, annualized whole-circuit economics, and residue destination. The review proposes an evidence-qualified decision framework and identifies continuous campaigns, full impurity and wash balances, quantitative filtration data, activity-based thermodynamics, technoeconomic assessment, and life-cycle verification as research priorities.

Keywords: Jarosite precipitation; iron removal; circuit integration; impurity partitioning; solid–liquid separation; residue valorization

Highlights

- Controlled jarosite is assessed primarily as a multifunctional circuit-integration tool.
- Ideal jarosites generate 2.86–2.99 kg solid and 1.76 kg H₂SO₄ equivalent per kg Fe.
- Direct evidence is strongest for zinc purification; several downstream benefits remain inferential.
- Evidence maturity, particle quality, annualized economics, and residue fate govern route selection.

Graphical abstract





1. INTRODUCTION

1.1 Iron as a circuit-wide hydrometallurgical constraint

Iron is not merely a dissolved impurity that must be reduced before product recovery. In sulfate hydrometallurgy, it participates in redox reactions, hydrolysis, complexation, secondary-phase formation, and the transfer of acidity and water between unit operations. Excess dissolved iron can increase neutralization demand, overload solvent-extraction circuits, contaminate products, promote scaling, complicate crystallization, and increase the mass of residues that require washing and disposal. Conversely, engineers can design iron-bearing phases to remove sulfate, capture contaminants, provide reactive surfaces, or generate secondary raw materials. The practical problem is therefore not simply whether iron precipitates, but where it precipitates, in which phase, with what physical properties, and with what consequences for the complete flowsheet (Buriti et al., 2024; Cruells & Roca, 2022; Eftekhari et al., 2020a; Höber & Steinlechner, 2021; Pereira, 2026a).

Jarosite-type compounds occupy a distinctive position because they are stable over a useful acidic operating window, incorporate a large monovalent or charge-compensated cation in the A site, and bind sulfate within an iron hydroxy-sulfate framework. Industrial zinc circuits have long used jarosite precipitation to control iron, yet the same family of phases may form unintentionally during copper sulfide leaching, acid mine drainage neutralization, or the processing of secondary resources. The recent literature consequently presents two apparently contradictory images: jarosite as a reliable purification product and jarosite as a source of passivation, metal loss, and environmental liability (Asimi et al., 2020; Chen et al., 2025; Cruells & Roca, 2022; Eftekhari et al., 2020a; Höber & Steinlechner, 2021; Kushwaha et al., 2023; Singh et al., 2023).

1.2 From residue generation to multifunctional integration and conditional intensification

Process intensification means a substantial, measurable change in equipment size, energy or resource use, waste, safety, or productivity—not incremental parameter optimization (Moulijn et al., 2008; Stankiewicz & Moulijn, 2000). Process integration links material and energy flows across operations; optimization improves a defined configuration; solution conditioning prepares liquor for separation; and multifunctionality combines useful functions in one stage. These concepts overlap but are not interchangeable.

Accordingly, this review treats controlled jarosite formation primarily as a multifunctional circuit-integration tool and classifies it as process intensification only when comparison with a defined baseline shows substantial circuit-level improvement—for example, fewer unit operations; reduced equipment volume, energy, reagent or water demand, impurity load to SX/IX/EW, annualized cost or verified environmental impact; or greater volumetric productivity or overall metal recovery. Fe removal alone or modestly improved batch precipitation is insufficient.

Jarosite becomes attractive when it reaches the required residual Fe specification while retaining target metals in solution, controlling sulfate, producing a settleable and washable solid, and enabling useful acid, water, seed, or product recycle. It becomes still more valuable when the solid immobilizes hazardous constituents or is deliberately routed to recovery of zinc, lead, silver, indium, gallium, germanium, copper, or iron (Ahamed et al., 2021; Chen et al., 2025; Conić et al., 2024; De-la-Cruz-Moreno et al., 2021; Dong et al., 2025; Kamberović et al., 2021; Singh et al., 2023; Y. Wang et al., 2020; Zhou et al., 2025; Zhu et al., 2025). These functions constitute intensification only when the integrated benefit is demonstrated against goethite, hematite, or another credible flowsheet.

1.3 Scope, novelty, and review questions

Existing reviews have clarified jarosite structure, reactivity, environmental behavior, and valorization options, while broader assessments have compared iron-precipitation residues and recovery technologies (Buriti et al., 2024; Chen et al., 2025; Cruells & Roca, 2022; Dutrizac & Jambor, 2000; Eftekhari et al., 2020a; Höber & Steinlechner, 2021; Singh et al., 2023). The present review differs by organizing the evidence around a circuit-

level question: under which conditions does deliberately formed jarosite provide a net technical, economic, and environmental advantage?

The synthesis combines recent work from 2020–2026 with selected seminal studies on phase equilibria, precipitation chemistry, impurity incorporation, seeding, continuous precipitation, and industrial zinc practice (Dutrizac, 1980, 1983, 1996, 1999, 2008; Dutrizac et al., 1980; Dutrizac & Dinardo, 1983; Dutrizac & Kaiman, 1975, 1976; Elgersma et al., 1993; Kershaw & Pickering, 1980). Six questions guide the discussion: (i) which solution conditions favor selective Fe removal; (ii) how are hazardous and valuable elements partitioned; (iii) which variables govern particle quality; (iv) how does precipitation affect acid and sulfate balances; (v) when is jarosite preferable to goethite or hematite; and (vi) which residue routes are sufficiently mature to influence present-day process selection.

Figure 1 summarizes the circuit concept used throughout the review, showing process boundaries and recycles but not the decision logic in Figure 6.

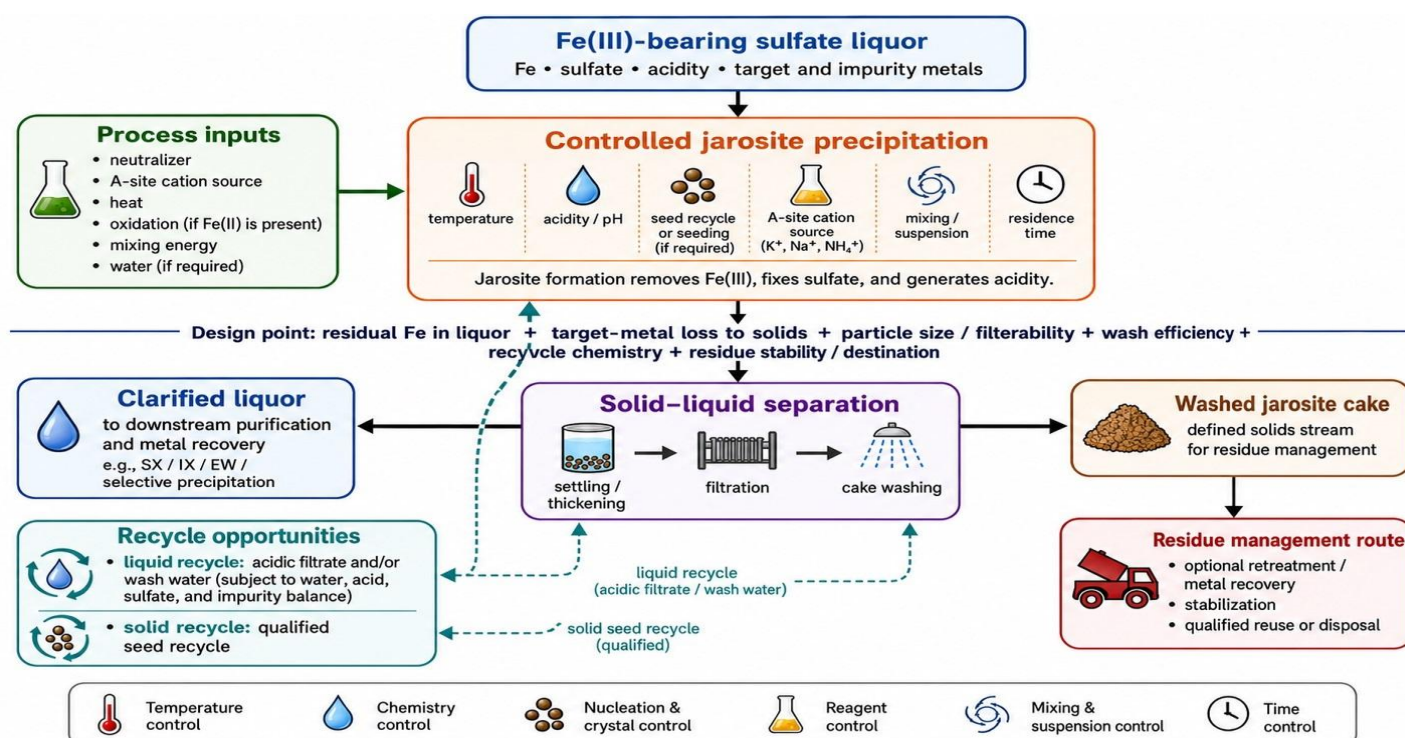


Figure 1. Process boundaries and recycle streams for controlled jarosite integration in a hydrometallurgical circuit.

Note. Adapted from multiple sources (Asimi et al. (2020), Cruells and Roca (2022), Dutrizac (1980), Höber and Steinlechner (2021), Neisiani et al. (2023), and Y. Wang et al. (2020)).

Figure 1 fixes the process and recycle boundary; Figure 6 separately provides branch logic and pass/fail criteria.

2. REVIEW METHODOLOGY

2.1 Review design and evidence base

This article is a critical narrative review with a transparent, structured search and evidence-coding protocol. It is not presented as a systematic review, and no claim of PRISMA compliance, exhaustive retrieval, or meta-analytic completeness is made. We selected this designation because the evidence includes phase-equilibrium studies, kinetic experiments, industrial observations, environmental investigations, residue-treatment studies, and conceptual process assessments that are too heterogeneous for a single quantitative meta-analysis.



The literature set was updated on 2 August 2026. Recent evidence was sought on ScienceDirect, SpringerLink, Wiley Online Library, ACS Publications, MDPI, PubMed, Crossref-indexed web search, and publisher reference lists. Backward and forward citation chaining was used to recover seminal primary studies before 2020. The revised bibliography comprises 128 distinct sources, encompassing primary studies, reviews, methodological contributions, and process-context publications. The emphasis remains 2020–2026, but foundational literature from 1971 onward is used for structure, stability, industrial development, continuous precipitation, seed effects, and impurity behavior.

2.2 Search concepts, eligibility, and coding

The principal search expression was: (jarosite* OR natrojarosite OR ammonium-jarosite OR potassium-jarosite OR lead-jarosite) AND (precipitat* OR formation OR iron-removal OR hydrometallurg* OR residue*) AND (selectiv* OR impurit* OR sulfate OR kinetics OR seed* OR filtration OR passivation OR valorization). Thematic searches added the terms continuous precipitation, residence-time distribution, zinc incorporation, arsenic, lead, silver, indium, gallium, goethite, hematite, solvent extraction, electrowinning, crystallization, and technoeconomic assessment. Search fields were those available in each platform, principally title, abstract, keywords, and indexed metadata.

English-language peer-reviewed articles and reviews published through 2 August 2026 were eligible when they addressed jarosite precipitation, dissolution, transformation, impurity partitioning, industrial application, environmental stability, or residue use. Seminal conference chapters were included selectively when they documented industrial development or phase equilibria. Preprints were excluded when a peer-reviewed version was available. Planetary, magnetic, and purely crystallographic jarosite studies without hydrometallurgical or environmental process relevance were excluded. Duplicates were removed first by DOI and then by normalized title, first author, and year.

Each source was coded for study family, material realism, scale, operating mode, precipitation or treatment conditions, A-site reagent, seeding, residence time, Fe removal, target-metal loss, phase identification, solid–liquid separation data, mass-balance reporting, residue destination, and evidence maturity. A value was coded as NR when it was not explicitly reported; NR was not interpreted as zero or as evidence that the measurement was not performed. Reviews were used to frame consensus and identify older sources but were not counted as direct experimental evidence.

Study-level coding is provided in Supplementary Table S1. The original study-level coding and evidence classification require reconciliation with the expanded 128-source bibliography before quantitative category counts can be reported as final. Industrial-scale and continuous studies remain relatively uncommon (Asimi et al., 2020; Elgersma et al., 1993; Soe et al., 2021). This profile confirms that laboratory batch evidence dominates the field. The matrix marks unreported fields as NR rather than inferring values from general knowledge.

2.3 Critical synthesis and limitations

The synthesis separates direct observations from engineering inference. Evidence classes used in the text and tables are: I, direct industrial or field evidence; II, pilot, continuous, or industrial-material evidence; III, controlled laboratory evidence using real residues or liquors; IV, synthetic-solution or model-system evidence; and V, review, contextual synthesis, or engineering inference. Evidence class describes transferability, not study quality.

Screening and coding were performed by a single reviewer. Bias was reduced by using a predefined extraction form, conducting a second author–year citation audit, coding unreported fields conservatively as NR, and checking major conclusions against both recent reviews and seminal primary studies. Nevertheless, the review may underrepresent non-English literature, proprietary plant data, and negative industrial results. The evidence map also shows recurring reporting gaps: few studies combine closed solution–solid–wash balances with particle-size distribution, specific cake resistance, cake moisture, and long-duration recycle operation. These limitations constrain numerical generalization and are carried explicitly into the conclusions.



3. CHEMISTRY, STRUCTURE, THERMODYNAMICS, AND KINETICS OF JAROSITE FORMATION

3.1 Structural flexibility and principal jarosite species

Jarosite-group minerals are commonly represented by $AFe_3(SO_4)_2(OH)_6$, where A is typically K^+ , Na^+ , NH_4^+ , or H_3O^+ . Divalent ions such as Pb^{2+} can occupy the A site through vacancies or other charge-compensation mechanisms, and oxyanions may partially replace sulfate. This structural flexibility explains both the technological utility and the risk of the phase: jarosite can be tailored by the choice of precipitating cation, but it can also incorporate contaminants and valuable elements through substitution, adsorption, coprecipitation, secondary-phase formation, or trapped liquor (Cheremisina et al., 2025; Cogram et al., 2023; Cruells & Roca, 2022; Dutrizac & Kaiman, 1975, 1976; Hernández-Lazcano et al., 2021; Jambor, 1999; Nolasco et al., 2022; Peng et al., 2023b; Shi et al., 2022).

For an ideal monovalent A-site jarosite, precipitation can be written as $A^+ + 3Fe^{3+} + 2SO_4^{2-} + 6H_2O \rightarrow AFe_3(SO_4)_2(OH)_6(s) + 6H^+$. The equation highlights four circuit effects: Fe(III) is transferred to the solid; sulfate and the A-site cation are consumed; water becomes structural hydroxyl; and acidity is generated. The precipitation stage must therefore provide continuous or staged neutralization, and its net acid value depends on whether the generated acidity can be recycled to leaching or creates additional neutralization demand elsewhere.

On a pure-phase stoichiometric basis, precipitation of 1 kg of Fe produces 2.99 kg of K-jarosite, 2.89 kg of natrojarosite, or 2.86 kg of ammonium jarosite. The same reaction fixes 1.15 kg of sulfate and releases six moles of H^+ per three moles of Fe, equivalent to approximately 1.76 kg of H_2SO_4 per kilogram of Fe precipitated. These are theoretical values calculated from ideal formulas; vacancies, hydronium substitution, coprecipitated phases, entrained liquor, and incomplete washing alter industrial mass balances. Nevertheless, they provide a quantitative lower-level constraint on neutralizer demand, residue generation, and sulfate transfer.

Table 1 summarizes the principal jarosite-type phases and the process consequences of choosing their A-site chemistry. The table is intended as a selection aid rather than a complete mineralogical classification.

Table 1. *Principal jarosite-type phases and their hydrometallurgical roles.*

Phase or family	Typical A-site chemistry	Potential process role	Principal qualification issue
Potassium jarosite	K^+	Rapid Fe precipitation; seed production; possible impurity scavenging	K introduction, metal incorporation, and product stability
Natrojarosite	Na^+	Industrial Fe removal using widely available sodium reagents	Na accumulation in recycle liquors and residue mass
Ammonium jarosite	NH_4^+	Fe removal with potentially different kinetics and residue behavior	Ammonia handling, nitrogen balance, and reagent cost
Hydronium-rich jarosite	H_3O^+ with vacancies/substitution	Formation under strongly acidic or cation-limited conditions	Non-stoichiometry and variable stability
Plumbojarosite/lead-bearing jarosite	Pb^{2+} with charge compensation	Lead immobilization or concentration into a recoverable phase	Leachability, valuable-metal association, and hazardous classification



Argentojarosite/silver-bearing jarosite	Ag ⁺ and/or associated Ag phases	Silver capture and possible preconcentration	Loss from primary circuit and need for selective recovery
Oxyanion-bearing jarosite	SO ₄ ²⁻ partly replaced or accompanied by As/Sb species	Removal or immobilization of hazardous oxyanions	Transformation-driven remobilization and long-term verification

Note. A-site occupancy and impurity association may be non-ideal and solution dependent. Adapted from multiple sources (Cerecedo-Sáenz et al., 2022; Cheremisina et al., 2025; Cogram et al., 2023; Cruells & Roca, 2022; Hernández-Lazcano et al., 2021; Nolasco et al., 2022; Peng et al., 2023b; Shi et al., 2022; Sowers et al., 2022).

Selection among K-, Na-, and NH₄-jarosite must consider reagent cost, downstream tolerance, seed quality, residue classification, and recycle accumulation, as similar Fe removal can mask different operating economics (Asimi et al., 2020; Neisiani et al., 2023).

3.2 Speciation, supersaturation, and phase competition

Jarosite formation requires ferric iron and is strongly influenced by ferric–sulfate complexation, water activity, ionic strength, and proton activity. Higher temperatures generally accelerate hydrolysis, nucleation, and growth, but the effect on product quality depends on the supersaturation trajectory. Strong neutralization at a single addition point can create local high-pH zones in which poorly crystalline ferric hydroxysulfates or hydroxides form, then reorganize into jarosite. Conversely, excessive acidity suppresses hydrolysis and may extend induction time. Concentrated industrial solutions therefore cannot be interpreted reliably through pH alone because activity coefficients and complexation change the effective driving force (Buriti et al., 2024; Buriti et al., 2025b; Cruells & Roca, 2022; Hernández-Lazcano et al., 2021; Nordstrom, 2020; Peng et al., 2024; Rabbani & Ahmadi, 2020). Foundational phase-equilibrium and precipitation studies established the strong effects of temperature, acidity, alkali availability, and ionic strength (Brown, 1971; Drouet & Navrotsky, 2003; Dutrizac, 1980, 1983; Dutrizac et al., 1980; Kershaw & Pickering, 1980). In classical alkali-jarosite tests at 97 °C, product yield increased with retention time to approximately 15 h before approaching a plateau, and sufficient agitation was required to prevent coating of the apparatus (Dutrizac, 1983).

Competing phases include goethite, hematite, ferrihydrite-like solids, schwertmannite, basic ferric sulfate, gypsum, and impurity-specific compounds. Temperature, acidity, redox state, sulfate concentration, residence time, seed mineralogy, and the availability of A-site ions affect phase selection. Hydrothermal treatments can intentionally transform ferric hydroxides or jarosite into denser iron oxides, while high K⁺ or Na⁺ concentrations may stabilize jarosite and alter the conditions required for conversion (Das & Li, 2023; He et al., 2023; Liakyn et al., 2025a; Niu et al., 2021; Xing et al., 2024a; Xing et al., 2024b; Zeng et al., 2023).

3.3 Nucleation, crystal growth, aging, and dissolution

The precipitation pathway includes induction, nucleation, crystal growth, aggregation, and aging. High supersaturation favors a large number of nuclei and fine particles; lower, controlled supersaturation favors growth on existing surfaces. Seeding can shorten induction time, reduce uncontrolled nucleation, and shift product size upward, but only if seed surfaces remain active and are not coated by competing phases. Temperature and residence time influence both chemical conversion and crystal ordering, while agitation simultaneously controls mass transfer and aggregate breakage (Asimi et al., 2020; Buriti et al., 2025b; Hernández-Lazcano et al., 2021; Oladipo & Ojumu, 2023; Peng et al., 2024; Wu et al., 2025). Seeded studies at approximately 98 °C showed that the initial precipitation rate increased nearly linearly with seed loading and that different jarosite species could serve as effective seed surfaces (Dutrizac, 1996, 1999). Continuous work measured residence-time distribution, steady-state conversion, crystal growth, nucleation, solids density, and zinc incorporation, providing a rare direct bridge between fundamental crystallization and reactor design (Elgersma et al., 1993). More recent industrial-scale work found improved iron removal near 90 °C with

controlled pH and agitation around 500 rpm, although the numerical optimum remains plant- and slurry-specific (Asimi et al., 2020).

Dissolution behavior is equally important because washing, reprocessing, disposal, and accidental exposure may occur under acidic, reducing, or complexing conditions. Kinetic studies show that temperature, proton activity, structural substitutions, reductants, and complexing ligands can change dissolution rates and release pathways. Thiourea–oxalate systems, inorganic sulfur compounds, and Fe(II)-induced transformation illustrate that a residue stable in its production liquor may behave differently during treatment or environmental aging (Buriti et al., 2025a; Calla-Choque & Lapidus, 2020; Calla-Choque & Lapidus, 2021; Chen et al., 2022; Nolasco et al., 2022; Trueman et al., 2020; Wu et al., 2021).

Figure 2 shows the coupled mechanisms of formation and impurity capture.

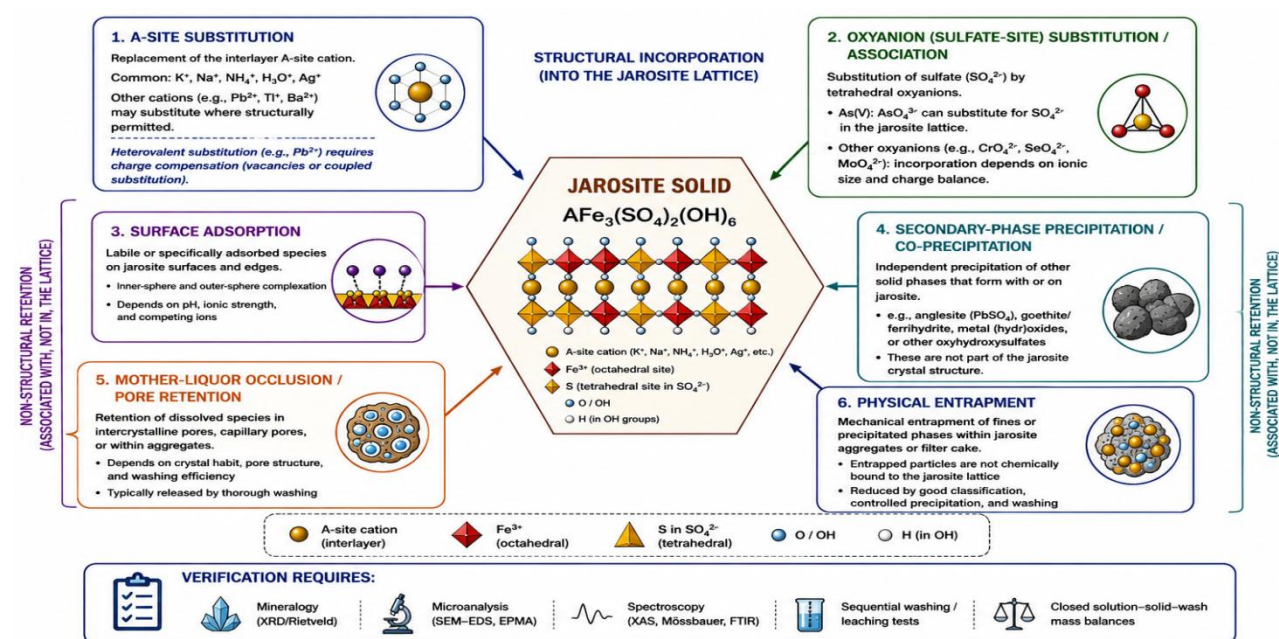


Figure 2. Jarosite structure and mechanisms of element incorporation during precipitation.

Note. Adapted from multiple sources (Cogram et al., 2023; Cruells & Roca, 2022; Hernández-Lazcano et al., 2021; Nolasco et al., 2022; Peng et al., 2023b; Ryu & Kim, 2022; Shi et al., 2022).

Figure 2 shows why bulk solid assays cannot distinguish lattice incorporation, removable surface species, secondary phases, and entrained liquor; mineralogy, microanalysis, washing tests, and closed mass balances are therefore required.

Further work addresses biofilm-supported jarosite formation, experimental precipitation kinetics, and crystal ordering; these studies should be distinguished from long-duration demonstrations of industrial filterability and recycle stability (Buriti et al., 2024; Buriti et al., 2025a; Buriti et al., 2025b; Cheremisina et al., 2025; Elgersma et al., 1993).

Further work addresses biofilm-supported jarosite formation, experimental precipitation kinetics, and crystal ordering; these studies should be distinguished from long-duration demonstrations of industrial filterability and recycle stability (Kamberović et al., 2023; Neisiani et al., 2023; Olcay et al., 2025; Wu et al., 2021; Yu et al., 2026).

Further work addresses biofilm-supported jarosite formation, experimental precipitation kinetics, and crystal ordering; these studies should be distinguished from long-duration demonstrations of industrial filterability and recycle stability (Zhai et al., 2023).



4. CONTROLLED JAROSITE PRECIPITATION FOR SELECTIVE IRON AND SULFATE MANAGEMENT

4.1 Defining selectivity at circuit level

Selective iron removal should be defined against the requirements of the next operation rather than against maximum Fe extraction. No single ratio adequately represents a multimetal precipitation system. The primary reported responses should therefore be: Fe removal fraction (E_{Fe}), residual Fe concentration ($C_{Fe,res}$), and retention of each valuable metal in solution ($RM = 1 - EM$), where EM is the fraction of metal M transferred from the feed liquor to the separated solid and associated wash streams. All fractions are dimensionless and must be accompanied by analytical uncertainty and the mass-balance basis.

$$Q_{Fe/M} = E_{Fe} \times (1 - EM) = E_{Fe} \times RM \quad (1)$$

The bounded screening score $Q_{Fe/M}$ ranges from 0 to 1 and is used only to compare tests conducted on the same feed and analytical basis. For example, $E_{Fe} = 0.95$ and $EM = 0.02$ give $Q_{Fe/M} = 0.931$. If the standard uncertainties are $u(E_{Fe}) = 0.01$ and $u(EM) = 0.005$, first-order propagation gives $u(Q) \approx [(RM \cdot u(E_{Fe}))^2 + (E_{Fe} \cdot u(EM))^2]^{1/2} = 0.011$. The score does not replace $C_{Fe,res}$, economic weighting, or a multimetal recovery vector, and it should not be compared across studies with different washing or sampling protocols.

Industrial and laboratory studies show that pH, temperature, residence time, seed loading, A-site reagent, initial Fe concentration, and neutralization profile jointly affect iron removal and contaminant levels. Low-contaminant operation is achievable, but it requires suppression of local supersaturation, adequate aging, and management of solution entrainment. In an electric-arc-furnace-dust leachate, As-bearing jarosite purification reduced arsenic to below 0.1 mg/L and iron to below 50 mg/L before zinc electrowinning, illustrating a direct solution-specification endpoint rather than a percentage-only metric (Hazaveh et al., 2020). In zinc and secondary-resource liquors, reagent choice must also account for the accumulation of sodium, potassium, or ammonium (Asimi et al., 2020; Javed & Asselin, 2020; Leiva et al., 2022; Neisiani et al., 2023; Peng et al., 2024; X. Zhou et al., 2024).

Table 2 condenses the process variables that should be reported and controlled when jarosite is used deliberately rather than allowed to form as an uncontrolled by-product.

Table 2. *Influence of operating variables on iron removal, selectivity, and solid quality.*

Variable	Primary chemical effect	Expected operational response	Control criterion
Temperature	Changes hydrolysis, nucleation, growth, and phase stability	Higher rate and crystallinity, but possible impurity redistribution	Use heat integration and verify phase purity
pH/acidity	Controls ferric hydrolysis and supersaturation	Low pH slows formation; local high pH creates fines/competing phases	Measure continuously and avoid pointwise over-neutralization
Sulfate concentration	Controls complexation and provides structural sulfate	Affects driving force, ionic strength, and sulfate removal	Use activity-aware interpretation in concentrated liquors
A-site cation and dosage	Determines jarosite type and reagent contamination	Changes kinetics, cost, recycle accumulation, and residue behavior	Select on whole-circuit basis, not precipitation yield alone
Seed loading and quality	Provides heterogeneous nucleation surface	Shorter induction, larger particles, reduced spontaneous nucleation	Control mineralogy, surface activity, and recycle age



Neutralization rate/location	Sets the supersaturation trajectory	Controls ultrafines, scale, and impurity coprecipitation	Use distributed or staged addition with rapid micromixing
Residence time/aging	Permits conversion, growth, and reorganization	Improves crystallinity and separation up to a productivity penalty	Balance reactor volume against filtration benefit
Agitation and solids content	Controls transfer, suspension, aggregation, and breakage	Poor mixing creates gradients; excessive shear breaks aggregates	Scale using power and mixing-time criteria

Note. Effects are directionally dependent on solution composition and cannot be reduced to a single universal optimum. Adapted from multiple sources (Asimi et al., 2020; Buriti et al., 2025b; Cruells & Roca, 2022; Hernández-Lazcano et al., 2021; Leiva et al., 2022; Neisiani et al., 2023; Oladipo & Ojumu, 2023; Peng et al., 2024; Pereira, 2026b).

Table 2 shows that chemistry and particle engineering are inseparable: maximum instantaneous Fe conversion may create a difficult solid. Optimization therefore requires residual Fe, valuable-metal recovery, size distribution, settling flux, cake resistance and moisture, and washing efficiency.

4.2 Sulfate incorporation and acidity generation

Jarosite transfers sulfate to the solid, which can assist circuits limited by sulfate accumulation or salt crystallization. The benefit is partial rather than universal because sulfate removal is coupled stoichiometrically to Fe precipitation and A-site cation consumption. In some biodesulfurization and lithium-bearing systems, jarosite precipitation has been exploited to remove sulfate or to separate potassium, illustrating that the phase can serve a targeted salt-management function beyond conventional zinc processing (Rabbani & Ahmadi, 2020; Xue et al., 2021; Zhai et al., 2023).

Acidity generation is the corresponding penalty and potential integration opportunity. Neutralizing agents may include hydroxides, carbonates, limestone, lime, magnesia, or alkaline industrial by-products. Low-cost slag and kiln dust have been investigated as iron-precipitation reagents in lateritic nickel processing, while hydrothermal or catalytic routes attempt to reduce waste generation or produce denser solids (Caetano et al., 2025; Liakyn et al., 2025a; Niu et al., 2021). A rigorous balance must quantify the acid generated in precipitation, the alkalinity consumed, the gypsum or other secondary solids formed, the cations introduced, the wash-water demand, and the amount of acidic liquor that can be returned to leaching.

4.3 Residual-iron specification and operating window

The appropriate operating endpoint depends on the downstream process. Solvent extraction may tolerate a different ferric concentration than ion exchange or sulfate crystallization, and electrowinning sensitivity depends on metal system, electrolyte composition, and impurity recirculation. Over-precipitation should be avoided when the marginal decrease in Fe causes disproportionate target-metal loss or creates a poorly filtering final fraction. A staged design can be superior: a first stage removes bulk Fe under conditions favoring productivity, and a polishing stage reaches the specification under lower supersaturation or with a different precipitant.

5. IMPURITY CAPTURE, VALUABLE-METAL LOSSES, AND SOLID STABILITY

5.1 Beneficial removal of hazardous elements

Jarosite can remove arsenic, lead, and other hazardous elements through several mechanisms, including incorporation, adsorption, coprecipitation, and formation of associated phases. This behavior has been used in the purification of zinc-bearing solutions from electric-arc-furnace dust, treatment of acid mine drainage, conversion of contaminated soils, and production of jarosite-derived adsorbents (Cerecedo-Sáenz et al., 2022; Dutrizac & Jambor, 1987; Demir et al., 2021; Hazaveh et al., 2020; Hou et al., 2021; López-Martínez &

Gamero-Melo, 2023; Singh et al., 2024; Song et al., 2025; Sowers et al., 2022; Sowers et al., 2023). The operational benefit is highest when contaminant capture improves liquor quality without creating a residue whose hazard classification or long-term liability exceeds that of the original stream.

Removal efficiency alone is not evidence of immobilization. Mineral transformation, acid dissolution, reducing conditions, or changes in competing ions can alter oxyanion and metal mobility. Studies of arsenic- and lead-bearing jarosites demonstrate the need to examine phase-specific occurrence, leaching toxicity, bioaccessibility, and transformation products rather than relying only on total concentration (Huang et al., 2024; Peng et al., 2023a; Peng et al., 2023b; Picazo-Rodríguez et al., 2023; Ryu & Kim, 2022; Shi et al., 2022; Sowers et al., 2022; Sowers et al., 2023).

5.2 Valuable-metal deportment

The same capture mechanisms that remove hazardous elements can cause losses of silver, indium, gallium, germanium, zinc, copper, nickel, and cobalt. Silver may enter jarosite-family phases or occur in associated compounds; gallium and indium can change occurrence state during jarosite precipitation; and Pb(II) can be incorporated or coprecipitated with natrojarosite. These effects can be detrimental in a primary recovery circuit but beneficial when jarosite is used deliberately as a preconcentration intermediate followed by selective residue treatment (Cheremisina et al., 2025; Cogram et al., 2023; Dong et al., 2024; Dong et al., 2025; Javed & Asselin, 2020; Peng et al., 2023b; Shi et al., 2022).

A complete deportment assessment should separate six contributions: structural substitution, surface adsorption, coprecipitated secondary minerals, intergrowth, occluded mother liquor, and residual wash liquor. Microanalysis and mineralogical mapping are particularly important for detecting low-concentration scattering metals, while wash tests reveal the fraction attributable to entrainment. Without these distinctions, apparent selectivity may reflect incomplete washing rather than intrinsic precipitation chemistry (Dong et al., 2024; Dong et al., 2025; Pereira, 2026a).

Table 3 presents a mechanism-based interpretation of impurity capture and the corresponding evidence needed to claim either beneficial scavenging or controlled metal loss.

Table 3. *Mechanisms of impurity association with jarosite and their process significance.*

Mechanism	Diagnostic evidence	Potential benefit	Principal risk
A-site or lattice substitution	XRD refinement, spectroscopy, microanalysis, selective dissolution	Strong capture and possible preconcentration	Difficult release and altered phase stability
Oxyanion substitution/association	Spectroscopy, speciation, transformation testing	Arsenic or antimony removal	Remobilization during phase conversion
Surface adsorption	Surface spectroscopy, pH-edge tests, desorption	Rapid polishing at low impurity concentration	Reversible release during washing or storage
Secondary-phase coprecipitation	Mineralogical identification and saturation modeling	Selective formation of recoverable impurity phase	Misattribution to jarosite and variable product quality
Occluded or entrained liquor	Wash curves, pore-volume estimate, soluble-salt analysis	None unless liquid recycle is intended	Apparent metal loss and high soluble contamination
Interparticle entrapment/intergrowth	Microscopy and liberation analysis	Possible preconcentration	Poor washing and difficult downstream liberation

Note. A defensible mechanism normally requires more than bulk solid composition. Adapted from multiple sources (Cogram et al., 2023; Dong et al., 2024; Dong et al., 2025; Peng et al., 2023b; Picazo-Rodríguez et al., 2023; Ryu & Kim, 2022; Shi et al., 2022; Song et al., 2025).



The table indicates why selective impurity scavenging should be designed with a destination in mind. Lattice-bound lead may be desirable for environmental stabilization but undesirable when lead recovery is planned by mild washing. Conversely, a silver-bearing associated phase may represent a valuable concentrate if subsequent chloride, thiourea, cyanide, or thermal treatment is available.

5.3 Stability, washing, and release scenarios

Solid stability must be evaluated over production, washing, transport, storage, reprocessing, and final use. Acidic dissolution studies show that temperature, substitution, and complexants can accelerate release, while Fe(II) and microbial reductants can transform or dissolve jarosite. Thermal treatment may volatilize or redistribute toxic elements if gas cleaning and product partitioning are not considered (Buriti et al., 2025a; Calla-Choque & Lapidus, 2021; Chen et al., 2022; Nolasco et al., 2022; Olcay et al., 2025; Trueman et al., 2020; Wu et al., 2021). Consequently, a jarosite route that appears selective in the reactor can transfer risk to a later unit operation unless the full transformation pathway is characterized.

Environmental and phase-transfer studies address arsenic uptake, iron–arsenic coprecipitation, acid mine drainage, and the chemical stability of iron-bearing residues. Their transferability depends on solution chemistry, weathering, and release tests rather than nominal bulk composition alone (Ahoranta et al., 2020; Cerecedo-Sáenz et al., 2022; Chen et al., 2025; Demir et al., 2021; Eftekhari et al., 2020b).

Environmental and phase-transfer studies address arsenic uptake, iron–arsenic coprecipitation, acid mine drainage, and the chemical stability of iron-bearing residues. Their transferability depends on solution chemistry, weathering, and release tests rather than nominal bulk composition alone (Hazaveh et al., 2020; Hou et al., 2021; Huang et al., 2024; Shi et al., 2022; Singh et al., 2024).

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6. PARTICLE ENGINEERING AND SOLID–LIQUID SEPARATION

6.1 Product quality as a design response

Jarosite precipitation should be specified by both chemical and physical responses. Relevant physical attributes include particle-size distribution, crystallinity, morphology, aggregate strength, density, surface area, settling rate, thickener flux, specific cake resistance, permeability, compressibility, cake moisture, and wash displacement efficiency. These properties control reactor inventory, thickener area, filter size, wash-water consumption, soluble metal loss, and the feasibility of seed recycle. A chemically satisfactory but poorly filtering precipitate can dominate capital and operating cost (Asimi et al., 2020; Buriti et al., 2025b; Pereira, 2026b).

6.2 Supersaturation trajectory, seeding, and mixing

High local supersaturation generates many small nuclei and increases the probability of amorphous or poorly ordered precursors. Controlled base addition, rapid micromixing, distributed neutralization, and adequate seed surface can redirect precipitation toward crystal growth. Seeding is not inherently beneficial: old or contaminated seed may exhibit low activity, and scale-forming substrates can promote heterogeneous crystallization at undesirable locations. Recent work on inhibiting jarosite growth on anglesite demonstrates that surface competition can be deliberately manipulated, suggesting a broader opportunity to engineer where nucleation occurs (Buriti et al., 2025b; Hernández-Lazcano et al., 2021; Peng et al., 2024; Wu et al., 2025).

Agitation has a dual role. It must eliminate concentration and temperature gradients and maintain solids suspension, but excessive shear can break aggregates and increase the fine fraction. Scale-up should therefore preserve mixing time, power dissipation, feed-point intensity, and solids suspension rather than merely duplicating laboratory impeller speed. Continuous operation also requires control of residence-time distribution because short-circuiting produces incompletely aged particles while over-aged solids may become heavily coated or difficult to resuspend.

The relationships among chemistry, nucleation, aggregation, and separation are summarized in Figure 3.

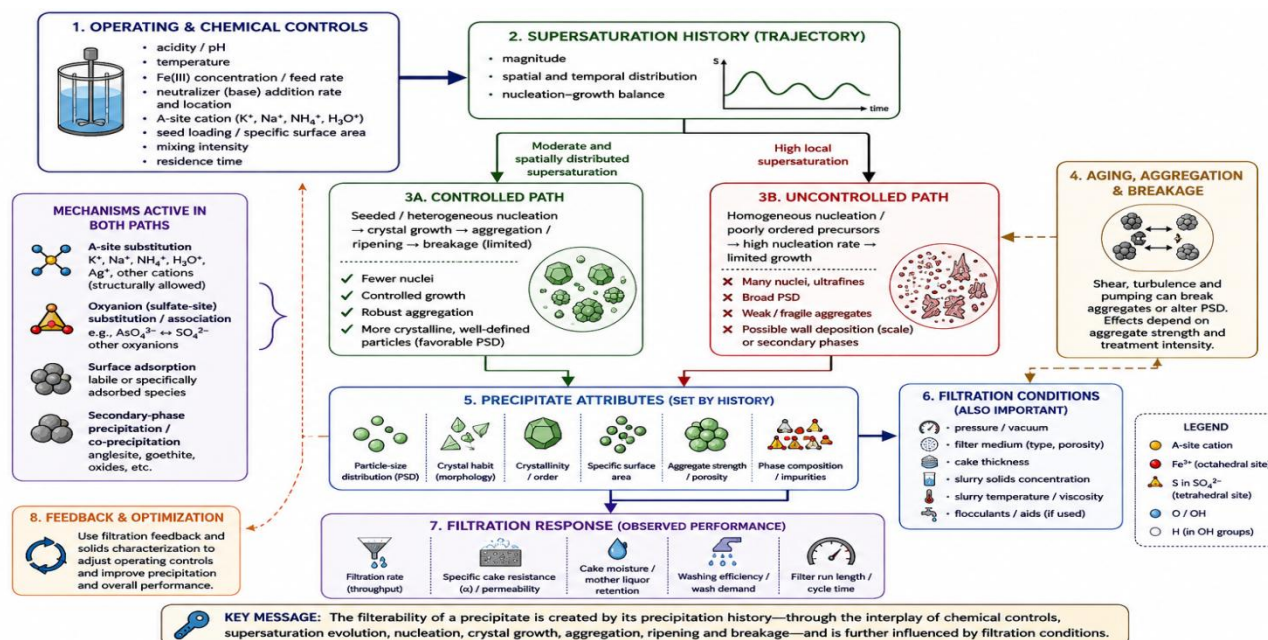


Figure 3. Link between supersaturation control, particle formation, and solid-liquid separation.

Note. Adapted from multiple sources (Asimi et al., 2020; Buriti et al., 2025b; Hernández-Lazcano et al., 2021; Oladipo & Ojumu, 2023; Peng et al., 2024; Pereira, 2026b; Wu et al., 2025).

Figure 3 presents filtration as an integrated consequence of chemistry, hydrodynamics, nucleation, growth, aggregation, breakage, and aging rather than as an independent post-treatment property.

Table 4 provides a minimum characterization set for studies intended to support industrial design.

Table 4. Minimum characterization for linking jarosite precipitation to solid-liquid separation.

Response	Recommended measurement	Why it matters	Common reporting weakness
Phase composition	XRD with quantified or semi-quantified phases	Confirms jarosite and competing phases	Reporting only peak identification
Particle-size distribution	Laser diffraction plus microscopy	Supports settling and filtration interpretation	No dispersion protocol or aggregate distinction
Morphology/crystallinity	SEM and crystallographic indicators	Reveals growth, aggregation, and aging	Images without representative statistics
Settling behavior	Initial rate, interface curve, solids flux	Supports thickener sizing	Single settling time without concentration basis



Filtration	Flux or specific cake resistance versus pressure	Supports filter sizing and cake diagnosis	Reporting only qualitative “good filtration”
Cake and washing	Moisture, permeability, soluble-metal wash curve	Quantifies water demand and entrained losses	No mass balance around washing
Scale tendency	Deposit location, rate, mineralogy, adhesion	Supports operability and cleaning strategy	Scale inferred but not sampled

Note. The measurement set is intended for comparative process development. Adapted from multiple sources (Asimi et al., 2020; Buriti et al., 2025b; Peng et al., 2024; Pereira, 2026b; Wu et al., 2025).

For critical review purposes, claims of improved filterability were considered stronger when accompanied by pressure, cake thickness, solids concentration, filtrate viscosity, and wash conditions. Settling rate alone cannot predict filtration because compressibility and pore structure may change independently.

7. INTEGRATION WITH DOWNSTREAM HYDROMETALLURGICAL OPERATIONS

7.1 Solvent extraction and ion exchange

Direct evidence is strongest where jarosite precipitation is used to condition zinc- or copper-bearing sulfate liquors before established purification and extraction steps. Lower dissolved Fe and suspended solids can potentially reduce ferric transfer, reagent consumption, crud formation, and contamination of strip liquor or electrolyte, but the magnitude depends on extractant chemistry, Fe oxidation state, residual acidity, and the solids-removal train. The benefit must be measured against pH adjustment and target-metal losses during precipitation (Eftekhari et al., 2020b; Hazaveh et al., 2020; Javed & Asselin, 2020; X. Zhou et al., 2024).

For ion exchange, the expected advantages—lower Fe competition and less precipitate fouling—are mainly engineering inferences from general resin behavior rather than direct jarosite-stage demonstrations in the reviewed corpus. Residual colloids and ultrafine jarosite could still foul beds even when dissolved Fe is low. Consequently, resin capacity, breakthrough, pressure drop, backwash behavior, and regeneration chemistry should be tested with the actual clarified and recycled liquor before a downstream benefit is claimed.

7.2 Electrowinning, precipitation, crystallization, and membrane polishing

Electrowinning circuits require impurity control because ferric species can participate in parasitic redox cycles, lower current efficiency, affect cathode morphology, and contribute to sludge. Jarosite precipitation can potentially reduce this burden, and direct solution-specification evidence exists for selected zinc systems; however, jarosite-specific plant data linking the precipitation stage to current efficiency or cathode quality remain limited. The introduction of Na⁺, K⁺, NH₄⁺, or soluble species from alternative neutralizing agents may also create new recycling constraints. Lower Fe can similarly favor the production of high-purity hydroxide, carbonate, or sulfate, but direct evidence is process-specific and should not be generalized across all battery-material circuits.

Membrane and polishing benefits are the least directly demonstrated. These operations are sensitive to dissolved Fe, saturation indices, colloids, and suspended fines, but no direct jarosite–membrane performance dataset was identified in the coded corpus. Claims should therefore be framed as testable hypotheses and quantified through membrane flux, rejection, cleaning interval, turbidity, particle breakthrough, and secondary precipitation under actual recycle conditions.

Table 5 relates jarosite-stage outputs to downstream responses and explicitly distinguishes direct evidence from engineering inference. This distinction prevents equivalent wording from being applied to operations supported by very different evidence bases.



Table 5. *Expected effects of controlled jarosite precipitation on downstream operations.*

Downstream operation	Beneficial jarosite-stage output	Performance indicator	Integration risk	Evidence status
Solvent extraction	Low dissolved Fe and low suspended fines	Fe transfer, phase disengagement, crud rate, organic loss	Over-neutralization and target-metal coprecipitation	I/III: direct
Ion exchange	Low Fe competition and colloid load	Capacity, breakthrough, pressure drop, regeneration demand	Bed fouling by ultrafines	IV: inference
Electrowinning	Electrolyte-compatible Fe level	Current efficiency, cathode purity, sludge formation	Accumulation of introduced A-site ions	I/III: direct; attribution limited
Selective precipitation	Reduced Fe contamination	Product grade, reagent demand, recovery	Changed pH buffering and sulfate activity	III: laboratory
Sulfate crystallization	Controlled impurity and sulfate inventory	Crystal purity, yield, mother-liquor recycle	Excess sulfate removal or salt introduction	III/IV: lab + inference
Membrane polishing	Low turbidity and reduced scaling precursors	Flux, rejection, cleaning interval	Fine-particle passage and secondary precipitation	IV: inference only

Note. Evidence classes indicate transferability: I = direct industrial/field; III = laboratory with real material or liquor; IV = synthetic/model evidence or engineering inference. Status refers to jarosite-specific support in the reviewed corpus, not to the general sensitivity of each downstream operation. Adapted from multiple sources (Eftekhari et al. (2020b), Faris et al. (2021), Hazaveh et al. (2020), Hosseini Nasab et al. (2022), Javed and Asselin (2020), Leiva et al. (2022), Rabbani and Ahmadi (2020), and X. Zhou et al. (2024)).

Integrated piloting should retain the actual recycle streams. Testing precipitation on fresh synthetic liquor and downstream separation on independently prepared solution can miss the accumulation of sodium, potassium, ammonium, sulfate, soluble metals, and colloids that determines long-term operability.

8. APPLICATIONS IN PRIMARY METALS, SECONDARY RESOURCES, AND ENVIRONMENTAL TREATMENT

8.1 Zinc hydrometallurgy

Zinc hydrometallurgy remains the reference application because jarosite precipitation is compatible with acidic sulfate liquors and atmospheric operation. The principal objectives are the removal of ferric iron after calcine leaching, the protection of purification and electrolysis, and the management of sulfate and neutralization. Recent work extends the conventional process through low-contaminant industrial operation, alternative precipitants, hydrothermal crystallization, catalytic hematite conversion, and integrated residue recycling (Asimi et al., 2020; Leiva et al., 2022; Liakyn et al., 2025a; Peng et al., 2024; Y. Wang et al., 2020).

The principal weakness is residue generation and the association of Zn, Pb, Ag, In, Ga, Ge, Cu, and other metals with the solid. Microanalytical studies show that gallium occurrence and Ga/In evolution can be closely linked to jarosite precipitation, supporting both the need to minimize unintended loss and the possibility of using precipitation as a deliberate enrichment step (De-la-Cruz-Moreno et al., 2021; Dong et al., 2024; Dong et al., 2025; Janošević et al., 2023; Zhu et al., 2025).



8.2 Copper hydrometallurgy

In copper circuits, jarosite has two contrasting roles. Deliberate precipitation can purify Cu–Fe liquors or raffinate, including biologically seeded iron removal. Uncontrolled jarosite formation during chalcopyrite leaching can increase surface coverage, alter the iron balance, consume sulfate, and interact with elemental sulfur or other passivating layers. The net effect depends on leach chemistry, chloride, microbial contact, light, solids abrasion, and the location of precipitation (Dakkoune et al., 2023; Eftekhari et al., 2020b; Javed & Asselin, 2020; Kartal et al., 2020; Ma et al., 2021; Quezada et al., 2021; Soe et al., 2021; Vakylabad et al., 2022; Winarko et al., 2024; Yang et al., 2020).

The distinction between beneficial bulk-solution precipitation and harmful surface precipitation is crucial. A circuit may intentionally oxidize Fe(II) and precipitate Fe(III) in a separate reactor, while suppressing heterogeneous jarosite growth on chalcopyrite or anglesite in the leach. Attrition, chloride control, alternative oxidants, and competitive substrates illustrate strategies for decoupling these functions (Dakkoune et al., 2023; Kartal et al., 2020; Quezada et al., 2021; Vakylabad et al., 2022; Winarko et al., 2024; Wu et al., 2025).

8.3 Nickel–cobalt systems

Laterite and nickel production liquors contain Fe along with Ni, Co, Mn, Al, Mg, and other impurities. Partial neutralization studies show that valuable-metal behavior can change with pH and pulp composition, while selective iron precipitation and alternative alkaline residues offer routes to lower-cost purification. Jarosite must be compared with goethite and other iron phases in terms of Ni/Co loss, product requirements, neutralization demand, and solids handling (Caetano et al., 2025; Das & Li, 2023; Faris et al., 2021; Hosseini Nasab et al., 2022; Thibault et al., 2020; L. Wang et al., 2020).

For battery-material applications, the residual impurity specification is stringent and cumulative recycle effects are important. A jarosite route may be attractive when it removes Fe and sulfate simultaneously, but only if ammonium, sodium, potassium, or trace-element contamination does not impair subsequent crystallization or cathode-material synthesis.

8.4 Secondary resources and environmental systems

Secondary-resource applications include electric-arc-furnace dust, spent lithium-ion batteries, aerospace magnetic-material scrap, zinc oxide dust, vanadium-bearing black shale, spent catalysts, and mixed metallurgical residues. In these systems, jarosite may be precipitated to purify a leachate, recover potassium, concentrate critical metals, or create an intermediate for thermal or hydrometallurgical conversion (Hazaveh et al., 2020; Liu et al., 2024; Peng et al., 2024; Xue et al., 2021; Zhai et al., 2023; X. Zhou et al., 2024).

Environmental applications include acid mine drainage treatment, biogenic iron oxidation, arsenic co-precipitation, and contaminated soil remediation. Biogenic jarosite can serve as a carrier for iron-oxidizing biofilms, while pH and aeration govern the solid's properties and formation. These applications demonstrate functional versatility but also require verification of oxyanion mobility and long-term stability (Ahoranta et al., 2020; Demir et al., 2021; Hou et al., 2021; Nordstrom, 2020; Oladipo & Ojumu, 2023; Ryu & Kim, 2022; Song et al., 2025; Sowers et al., 2022; Sowers et al., 2023).

Table 6 compares the dominant objectives and constraints across sectors.

Industrial transferability was assessed on a five-level ladder: synthetic dilute solution; synthetic concentrated solution; filtered industrial liquor or real residue; industrial pulp or pilot/continuous operation; and sustained plant or field operation with actual recycles. Evidence from a lower level was not treated as proof of a higher level. Plant readiness additionally requires residence-time distribution, seed age and recycle, distributed neutralizer addition, scale growth, Na⁺/K⁺/NH₄⁺ accumulation, wash-water and filtrate recycle, feed variability, and campaign duration.



Table 6

Sector-specific objectives and constraints for controlled jarosite formation.

Application	Primary objective	Valuable species at risk	Critical operating constraint
Zinc hydrometallurgy	Bulk Fe removal and electrolyte protection	Zn, Pb, Ag, In, Ga, Ge	Residue mass, washing, and recycle-cation accumulation
Copper leach/SX circuits	PLS conditioning or Fe balance control	Cu and acid value	Prevent surface passivation and suspended fines
Nickel–cobalt processing	Selective Fe removal before purification	Ni, Co, Mn	Tight product specifications and neutralization cost
Battery and secondary resources	Purify complex leachates or concentrate elements	Li, Ni, Co, Mn, Ga, In, Zn	Highly variable feed and multiple impurity phases
Acid mine drainage/effluents	Remove Fe, sulfate, and hazardous elements	Potentially recoverable metals	Long-term stability and sludge management
Contaminated soils/materials	Reduce Pb/As bioaccessibility	Not normally a primary recovery target	Durability under changing environmental conditions

Note. Sector selection must be linked to the downstream specification and residue route. Adapted from multiple sources (Ahoranta et al., 2020; Asimi et al., 2020; Caetano et al., 2025; Demir et al., 2021; Dong et al., 2025; Eftekhari et al., 2020b; Hazaveh et al., 2020; Hosseini Nasab et al., 2022; Liu et al., 2024; Oladipo & Ojumu, 2023; Peng et al., 2024; Soe et al., 2021; Sowers et al., 2023; Xue et al., 2021; X. Zhou et al., 2024).

The cross-sector evidence supports a general rule: jarosite is most useful when the A-site reagent is compatible with the circuit, the impurity inventory is known, and the precipitate has a defined separation and end-of-life route. Transferring an operating window from zinc hydrometallurgy to a battery leachate or mine-water system without re-evaluating speciation and impurity behavior is not justified.

9. UNDESIRABLE JAROSITE FORMATION AND COMPARISON WITH GOETHITE AND HEMATITE

9.1 Passivation, scaling, and unplanned precipitation

Jarosite formation is detrimental when it occurs on reactive mineral surfaces, heat-transfer surfaces, pipelines, filters, or other locations where it restricts transport or reduces equipment volume. During chalcopyrite leaching, jarosite may coexist with sulfur-rich layers and other products, and its contribution to passivation varies with chloride, microbial regime, abrasion, light, and ferric chemistry. The operational response should therefore be based on direct surface and residue characterization rather than assuming that every ferric precipitate is the dominant barrier (Dakkoune et al., 2023; Kartal et al., 2020; Ma et al., 2021; Quezada et al., 2021; Soe et al., 2021; Vakylabad et al., 2022; Winarko et al., 2024; Yang et al., 2020).

Scaling arises when nucleation is favored on equipment or pre-existing solids rather than in the controlled precipitation volume. Local heating, pH gradients, stagnant zones, and rough surfaces can create persistent deposits. The same heterogeneous nucleation principles used to improve seeded precipitation can be redirected to suppress deposition on anglesite or equipment surfaces by controlling substrate competition and supersaturation (Wu et al., 2025).

9.2 Jarosite versus goethite and hematite

Jarosite, goethite, and hematite occupy different regions of temperature, acidity, redox, and pressure. Jarosite operates effectively in acidic sulfate media and incorporates sulfate, but produces a lower-iron solid and often

more residue. Goethite can operate under moderately acidic conditions but requires careful control of Fe(II)/Fe(III), hydrolysis, and phase quality. Hematite offers a high-iron, potentially lower-volume product, but usually requires more severe hydrothermal conditions or a conversion step. Hybrid routes may use jarosite for selective impurity capture or sulfate management followed by conversion to hematite (Das & Li, 2023; Höber & Steinlechner, 2021; Liakyn et al., 2025a; Niu et al., 2021; Pereira, 2025; Pereira, 2026c; Thibault et al., 2020; Xing et al., 2024a; Xing et al., 2024b).

Table 7 provides a multicriteria comparison and adds ideal-phase stoichiometric benchmarks. These values do not predict the composition of industrial residues, but they quantify the intrinsic mass and acid effects of the selected iron phase.

Table 7. *Multicriteria comparison of jarosite, goethite, and hematite iron-removal routes.*

Criterion	Jarosite	Goethite	Hematite
Typical medium	Acidic sulfate; generally atmospheric	Moderately acidic; atmospheric with redox control	Hydrothermal; often elevated temperature/pressure
Sulfate incorporation	Substantial structural incorporation	Limited	Limited
Iron grade of solid	Lower	Intermediate	Higher
Residue mass per Fe removed	Generally higher	Intermediate	Generally lower
Impurity capture	Can be high and structurally diverse	Can be high; pH/redox dependent	Often lower but process dependent
Particle quality	Good when seeded and aged; fines possible	Variable; gelatinous precursors possible	Often dense and filterable when well crystallized
Key penalty	Acid generation, A-site reagent, residue volume	Redox and pH control	Energy, pressure, and equipment severity
Best-fit role	Acidic purification plus sulfate/impurity control	Atmospheric Fe removal with moderate acidity	Low-volume iron product or conversion endpoint
Theoretical solid mass per kg Fe	2.86–2.99 kg/kg Fe, depending on NH ₄ ⁺ , Na ⁺ , or K ⁺	1.59 kg/kg Fe	1.43 kg/kg Fe
Theoretical sulfate fixed	1.15 kg SO ₄ ²⁻ /kg Fe	None in ideal phase	None in ideal phase
Theoretical acidity generated	1.76 kg H ₂ SO ₄ equivalent/kg Fe	Hydrolysis-dependent; not structurally fixed	Hydrothermal hydrolysis-dependent

Note. General tendencies; actual performance is solution- and flowsheet-specific. Stoichiometric values were calculated from ideal formulas K/Na/NH₄Fe₃(SO₄)₂(OH)₆, FeOOH, and Fe₂O₃ and exclude vacancies, impurity substitution, entrained liquor, and secondary phases. Adapted from multiple sources (Brown (1971), Das and Li (2023), Dutrizac (1980), Höber and Steinlechner (2021), Kershaw and Pickering (1980), Liakyn et al. (2025a), Niu et al. (2021), Pereira (2025), Thibault et al. (2020), and Xing et al. (2024a, 2024b)).

Route comparison should include the cost of the entire solid–liquid separation train and the value or liability of the product. A dense hematite product may justify higher reactor severity, while jarosite may be preferred when sulfate control and hazardous-element capture create additional value. Sequential or hybrid routes can exploit these differences rather than forcing a single phase to satisfy every objective.

The boundary between beneficial and detrimental formation is summarized in Figure 4.

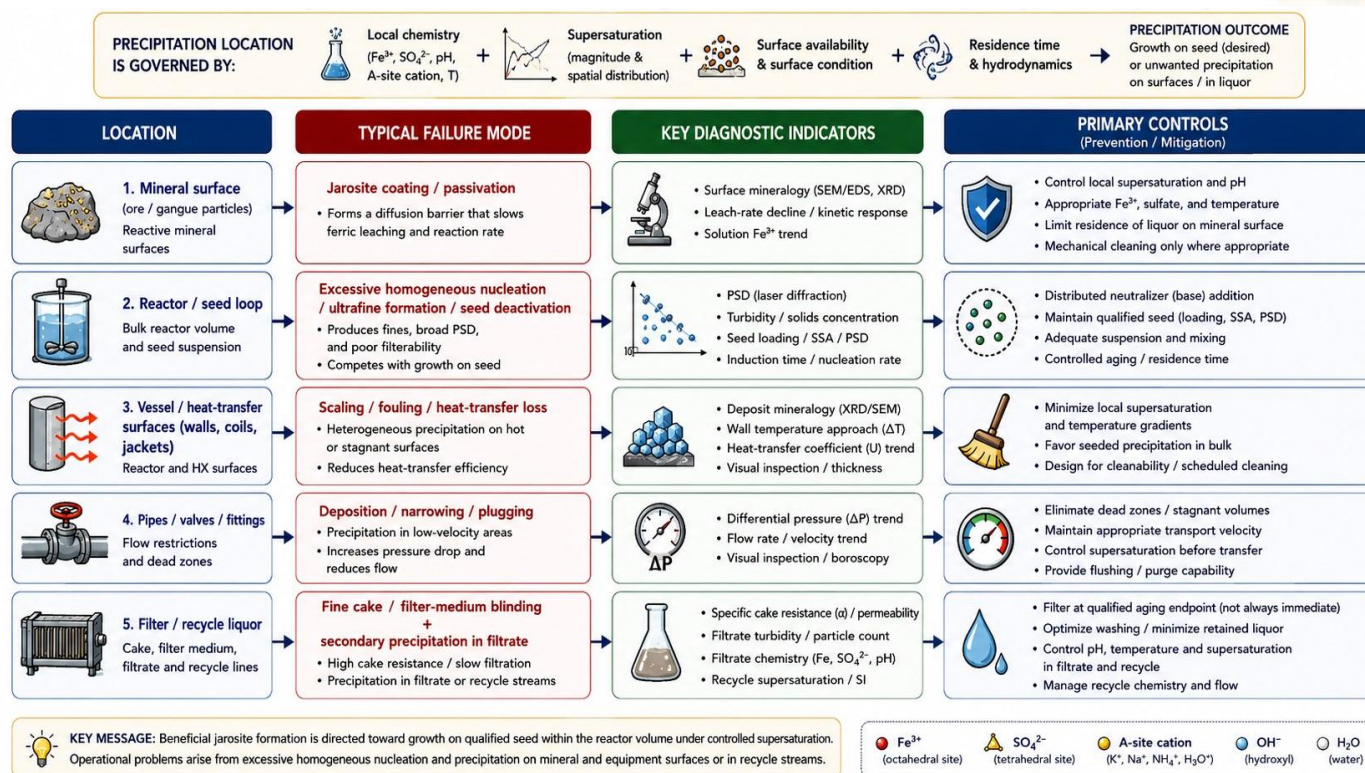


Figure 4. Location-specific failure modes, diagnostics, and controls for undesirable jarosite formation.

Note. Adapted from multiple sources (Asimi et al., 2020; Dakkoune et al., 2023; Höber & Steinlechner, 2021; Kartal et al., 2020; Pereira, 2026a; Pereira, 2026b; Soe et al., 2021; Wu et al., 2025; Yang et al., 2020).

Figure 4 addresses local failure diagnosis and control; the broader route-selection decision remains in Figure 6.

Comparative studies of goethite and other ferric precipitates are useful baselines for assessing acidity, separation performance, and metal entrainment; direct head-to-head tests under matched feeds remain necessary (Caetano et al., 2025; Faris et al., 2021; Hosseini Nasab et al., 2022; Höber et al., 2022; Liakyn et al., 2025).

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10. TREATMENT AND VALORIZATION OF JAROSITE RESIDUES

10.1 Hydrometallurgical recovery

Hydrometallurgical treatment seeks to dissolve jarosite selectively or transform it into a more leachable phase while recovering associated metals. Acid decomposition with complexants, chloride leaching, cyanide or non-cyanide silver leaching, ionic liquids, bioleaching, and staged washing have been investigated. The preferred route depends on whether the target is Pb, Ag, Zn, In, Ga, Cd, Sr, Cu, or iron and on the occurrence of these elements within the residue (Anđić et al., 2026; Calla-Choque & Lapidus, 2020; Calla-Choque & Lapidus, 2021; Conić et al., 2024; De-la-Cruz-Moreno et al., 2021; Höber et al., 2022; Islas et al., 2021; Janošević et al., 2023; Kushwaha & Agarwal, 2024; Kushwaha & Agarwal, 2025; Liakyn et al., 2025b; Singh et al., 2024; Singh et al., 2025; Yu et al., 2026).

Selective dissolution is challenging because releasing one metal may also mobilize arsenic, lead, sulfate, or iron. Pretreatment can improve liberation or change phase stability, but it adds reagent and residue streams. Mechanistic kinetic studies are valuable because they distinguish surface-reaction control, diffusion through

product layers, and structural relaxation, helping identify whether higher temperature, chloride, complexant concentration, or pretreatment will improve selectivity (Andić et al., 2026; Buriti et al., 2025a; Calla-Choque & Lapidus, 2021; Kamberović et al., 2023; Yu et al., 2026).

10.2 Pyrometallurgical and hydrothermal transformation

Thermal routes include decomposition, reduction, chlorination, oxidizing roasting, smelting, and integration with cement kilns. They can recover Pb–Ag alloys, metallic iron, reduced iron powder, or separate volatile and nonvolatile fractions. Hydrothermal treatment can convert jarosite to hematite, magnetite-related products, Fe_2O_3 and PbCl_2 , or other crystalline phases. These routes reduce residue volume or create marketable products but require careful control of sulfur gases, arsenic and lead partitioning, reductant demand, and energy integration (Ge et al., 2023; Ge et al., 2024; Ge et al., 2025; He et al., 2023; Jiménez-Lugos et al., 2024a; Jiménez-Lugos et al., 2024b; Kamberović et al., 2021; Kamberović et al., 2023; Lu et al., 2023; Olcay et al., 2025; Sanchez Vite et al., 2024; Sanchez Vite et al., 2025; Wang et al., 2025; Xing et al., 2024a; Xing et al., 2024b; Zeng et al., 2023; Zhou et al., 2025; S. Zhou et al., 2024; Zhu et al., 2025).

Biomass-derived reductants, slurry electrolysis, and combined oxidizing roasting–reduction–smelting–electrorefining illustrate the trend toward integrated flowsheets. Their technical promise should be judged by full mass balance, product purity, gas treatment, water use, and recovery of low-concentration critical metals, not only by iron conversion or residue mass reduction (Ge et al., 2024; Ge et al., 2025; Wang et al., 2025; S. Zhou et al., 2024; Zhu et al., 2025).

10.3 Construction and functional materials

Jarosite has been evaluated as a precursor or component in concrete, hybrid composites, adsorbents, ceramics, pigments, and iron-bearing functional materials. These applications can consume larger tonnages than selective metal recovery, but they require stricter qualification than simple strength testing. Sulfate release, expansion, leaching under service conditions, variability, dust, durability, and end-of-life behavior must be addressed. Adsorbent applications also require regeneration or spent-media management (Ahamed et al., 2021; Cerecedo-Sáenz et al., 2022; Kushwaha et al., 2023; López-Martínez & Gamero-Melo, 2023; Pandiyan & Solaiyan, 2024; Pugar et al., 2024).

Table 8 compares the main valorization families and the evidence required before a route can influence primary jarosite-process design.

Table 8. *Treatment and valorization routes for jarosite residues.*

Route family	Potential products	Main advantage	Critical qualification tests
Selective hydrometallurgy	Ag, Pb, Zn, In, Ga, Cu solutions or concentrates	Targets high-value elements under moderate temperature	Selectivity, reagent recycle, impurity release, full water balance
Bioleaching/reductive dissolution	Dissolved metals and transformed Fe phase	Potentially mild conditions and selective microbial chemistry	Rate, pulp tolerance, sulfur balance, effluent treatment
Thermal decomposition/roasting	Oxides, chlorides, calcine, sulfur-bearing gas	Destroys jarosite and improves liberation	Gas cleaning, volatilization, energy, product leachability
Reduction/smelting/electrolysis	Metallic iron, Pb–Ag alloy, separated metal products	High recovery and major residue reduction	Reductant/energy use, slag quality, trace-metal partitioning
Hydrothermal transformation	Hematite/ Fe_2O_3 and recoverable lead products	Dense crystalline products and lower residue volume	Pressure equipment, chloride recycle, phase purity

Construction/composites	Concrete, binder, aggregate, hybrid composite	Potential large-volume consumption	Durability, expansion, sulfate release, leaching, standards
Adsorbents/functional materials	As sorbent, pigments, ferritic or magnetic materials	Uses iron surface chemistry and may create higher-value products	Capacity in real media, regeneration, purity, market size

Note. A route should be considered mature only when the secondary wastes and product specifications are defined. Adapted from multiple sources (Ahamed et al., 2021; Andić et al., 2026; Chen et al., 2025; Conić et al., 2024; De-la-Cruz-Moreno et al., 2021; Ge et al., 2023; Ge et al., 2024; Ge et al., 2025; He et al., 2023; Höber et al., 2022; Janošević et al., 2023; Jiménez-Lugos et al., 2024a; Jiménez-Lugos et al., 2024b; Kamberović et al., 2021; Kushwaha et al., 2023; Kushwaha & Agarwal, 2024; Kushwaha & Agarwal, 2025; Liu et al., 2024; López-Martínez & Gamero-Melo, 2023; Pandiyan & Solaiyan, 2024; Pugar et al., 2024; Singh et al., 2023; Singh et al., 2025; L. Wang et al., 2020; Wang et al., 2025; Y. Wang et al., 2020; Yu et al., 2026; Zeng et al., 2023; Zhou et al., 2025; S. Zhou et al., 2024; Zhu et al., 2025).

The maturity of the routes varies widely. Some studies demonstrate selective recovery or product formation at laboratory scale, whereas fewer establish continuous operation, impurity recycle, gas treatment, product market acceptance, or a favorable cost basis. Valorization should therefore not be used automatically to justify residue generation; it should reduce the total liability relative to disposal and alternative iron-removal routes.

A life-cycle representation of the possible residue pathways should be inserted as Figure 5.

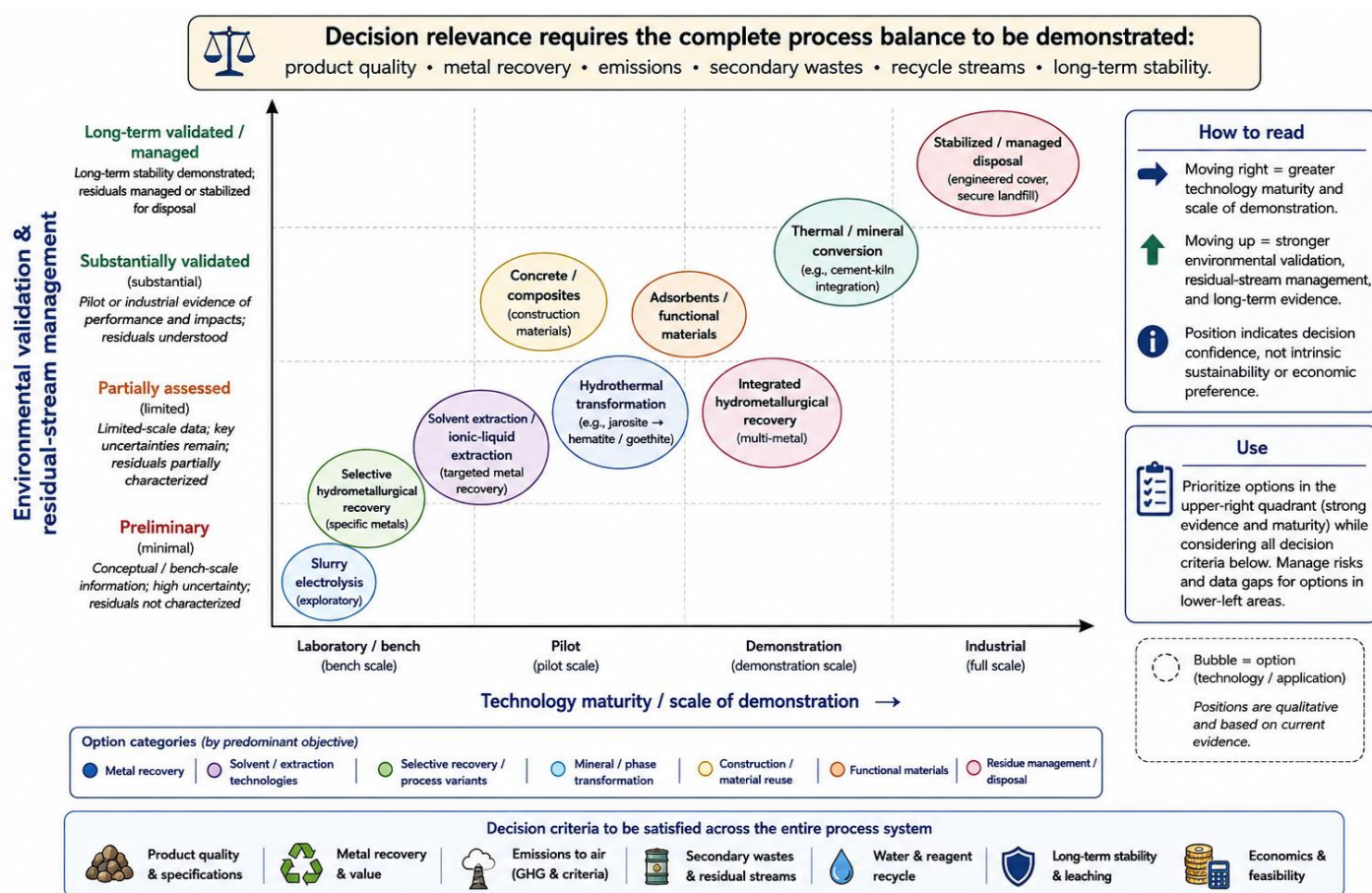


Figure 5. Evidence-maturity map for treatment, utilization, and disposal routes for jarosite residues.

Note. Adapted from multiple sources (Chen et al., 2025; Höber & Steinlechner, 2021; Huang et al., 2024;



Kushwaha et al., 2023; Pandiyan & Solaiyan, 2024; Peng et al., 2023a; Singh et al., 2023; Wang et al., 2025; Y. Wang et al., 2020; Zhou et al., 2025).

Figure 5 complements Table 8 by ranking maturity: high laboratory recovery remains low-transferability evidence without product specifications, secondary-stream closure, long-duration stability, and continuous operation.

Circular-economy studies span reductive roasting, cement or construction applications, and secondary-metal recovery. Material suitability and hazards must be evaluated with product-specific performance and leachability data (Anđić et al., 2026; Asimi et al., 2020; Conić et al., 2024; Dakkoune et al., 2023; De-la-Cruz-Moreno et al., 2021).

Circular-economy studies span reductive roasting, cement or construction applications, and secondary-metal recovery. Material suitability and hazards must be evaluated with product-specific performance and leachability data (Dong et al., 2024; Dong et al., 2025; Ge et al., 2024; Ge et al., 2025; Islas et al., 2021).

Circular-economy studies span reductive roasting, cement or construction applications, and secondary-metal recovery. Material suitability and hazards must be evaluated with product-specific performance and leachability data (Janošević et al., 2023; Jiménez-Lugos et al., 2024; Jiménez-Lugos et al., 2024; Kamberović et al., 2021; Kartal et al., 2020).

Circular-economy studies span reductive roasting, cement or construction applications, and secondary-metal recovery. Material suitability and hazards must be evaluated with product-specific performance and leachability data (Kushwaha et al., 2023; Leiva et al., 2022; Liakyn et al., 2025; Liu et al., 2024; Ma et al., 2021).

Circular-economy studies span reductive roasting, cement or construction applications, and secondary-metal recovery. Material suitability and hazards must be evaluated with product-specific performance and leachability data (Niu et al., 2021; Peng et al., 2023; Peng et al., 2023; Peng et al., 2024; Picazo-Rodríguez et al., 2023).

Circular-economy studies span reductive roasting, cement or construction applications, and secondary-metal recovery. Material suitability and hazards must be evaluated with product-specific performance and leachability data (Quezada et al., 2021; Sanchez Vite et al., 2024; Sanchez Vite et al., 2025; Singh et al., 2025; Soe et al., 2021).

Circular-economy studies span reductive roasting, cement or construction applications, and secondary-metal recovery. Material suitability and hazards must be evaluated with product-specific performance and leachability data (Trueman et al., 2020; Trueman et al., 2021; Vakylabad et al., 2022; Wang et al., 2020; Wang et al., 2020).

Circular-economy studies span reductive roasting, cement or construction applications, and secondary-metal recovery. Material suitability and hazards must be evaluated with product-specific performance and leachability data (Winarko et al., 2024; Xue et al., 2021; Zeng et al., 2023; Zhou et al., 2024; Zhou et al., 2025).

Circular-economy studies span reductive roasting, cement or construction applications, and secondary-metal recovery. Material suitability and hazards must be evaluated with product-specific performance and leachability data (Zhou et al., 2024; Zhu et al., 2025).

11. TECHNOECONOMIC, ENVIRONMENTAL, AND DECISION FRAMEWORK

11.1 Whole-circuit economic evaluation

The economic comparison must use a defined system boundary, plant capacity, price basis, project life,



discount rate, and annual operating period. The recommended metric is incremental equivalent annual cost or benefit relative to a specified baseline route, normally goethite, hematite, or the existing plant configuration. Credits include avoided downstream treatment, recovered metal or by-product value, avoided disposal, and recoverable acid or water. Debits include A-site reagent, neutralizer, oxidation, heat, seed preparation, residence volume, thickening, filtration, washing, maintenance, scale removal, water treatment, target-metal loss, residue treatment, and incremental capital. Comparative work on sodium and ammonium reagents confirms that reagent selection must be assessed at circuit rather than stoichiometric scale (Asimi et al., 2020; Neisiani et al., 2023).

$$\Delta EAB = [C_{\text{avoided}} + V_{\text{recovered}} + C_{\text{disposal,avoided}}] - [OPEX_{\text{precip}} + OPEX_{\text{separation}} + C_{\text{metal loss}} + OPEX_{\text{residue}}] - CRF \times \Delta CAPEX \quad (2)$$

In Equation (2), ΔEAB is the incremental equivalent annual benefit in currency per year; all C , V , and $OPEX$ terms are annual values on the same capacity and price basis; $\Delta CAPEX$ is incremental installed capital; and $CRF = i(1+i)^n / [(1+i)^n - 1]$, where i is the real discount rate and n is project life in years. Uncertainty should be treated with at least sensitivity ranges for metal prices, disposal cost, reagent consumption, recovery loss, campaign availability, and residue-product revenue. Environmental credits should be monetized only when a recognized cost, tax, or avoided liability is defined.

A hypothetical illustration shows the decision logic. At a fixed plant capacity, assume annual credits of USD 1.45 million, incremental operating debits of USD 0.85 million, metal-loss and residue debits of USD 0.15 million, and incremental CAPEX of USD 2.0 million. For $i = 10\%$ and $n = 10$ years, $CRF = 0.1627$ and annualized capital is USD 0.325 million; ΔEAB is therefore USD 0.125 million per year. If recovered-product revenue falls by USD 0.20 million per year, the route becomes unfavorable. The example is illustrative, not a cost estimate for any cited plant.

11.2 Environmental performance and risk

Environmental assessment should include reagent production, water consumption, energy, sulfate transfer, residue mass, leachability, toxic-element partitioning, dust, thermal emissions, transport, and long-term stability. Geochemical and leaching studies show that total metal concentration is insufficient to define risk; mineralogy, pH, redox, and transformation history govern mobility (Huang et al., 2024; Peng et al., 2023a; Peng et al., 2023b; Ryu & Kim, 2022; Trueman et al., 2020; Trueman et al., 2021). Construction or composite use requires service-life and end-of-life testing, while thermal routes require gas-phase accounting and secondary-solid characterization (Olcay et al., 2025; Pandiyan & Solaiyan, 2024; Pugar et al., 2024).

Life-cycle assessment remains uncommon in the coded literature set. Until comparative LCA and technoeconomic analyses are available, claims of sustainability should be qualified by technology readiness, duration of operation, feed variability, recovery completeness, and the management of secondary streams. Reviews of detoxification, metal recovery, and value-added products consistently identify this gap (Chen et al., 2025; Eftekhari et al., 2020a; Kushwaha et al., 2023; Singh et al., 2023).

11.3 Multicriteria decision framework

A practical decision begins with solution characterization: total iron, Fe(II)/Fe(III), sulfate, free acidity, ionic strength, target metals, hazardous impurities, suspended solids, and recycle contaminants. The second step is to define the primary objective and downstream specification. The third step selects the jarosite chemistry and neutralizing system. The fourth step establishes the supersaturation, seed, mixing, residence time, and solids-separation strategy. The fifth evaluates residue stability and recovery options. The final step compares the route against goethite, hematite, or hybrid alternatives using technical, economic, and environmental criteria.

Table 9 translates this sequence into stage gates applicable during conceptual and pilot-scale process development.

Table 9

Stage-gate framework for selecting controlled jarosite formation.

Gate	Required evidence	Pass criterion	Decision if not passed
1. Solution definition	Complete speciation-relevant assay, Fe redox, acidity, sulfate, recycle inventory	Feed variability and controlling impurities are bounded	Improve sampling/speciation before precipitation tests
2. Separation objective	Residual Fe and target-metal recovery specifications	A measurable downstream requirement is defined	Do not optimize solely on Fe removal
3. Chemistry selection	A-site reagent, neutralizer, phase map, contamination assessment	Jarosite is compatible with downstream and recycle	Test alternative jarosite or iron phase
4. Particle engineering	Seed, mixing, supersaturation, aging, settling, filtration, washing	Separable solid with acceptable water and metal loss	Redesign feed/base addition or seed loop
5. Stability and destination	Leaching, transformation, hazardous-element behavior, route maturity	Residue has a credible disposal or valorization route	Reject or add conversion/recovery stage
6. Whole-circuit value	Annualized mass/energy/water balance, evidence grade, sensitivity analysis, and comparison with goethite/hematite/hybrid route	$\Delta EAB > 0$ over credible sensitivity ranges and no unresolved environmental transfer	Select alternative route or limit jarosite duty

Note. The gates synthesize process, residue, and sustainability criteria. Adapted from multiple sources (Asimi et al., 2020; Chen et al., 2025; Cruells & Roca, 2022; Höber & Steinlechner, 2021; Neisiani et al., 2023; Pereira, 2026a; Pereira, 2026b; Singh et al., 2023; Y. Wang et al., 2020).

The framework deliberately allows a “limited jarosite duty” decision. Partial iron removal or targeted impurity scavenging may create more value than complete conversion, particularly when the final fraction of Fe is costly to precipitate selectively or generates ultrafines. Hybrid precipitation and transformation routes should therefore remain available throughout process development.

The complete decision logic should be visualized as in Figure 6.

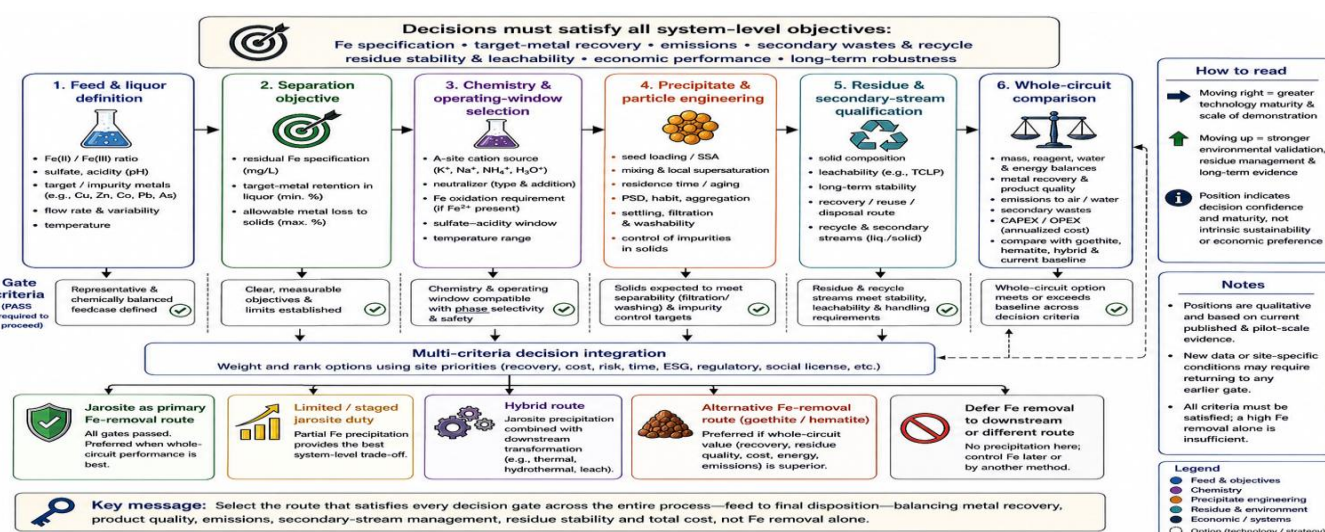


Figure 6. Evidence-qualified decision algorithm for controlled jarosite duty and alternative iron-removal routes.



Note. Adapted from multiple sources (Asimi et al., 2020; Chen et al., 2025; Cruells & Roca, 2022; Höber & Steinlechner, 2021; Neisiani et al., 2023; Pereira, 2026a; Pereira, 2026b; Singh et al., 2023; Y. Wang et al., 2020).

Figure 6 is iterative: new pilot evidence on residual Fe, impurity association, filtration, or washing returns the design to the affected gate.

Framework development should combine evidence on reactor operation, impurity capture, residue processing, and measured solid–liquid separation behavior with explicit uncertainty rather than assuming that every reported benefit translates to a circuit-level gain. (Ahamed et al., 2021; Chen et al., 2022; Cogram et al., 2023; Eftekhari et al., 2020a; Hernández-Lazcano et al., 2021).

Framework development should combine evidence on reactor operation, impurity capture, residue processing, and measured solid–liquid separation behavior with explicit uncertainty rather than assuming that every reported benefit translates to a circuit-level gain. (Lu et al., 2023; Moulijn et al., 2008; Nolasco et al., 2022; Pugar et al., 2024; Yang et al., 2020).

12. CRITICAL SYNTHESIS, KNOWLEDGE GAPS, AND RESEARCH PRIORITIES

12.1 Areas of consensus

The literature supports several robust conclusions. Ferric iron, sulfate, an appropriate A-site cation, and a controlled hydrolysis environment are required for purposeful jarosite formation. Temperature, acidity, supersaturation, seed, and residence time strongly affect rate and product quality. Jarosite can incorporate hazardous and valuable elements by multiple mechanisms, and solid–liquid separation performance is sensitive to precipitation history. Finally, residue stability and valorization cannot be inferred from bulk composition alone (Buriti et al., 2024; Buriti et al., 2025b; Chen et al., 2025; Cruells & Roca, 2022; Eftekhari et al., 2020a; Höber & Steinlechner, 2021; Pereira, 2026a; Pereira, 2026b; Singh et al., 2023).

12.2 Areas of disagreement and causes

Disagreement remains regarding the rate-controlling step, the identity of transient precursors, the extent to which particular elements are structurally incorporated, and the long-term stability of transformed products. Contradictory results often arise from synthetic versus industrial solutions, different pH definitions and measurement temperatures, incomplete washing, unclosed mass balances, variable seed histories, and inconsistent aging times. In chalcopyrite systems, disagreement also reflects the difficulty of separating the effects of jarosite, elemental sulfur, and other surface products (Buriti et al., 2025a; Buriti et al., 2025b; Dakkoune et al., 2023; Dong et al., 2025; Kartal et al., 2020; Ma et al., 2021; Ryu & Kim, 2022; Soe et al., 2021; Winarko et al., 2024; Yang et al., 2020).

Technology claims also differ because many valorization studies report extraction or conversion but do not include reagent recycle, gas cleaning, product qualification, or continuous operation. Recent integrated processes are promising, including slurry electrolysis, hydrothermal separation, selective lead extraction, and stepwise Zn–In–Ga–Fe recovery, but their comparative economics and life-cycle performance remain to be established (Wang et al., 2025; Yu et al., 2026; Zeng et al., 2023; Zhou et al., 2025; S. Zhou et al., 2024; Zhu et al., 2025).

12.3 Research priorities

Thermodynamic and kinetic models should address concentrated, multicomponent industrial liquors using activity-based descriptions and experimentally constrained phase data. Continuous precipitation studies should integrate residence-time distribution, online acidity control, seed populations, and population-balance models. Track impurities across solutions, washed solids, wash liquors, and downstream treatment, using microanalysis to distinguish structural from physical associations. Report comparable cake and pressure parameters in filterability studies. Long-term campaigns should quantify scale growth, seed deactivation, recycle buildup,



and process variability. Assess residue routes through integrated techno-economic and life-cycle analyses, plus market and regulatory qualification.

The priority matrix is summarized in Table 10.

Table 10

Knowledge gaps and priority research actions.

Area	Current limitation	Priority action	Decision enabled
Thermodynamics	Dilute-solution data and uncertain non-stoichiometry	Activity-based multicomponent models with validated phase equilibria	Reliable operating window and phase selection
Kinetics/mechanisms	Uncertain precursors and rate control	In situ measurements and mechanistic models across scale	Reactor and residence-time design
Selectivity	Bulk assays obscure association mechanism	Closed deportment plus microanalysis and wash partitioning	Metal-loss control and impurity scavenging
Particle engineering	Few population or shear-aware studies	Continuous seeded tests and population-balance modeling	Thickener/filter sizing and scale-up
Process integration	Downstream benefits frequently inferred rather than directly measured	Long-duration campaigns with actual SX/IX/EW/crystallization recycles and evidence grading	Verified circuit integration and, where criteria are met, process intensification
Residue stability	Short leach tests dominate	Transformation, aging, bioaccessibility, and service-life testing	Credible disposal or utilization route
Economics and LCA	Incomplete secondary-stream accounting	Comparative TEA/LCA against goethite, hematite, and hybrids	Defensible route selection and sustainability claims

Note. Priority actions reflect the critical synthesis of the coded literature set. Adapted from multiple sources (Buriti et al., 2024; Buriti et al., 2025b; Chen et al., 2025; Cruells & Roca, 2022; Dong et al., 2025; Höber & Steinlechner, 2021; Kushwaha et al., 2023; Pereira, 2026a; Pereira, 2026b; Singh et al., 2023; Wang et al., 2025; Wu et al., 2025; Yu et al., 2026; Zhu et al., 2025).

The most important research shift is from isolated precipitation yield to integrated operability. A future study should be considered process-relevant only when it identifies the solid phase, closes the metal and water balances, reports physical separation performance, and relates the resulting liquor and residue to a defined next operation.

13. CONCLUSIONS

Controlled jarosite formation is best described as a multifunctional hydrometallurgical circuit-integration tool. It qualifies as process intensification only when a defined baseline comparison demonstrates a substantial reduction in equipment, resources, waste, annualized cost, or environmental burden, or a substantial increase in productivity or overall recovery.

The strongest direct evidence supports ferric iron removal and solution purification in zinc hydrometallurgy and in selected sulfate-rich systems. Controlled precipitation can also potentially support downstream extraction, electrowinning, crystallization, ion exchange, or membrane polishing, but the evidence is not equally mature for all operations and should be qualified accordingly.

Ideal-phase stoichiometry makes the principal trade-off explicit: jarosite fixes sulfate but generates acidity and a larger solid mass per unit Fe than goethite or hematite. Chemical conversion must therefore be optimized



together with valuable-metal retention, residual Fe, seed behavior, particle size, cake permeability, washing, recycle accumulation, scale control, and residue destination.

The same chemistry becomes detrimental when precipitation occurs on mineral or equipment surfaces, local supersaturation produces ultrafines, or impurity capture transfers risk to an unstable or uneconomic residue. The preferred duty may consequently be partial, staged, hybrid, or absent.

Future progress depends on activity-based thermodynamics for concentrated liquors, continuous and long-duration precipitation campaigns, residence-time and population-balance modeling, closed solution–solid–wash balances, quantitative filtration data, direct downstream validation, annualized comparative economics, and life-cycle verification.

DECLARATIONS

Author Contributions

Antonio Clareti Pereira: Conceptualization, methodology, investigation, critical analysis, writing—original draft, writing—review and editing, and visualization planning.

Funding

This research received no external funding.

Data Availability

All study-level coding used in this review is provided in Supplementary Table S1. No new experimental data were generated.

Conflicts of Interest

The author declares no conflict of interest.

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