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Jarosite in Mineral Processing and Hydrometallurgy: A Structured Critical Review of Formation, Treatment, Environmental Risk, and Circular Valorization (2020–2025)

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Abstract

Jarosite-type phases are deliberately precipitated in sulfate hydrometallurgy to remove ferric iron. However, jarosite-rich industrial residues may retain zinc, lead, silver, indium, copper, arsenic, and other elements through structural substitution, sorption, occlusion, discrete mineral hosting, and pore-liquid entrainment. This structured critical review with evidence-informed qualitative appraisal evaluates 95 references published from 1 January 2020 through 31 December 2025; the search was updated on 27 July 2026 solely to capture 2025 articles indexed after the analytical period. The evidence set comprises 86 primary studies, six prior reviews, and three foundational or methodological sources. Searching, screening, coding, and appraisal were conducted by a single reviewer without independent calibration; therefore, no inter-rater reliability coefficient was calculated, confidence categories are reviewer-assessed, and the work is not presented as a systematic review. The synthesis distinguishes controlled synthetic jarosites from heterogeneous jarosite-rich industrial residues and compares jarosite precipitation with alternative iron-removal routes. The strongest evidence concerns precipitation chemistry, dissolution and transformation mechanisms, and proof-of-concept recovery of silver, indium, base metals, and iron-rich products. Confidence is lower for process-wide reagent recycle, sulfate and water closure, long-term product stability, sustained pilot operation, and integrated techno-economic and life-cycle performance. Circularity and near-zero waste are therefore treated as decision criteria and a research agenda rather than as established outcomes for most routes. Jarosite management should be mineralogy-

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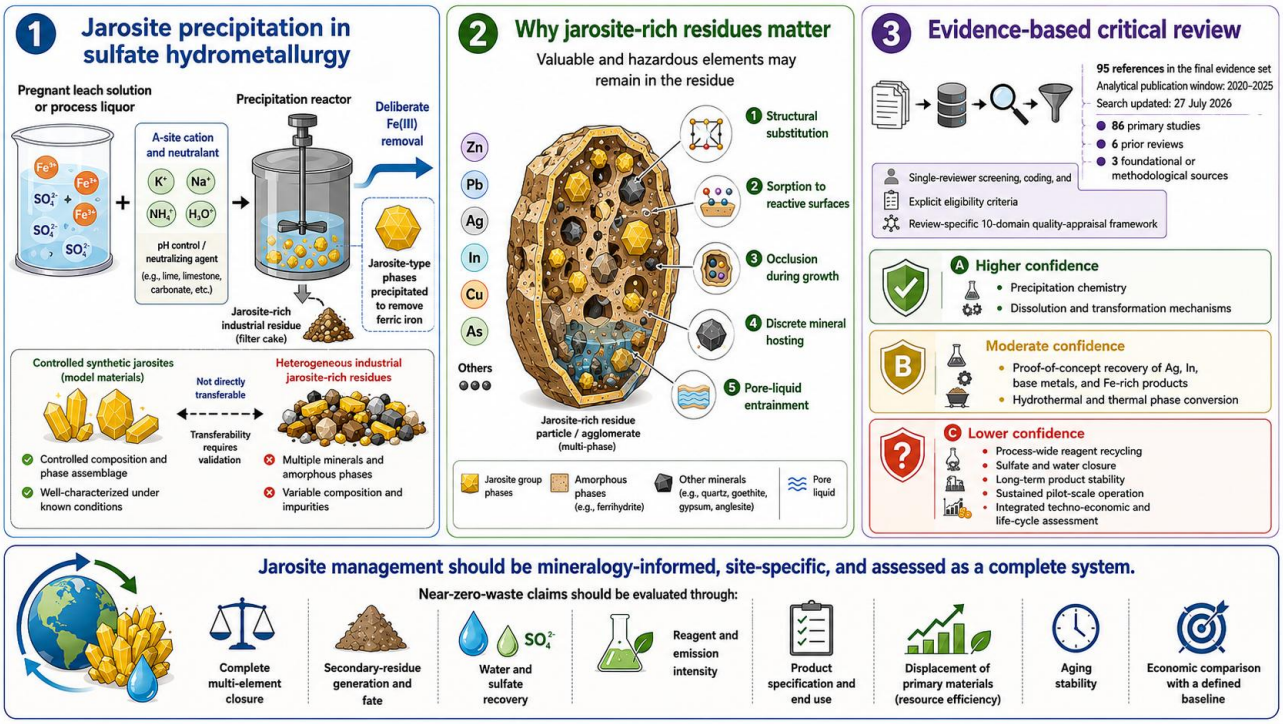
informed, site-specific, and assessed as a complete system rather than as an isolated extraction, stabilization, or reuse step.

Keywords: jarosite; iron precipitation; zinc hydrometallurgy; metal recovery; environmental stability; circular valorization.

Highlights

- Differentiates controlled synthetic jarosite from heterogeneous jarosite-rich industrial residues.
- Positions the review against six recent jarosite and iron-residue reviews and defines its process-mineralogy-informed contribution.
- Uses a transparent single-reviewer qualitative appraisal while explicitly limiting systematic-review and reliability claims.
- Defines auditable circularity criteria without treating near-zero waste as an established outcome for most routes.

Graphical abstract



1. Introduction

Jarosite belongs to the alunite supergroup and is commonly represented by the idealized formula $AFe_3(SO_4)_2(OH)_6$, in which the A site is occupied primarily by K^+, Na^+, NH_4^+, or H_3O^+. It forms in acidic, oxidizing, sulfate-rich media and is deliberately

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precipitated in hydrometallurgical circuits to remove dissolved ferric iron. In zinc processing, the jarosite route replaced poorly filterable amorphous ferric hydroxides with a more crystalline, separable iron-bearing solid, making it a long-established industrial iron-control operation (Cruells & Roca, 2022; Dutrizac & Jambor, 2000; Höber & Steinlechner, 2021).

The industrial filter cake is not a pure jarosite mineral. It may contain several jarosite-group phases, along with ferrihydrite, goethite, gypsum, anglesite, silica-rich gangue, unreacted calcine, sulfides, elemental sulfur, process additives, and entrained liquor. Valuable and hazardous elements may be structurally substituted, sorbed to reactive surfaces, occluded during crystal growth, hosted by accessory phases, or retained in pore solution. Consequently, bulk composition alone cannot determine reagent demand, liberation behavior, filtration, or environmental release (M. Chen et al., 2025; Huang et al., 2024; Peng, Liu, et al., 2023; R. Wang et al., 2020).

The literature from 2020 to 2025 shows a shift from disposal-oriented management to selective recovery, detoxification, phase conversion, and reuse. Techniques such as hydrometallurgical decomposition, multi-metal recovery, thermal transformation, biological treatment, and integrated residue utilization have been proposed, with varying degrees of maturity (Ahamed et al., 2021; M. Chen et al., 2025; Singh et al., 2023; Q. Zhou et al., 2025). Environmental research indicates jarosite can immobilize contaminants during precipitation but may release or redistribute them after pH, redox, complexation, or mineralogy changes (Burton et al., 2021; Ryu & Kim, 2022; Tang et al., 2020).

A critical assessment must therefore move beyond headline extraction percentages, short-term leaching compliance, or isolated material-strength results. It should determine whether the feed was representative, whether the proposed mechanism is supported by mineralogical evidence, whether the element and water balances close, whether reagent and energy inputs are credible, and whether all secondary solids, liquors, gases, and products have defined destinations. Resource-efficiency and techno-economic studies reinforce that an apparently effective unit operation can remain

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unattractive when residue volume, energy, reagent regeneration, product quality, and integration with the host plant are considered together (Abadías Llamas et al., 2020; Asimi Neisiani et al., 2023; Höber & Steinlechner, 2021).

Several recent reviews have addressed jarosite mineralogy and reactivity, processing strategies for iron-precipitation residues, dissolution and precipitation thermodynamics, residual-metal recovery, and detoxification or reutilization (Buriti et al., 2024; M. Chen et al., 2025; Cruells & Roca, 2022; Höber & Steinlechner, 2021; Ortiz-Castillo et al., 2021; Singh et al., 2023). However, these syntheses do not jointly address five questions that govern industrial decision-making: whether conclusions from synthetic phases are transferable to real filter cakes; whether avoiding jarosite formation is preferable to treating the residue; whether water, sulfate, reagents, gases, and secondary solids close at the flowsheet level; whether recovered materials meet product specifications after aging; and whether technology-readiness, techno-economic analysis, and life-cycle assessment are evaluated within a single boundary. Table 1 positions the present review relative to the most relevant prior syntheses.

This review has four objectives: to consolidate chemical and mineralogical knowledge of jarosite formation, substitution, dissolution, and transformation; evaluate evidence on precipitation, treatment, recovery, and valorization using explicit qualitative criteria; compare jarosite precipitation with alternative iron-removal methods and assess environmental claims at system level; and propose measurable research and implementation criteria linking metal recovery, sulfate and water management, product qualification, aging, technology readiness, and integrated TEA–LCA. Its contribution is a process-mineralogy-informed decision synthesis connecting published evidence to process selection, comparison, and circularity assessment.

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Table 1. Positioning of the present review relative to previous jarosite reviews

Review	Coverage emphasis	Principal strength	Gap addressed by the present review
Höber & Steinlechner (2021).	Iron-precipitation residues; hydro- and pyrometallurgical processing	Broad process comparison and industrial context	Limited formal quality scoring, product qualification, and synthetic–industrial transferability.
Cruells & Roca (2022).	Formation, structure, thermodynamics, reactivity, environment	Strong mineralogical and environmental foundation	Limited flowsheet closure, alternative Fe-removal comparison, and TEA/LCA.
Singh et al. (2023).	Chemical and biochemical recovery of residual metals	Wide recovery-route coverage	Limited precipitation baseline, technology readiness, and product qualification.
Buriti et al. (2024).	Precipitation and dissolution kinetics and thermodynamics	Deep kinetic synthesis and data-gap analysis	Limited heterogeneity in industrial residues, system balances, and product qualification.
M. Chen et al. (2025)	Detoxification and reutilization	Broad circular-management synthesis	Limited formal evidence scoring and cross-route baseline comparison.
Ortiz-Castillo et al. (2021).	Microorganisms in the formation, dissolution, and transformation of secondary minerals	Broad synthesis of biologically mediated mineral transformations	Broad mine-drainage and secondary-mineral scope; limited industrial jarosite-residue flowsheet closure and product qualification.
Present review	Formation, treatment, environmental risk, products, and system decision	Integrates synthetic–industrial distinction, alternative Fe removal, quality scoring, sulfate/water closure, product qualification, TRL, and TEA–LCA	Designed to connect mineralogical evidence with auditable process and circularity decisions.

Note. Author's elaboration based on Höber and Steinlechner (2021), Cruells and Roca (2022), Ortiz-Castillo et al. (2021), Singh et al. (2023), Buriti et al. (2024), and M. Chen et al. (2025).

Conceptual Positioning: A Process-Mineralogy-Informed Decision Framework

This review treats jarosite management as a coupled mineralogical, hydrometallurgical, environmental, and product-system decision problem. The relevant

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unit of analysis is therefore the complete flowsheet and its boundary conditions rather than a single extraction, decomposition, stabilization, or reuse result. Bulk recovery percentages are considered insufficient when phase identity, elemental deportment, secondary streams, product specifications, aging, and baseline performance are unresolved.

The manuscript distinguishes evidence extracted from included publications from author-developed synthesis. Descriptive counts and study findings are reported as literature evidence, whereas the operational indicators, development gates, scenario matrices, and circularity framework are explicitly labeled as the author's synthesis or proposed decision tools.

2. Review Methodology

2.1. Search Strategy, Time Window, and Eligibility

The review included records published from 1 January 2020 through 31 December 2025. The final search update was completed on 27 July 2026 solely to capture 2025 articles indexed after the analytical period; publications first issued in 2026 were excluded from the evidence synthesis. Foundational sources published before 2020 were retained only when they established industrial jarosite practice or evidence-synthesis methodology. The final evidence set contains 95 references: 86 primary studies, six prior reviews, and three foundational or methodological sources (Aromataris & Munn, 2020; Dutrizac & Jambor, 2000; Page et al., 2021).

The search combined jarosite and jarosite-residue terms with hydrometallurgy, mineral processing, precipitation, dissolution, leaching, detoxification, stabilization, recovery, transformation, recycling, environmental behavior, and valorization concepts. Sources included Scopus, Web of Science Core Collection, ScienceDirect, PubMed, and Google Scholar. Database fields, concept blocks, dates, and limits are summarized in Table 2. Reconstructed platform-specific strings used for the final verification update are provided in Supplementary Appendix S1. Because early exports and platform logs were not retained, the appendix does not claim to reproduce every historical query verbatim. Google Scholar was used only for citation chasing, exact-title verification, and metadata

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cross-checking; the number of result pages screened cannot be reconstructed and is not used in any retrieval-count claim.

Duplicate removal followed a hierarchy of DOI identity, exact normalized title, and combined first-author, year, and title similarity. Screening was conducted in two stages: title and abstract assessment followed by full-text evaluation of material identity, relevance, experimental detail, and publication metadata. All searching, screening, coding, and evidence appraisal were performed by the single author. No independent duplicate screening, second-reviewer calibration, or external classification audit was conducted; consequently, Cohen's kappa, Krippendorff's alpha, and other inter-rater reliability coefficients are not applicable. The retained evidence set was consolidated in a structured working matrix for descriptive mapping and qualitative appraisal. Because the earliest raw exports and the original study-level coding file were not retained in audit-ready form, this article is classified as a structured critical review with evidence-informed qualitative appraisal rather than a systematic review, and no PRISMA retrieval counts are reported.

Table 2. Database-specific search protocol used for the 2020–2025 evidence update

Database	Fields	Search concept	Last update	Limits
Scopus	Title, abstract, keywords	Jarosite terms AND processing, dissolution, recovery, transformation, environment, or valorization	27 July 2026	2020–2025; eligible articles, reviews, full papers, chapters
Web of Science Core Collection	Topic	Same concept blocks adapted to TS syntax	27 July 2026	2020–2025; eligible languages and document types
ScienceDirect	Title, abstract, keywords	Jarosite/residue terms AND hydrometallurgy or treatment terms	27 July 2026	Research and review articles, 2020–2025
PubMed	Title/Abstract	Jarosite terms AND environmental, dissolution, transformation, leaching, or recovery terms	27 July 2026	Journal articles and reviews, 2020–2025

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Database	Fields	Search concept	Last update	Limits
Google Scholar	Bibliographic record/citation chaining	Exact-phrase combinations plus exact-title verification	27 July 2026	Citation chasing and metadata cross-checking

Note. The table summarizes the documented concept blocks and limits. Reconstructed platform-specific strings are provided in Supplementary Appendix S1. These strings support transparency for the final verification update but do not retroactively recreate missing early platform logs. The analytical publication window ends on 31 December 2025.

The literature-selection procedure was designed to improve transparency and consistency within the limits of a single-author critical review. As shown in Figure 1, the workflow comprised database searching, DOI/title deduplication, two-stage screening, full-text eligibility assessment, structured evidence coding, and qualitative appraisal using the review-specific framework. The sequence was applied without reporting unverified intermediate retrieval counts, and the final evidence set of 95 references was preserved.

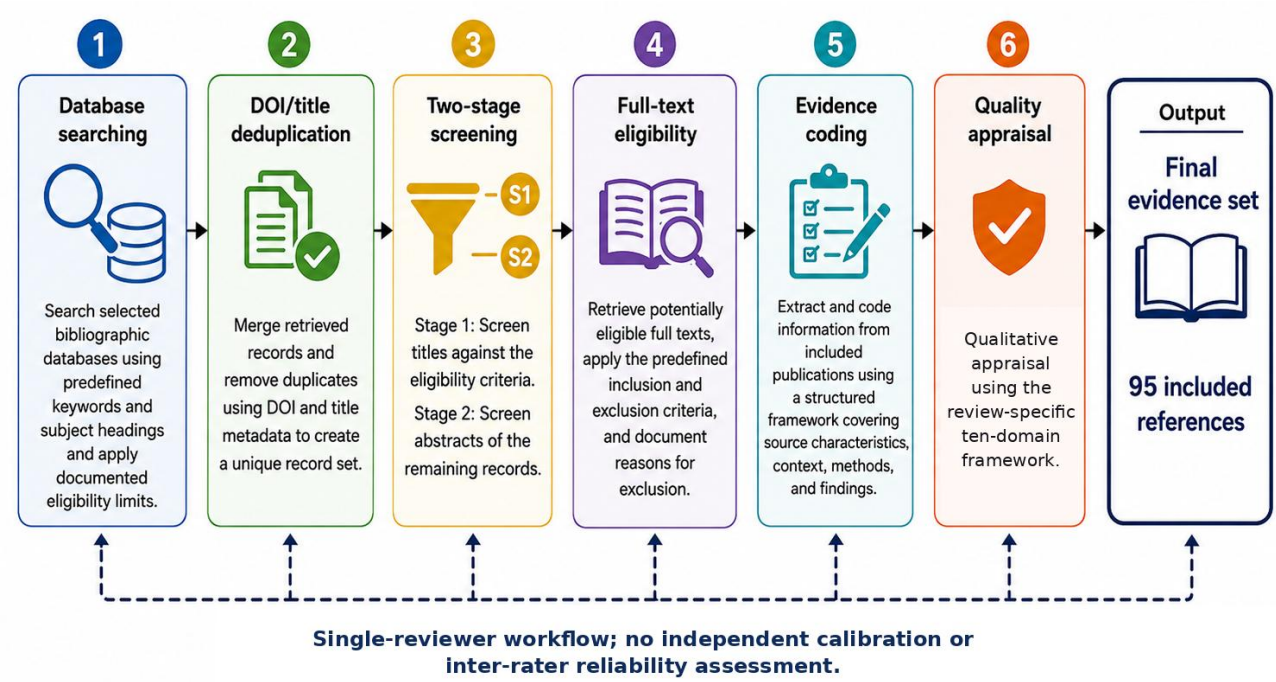

Figure 1. Literature selection, evidence coding, and qualitative appraisal workflow. Adapted from Aromataris and Munn (2020) and Page et al. (2021).

Figure 1 summarizes the progression from database identification to the final evidence set. Duplicate records were removed using DOI and title information, followed by title-and-abstract screening and full-text eligibility assessment. Eligible studies were coded for bibliographic information, material basis, process conditions, findings,

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limitations, and relevance to jarosite formation or management. Methodological quality and reporting completeness were then appraised using the review-specific ten-domain framework. Because all stages were completed by a single reviewer, the workflow reflects single-reviewer methodological consistency and does not imply independent calibration, consensus classification, or formal risk-of-bias assessment using external design-specific tools.

2.2. Data Extraction, Coding, and Descriptive Mapping

Each record was coded for publication year, evidence type, material basis, dominant treatment route, experimental scale, feed characterization, operating conditions, response variables, mass-balance reporting, secondary products, environmental testing, reagent recycle, product qualification, technology readiness, and principal limitation. 'Not reported' was retained as a valid code. Evidence from synthetic or natural jarosite was not generalized to jarosite-rich industrial residues unless the study showed comparable composition, phase, or transformation behavior. Supplementary Table S1 provides a reconstructed evidence inventory for all 95 references, including evidence type, material basis, dominant route, experimental scale, key process, environmental-test inclusion, product qualification, mass-balance reporting, and principal limitation. This inventory improves auditability but is explicitly a reconstruction from retained reference and manuscript records, not the lost original scoring file.

Dominant-topic coding identified 23 hydrometallurgical recovery studies, 19 hydrothermal or thermal studies, 17 environmental behavior studies, 12 formation or precipitation studies, nine reductive or biological studies, five product or material-reuse studies, one system-assessment study, and nine review, foundational, or methodological sources. By material basis, 51 records addressed industrial or process-derived residues or liquors, 18 used synthetic or controlled model systems, 17 examined natural, field, or environmental model systems, and nine were review or methodological sources. These are bibliographic-count distributions only; they do not weight publications by sample quality, experimental depth, scale, or reporting completeness.

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The verified descriptive mapping shown in Figure 2 is restricted to two mutually exclusive dimensions: the dominant processing route and the material basis. These categories can be reconciled directly to the 95-reference evidence set. Study scale and reporting features were considered during interpretation, but quantitative counts for those dimensions are not presented because the original study-level coding file was not retained in an audit-ready form.

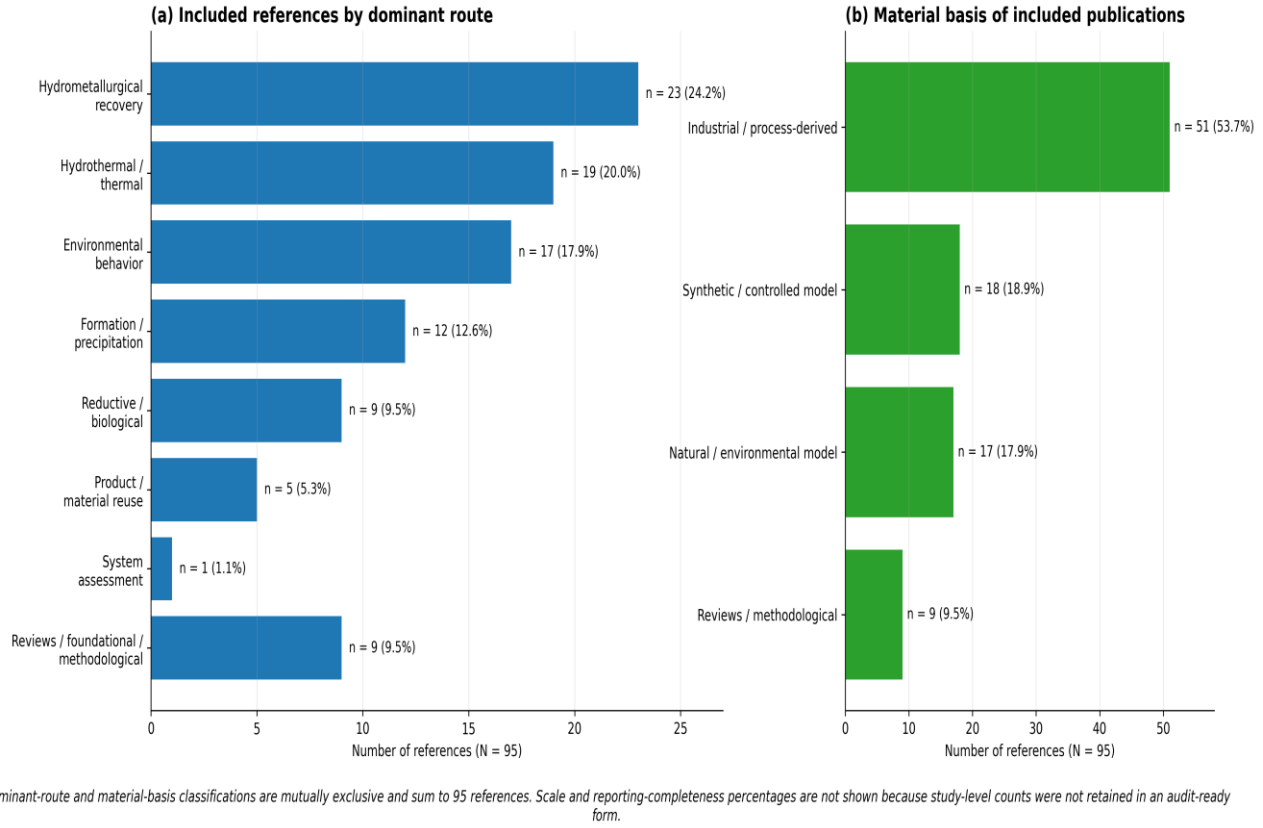

Figure 2. Bibliographic-count landscape of the 95-reference evidence set. Author's elaboration from the verified classifications described in Section 2.2. Panel (a) shows publication counts for the eight dominant-route classes, and panel (b) shows industrial/process-derived, synthetic/model, natural/environmental, and review/methodological material bases. Counts are publication frequencies, not evidence-weighted or quality-weighted estimates; reviews and methodological sources are displayed separately from primary studies.

Figure 2 provides a verified descriptive overview using the two classifications for which auditable counts were retained. Panel (a) reports the eight dominant-topic classes stated in Section 2.2. Panel (b) classifies publications by material basis. Industrial or process-derived materials provide the strongest direct connection to operating circuits

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and real residues; synthetic or controlled model systems support mechanistic interpretation; natural or environmental systems contribute evidence of aging and field behavior; and review or methodological publications consolidate prior findings without introducing a new experimental material basis. The visual prominence of a category should not be interpreted as evidence strength, because no quality or sample-size weighting was applied.

Panel (b) classifies publications by material basis. Industrial or process-derived materials provide the strongest direct connection to operating circuits and real residues; synthetic or controlled model systems support mechanistic interpretation; natural or environmental systems contribute evidence on aging and field behavior; and review or methodological publications consolidate prior findings without introducing a new experimental material basis.

The figure deliberately omits scale-distribution and reporting-completeness percentages. In the absence of an auditable study-level matrix, numerical claims for pilot-scale prevalence, complete elemental balances, aging tests, techno-economic assessment, or life-cycle assessment would not be reproducible. These features are therefore discussed qualitatively rather than estimated.

2.3. Structured Evidence Appraisal and Confidence Assessment

Primary studies were assessed by the single reviewer using the ten-domain framework in Table 3 as a qualitative rubric rather than a numerical ranking. The original study-level scoring file was not retained in audit-ready form; therefore, aggregate scores, medians, route-level score distributions, and study-specific quality categories are not reported. The rubric is retained to make the criteria underlying reviewer-assessed judgments of narrative confidence explicit. Supplementary Table S1 reports only reconstructable descriptive fields and does not recreate unsupported numerical quality scores.

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Table 3. Structured evidence-appraisal framework for primary studies

Domain	Limited evidence	Partial evidence	Strong evidence
Sample representativeness	Idealized or unspecified material	Single, partly characterized sample	Representative campaigns, blends, or justified synthetic model
Mineralogical characterization	No phase evidence	Basic XRD or bulk chemistry	Quantitative phase analysis plus microchemical/spectroscopic support
Experimental controls	No suitable control	Partial control or baseline	Controls isolate the claimed mechanism or treatment effect
Repeatability and uncertainty	No replication/uncertainty	Limited duplicates or descriptive error	Replicates and uncertainty/statistical treatment appropriate to design
Element and mass closure	Target response only	Partial solid/liquid accounting	Closed multi-element balance including washes and intermediate streams
Secondary-phase evaluation	Not evaluated	Final solid only	Time-resolved or stage-resolved secondary-phase characterization
Industrial relevance	Unspecified or unrealistic conditions	Realistic chemistry but simplified scale	Representative feed, solids loading, hydrodynamics, and integrated downstream context
Effluents and gases	Not considered	Qualitative identification	Quantified liquors, gases, dusts, treatment, and recycle
Product qualification	Product named only	Partial chemical or physical testing	Comparison with recognized product specification and end-of-life performance
Data transparency	Insufficient methods/data	Core methods reported	Traceable raw/processed data, assumptions, and calculation basis

Note. Author's elaboration based on evidence-synthesis principles in Aromataris and Munn (2020) and Page et al. (2021), adapted to jarosite-processing studies.

The framework supports consistent qualitative comparison across heterogeneous studies by considering sample representativeness, mineralogical characterization, experimental controls, repeatability, mass closure, secondary-phase assessment,

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industrial relevance, effluent and gas accounting, product qualification, and data transparency. It is used to identify the evidential strengths and limitations of each route, not to imply a precision unsupported by the retained records.

Confidence levels were assigned narratively by the single reviewer using explicit convergence criteria. High confidence was reserved for conclusions supported by multiple independent studies, representative or well-justified materials, convergent mineralogical and chemical evidence, appropriate controls, and sufficiently complete balances. Moderate confidence indicates consistent mechanistic or process evidence that remains predominantly bench-scale, site-specific, or incomplete in downstream accounting. Low confidence applies when evidence is sparse, highly idealized, lacks closed balances or aging tests, or depends on unverified product markets, reagent recycle, or integrated TEA–LCA. These categories are reviewer-assessed judgments rather than calibrated consensus ratings. On this basis, confidence is high for the effects of solution chemistry, A-site cation, pH, temperature, redox conditions, and substitution on jarosite formation and stability; moderate for selective Ag and In recovery, hydrothermal or thermal conversion, and staged multi-metal flowsheets; and low for universally achievable near-zero-waste performance, durable product markets, closed-loop reagent recycling, and comparative economic or life-cycle superiority.

2.4. Limitations of the Review

The review has six principal limitations. First, the earliest raw database exports and initial retrieval counts were not retained, so systematic-review completeness and PRISMA-style retrieval accounting cannot be claimed. Second, the original study-level coding and quality-scoring files were not retained in audit-ready form; Supplementary Table S1 is a transparent reconstruction rather than the original matrix, and quantitative mapping remains limited to counts based on verified routes and materials. Third, all searching, screening, coding, and appraisal were conducted by a single reviewer without independent duplicate verification, so no inter-rater reliability coefficient can be calculated, and all confidence judgments are assessed by the reviewer. Fourth, reconstructed search strings cannot recreate missing historical platform logs, and the

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number of Google Scholar result pages screened is unavailable. Fifth, heterogeneous terminology, incomplete phase quantification, and nonequivalent feeds, solids loadings, endpoints, and system boundaries precluded numerical meta-analysis. Sixth, regulatory classifications were not compared across jurisdictions; the discussion is limited to the scientific evidence needed to support responsible, jurisdiction-specific classification and reuse claims. These limitations are incorporated into the confidence statements and conclusions rather than used to justify overgeneralization.

3. Fundamentals of Jarosite and Related Iron Sulfate Phases

3.1. Composition, Structure, and Substitution

The jarosite subgroup is generally represented by $AFe_3(TO_4)_2(OH)_6$, where A is a large cation, and T is commonly S but may be partially replaced by other tetrahedral anions. The rhombohedral framework contains FeO_6 octahedra linked to sulfate tetrahedra, with A-site cations occupying interlayer cavities. This structural flexibility permits K-, Na-, NH_4-, H_3O-, Pb-, and Ag-bearing members and allows substitution by Al^{3+}, Cr^{3+}, AsO_4^{3-}, CrO_4^{2-}, and related species (Cruells & Roca, 2022; Dutrizac & Jambor, 2000; Grigg, Notini, et al., 2024; Hu et al., 2025).

Substitution is not merely a mineralogical descriptor because it changes lattice dimensions, defect density, solubility, thermal response, surface chemistry, and the partitioning of valuable or hazardous elements. Pb incorporation can modify microstructure and adsorption behavior, while Fe-site and tetrahedral substitutions alter transformation pathways and contaminant release. Lead-bearing jarosite formation and dissolution also depend on the interaction between jarosite and anglesite or other Pb phases (Grigg, Notini, et al., 2024; Hu et al., 2025; Shi, Min, Tian, et al., 2022; Shi, Min, Zhang, et al., 2023; Sun et al., 2025).

The residue matrix retains elements through four principal mechanisms: structural substitution, surface sorption, occlusion or inclusion during precipitation, and physical entrainment of process liquor. These mechanisms require different treatment responses and produce different environmental risks. Spectroscopic and transformation studies show that arsenic, antimony, chromium, and other oxyanions may be incorporated or

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sorbed in distinct configurations that respond differently to aging and redox change (Burton et al., 2021; Karimian et al., 2023; Peng, He, et al., 2023; Ryu & Kim, 2022).

Table 4 links the main compositional features of jarosite-group phases to their processing significance. The table is intended as a diagnostic guide rather than as a complete mineralogical classification.

Table 4. Jarosite-group compositional features and their implications for processing and environmental behavior

Feature	Typical examples	Processing implication	Critical implication
A-site occupancy	K^+, Na^+, NH_4^+, H_3O^+; partial Ag^+ or Pb^{2+} with charge compensation.	Influences precipitation selectivity, lattice parameters, acid balance, and thermal stability.	The A-site must be measured or inferred cautiously; ideal labels may hide mixed occupancy.
Fe-site substitution	Partial Al^{3+} or Cr^{3+} substitution.	Can modify crystallinity, dissolution, and transformation behavior.	Synthetic end members should not be assumed to represent Al-rich industrial phases.
Tetrahedral substitution	SO_4^{2-} partly replaced by AsO_4^{3-}, CrO_4^{2-}, Se species, or phosphate.	Controls contaminant retention and release during pH/redox change.	Total-element data alone cannot distinguish lattice incorporation from discrete phases.
Defects and vacancies	A-site vacancies, nonstoichiometry, poorly crystalline domains.	Increase heterogeneity and may create reactive or sorptive sites.	Peak broadening should not be interpreted only as small particle size.
Associated phases	Goethite, ferrihydrite, gypsum, anglesite, silica, sulfides, elemental sulfur.	Affect reagent consumption, filtration, liberation, and product quality.	“Jarosite residue” must be treated as a multiphase material.
Entrained liquor	Zn, sulfate, acid, and soluble impurities in cake moisture.	Raises apparent solid inventory and can dominate early wash/leach response.	Washed and unwashed compositions should be reported separately.

Note. Author's elaboration based on Dutrizac and Jambor (2000), Cruells and Roca (2022), Burton et al. (2021), Grigg, Notini, et al. (2024), Karimian et al. (2023), Ryu and Kim (2022), and Hu et al. (2025).

The table highlights a recurring weakness in the literature: bulk chemical composition is often presented without a defensible allocation of elements among jarosite, accessory phases, adsorbed fractions, and pore solution. This uncertainty propagates

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into recovery calculations, kinetic models, and environmental-risk statements. A robust characterization program should therefore combine XRD with Rietveld refinement, SEM–EDS mapping, particle-size analysis, sequential or selective extraction, and solution analysis after standardized washing.

Figure 3 provides a conceptual representation of the jarosite framework and the principal contaminant-retention mechanisms. The diagram is intentionally simplified so that the distinction among substitution, sorption, occlusion, and entrainment remains clear.

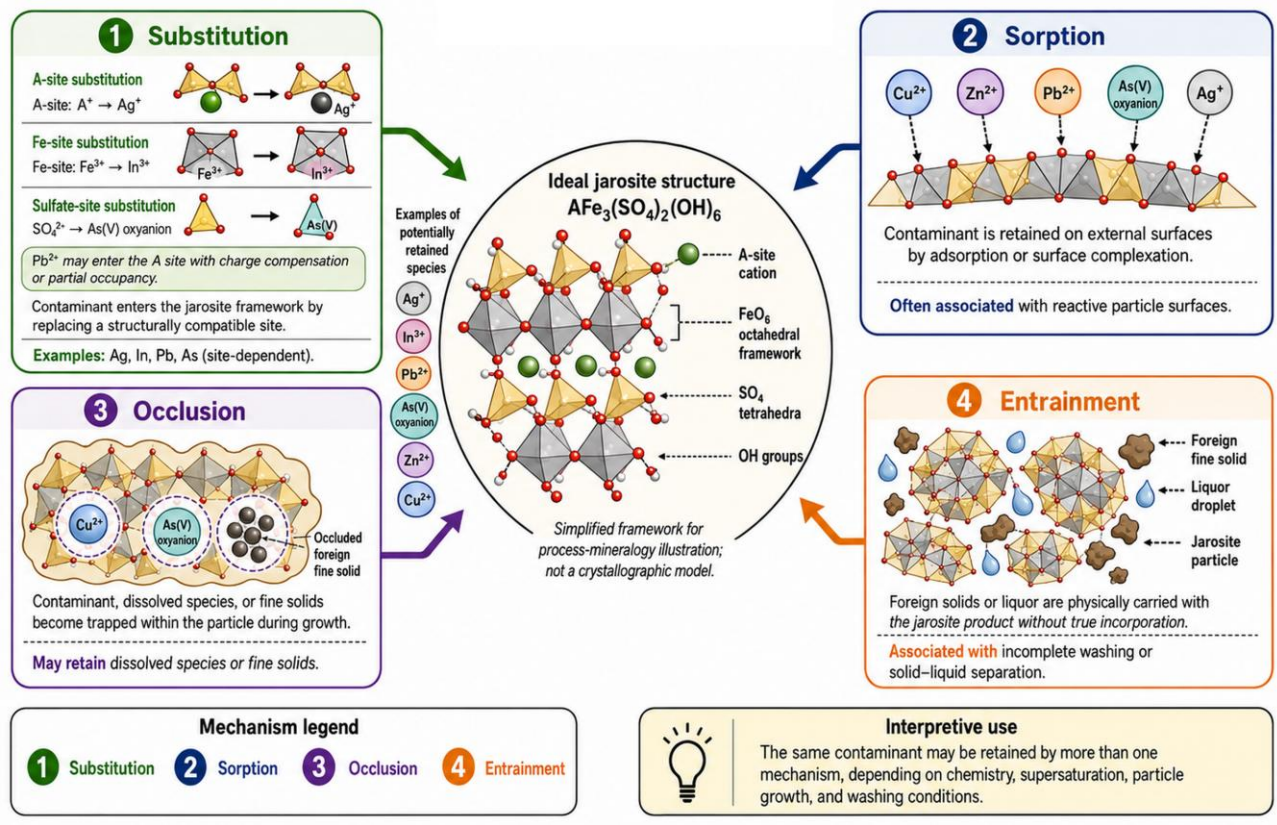

Figure 3. Conceptual representation of jarosite structure and contaminant-retention mechanisms. Author's elaboration based on Dutrizac and Jambor (2000), Cruells and Roca (2022), Burton et al. (2021), Shi, Min, Tian, et al. (2022), Shi, Min, Zhang, et al. (2023), Ryu and Kim (2022), and Hu et al. (2025). This is a conceptual process-mineralogy diagram, not a crystallographic model.

The mechanisms shown in Figure 3 indicate that “metal recovery from jarosite” is not a single reaction. Early-stage washing may recover entrained soluble species; mild leaching may remove surface-associated or discrete phases; and complete liberation of

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structurally incorporated elements may require substantial lattice decomposition. Sequential treatment can therefore be more selective than a single highly aggressive step, provided that the intermediate solids and liquors are characterized and the overall balance is closed.

3.2. Formation Mechanisms and Process Chemistry

For a monovalent A-site cation, the simplified jarosite precipitation reaction is:

$$3Fe^{3+} + A^{+} + 2SO_4^{2-} + 6H_2O \rightarrow AFe_3(SO_4)_2(OH)_6(s) + 6H^{+} \quad (1)$$

Equation 1 directly represents occupancy by K^+, Na^+, NH_4^+, or H_3O^+. Incorporation of divalent cations such as Pb^{2+} requires charge compensation via vacancies, coupled substitution, or mixed occupancy. The reaction removes ferric iron but generates acidity; industrial operation therefore requires controlled neutralization, sufficient A-site cation availability, and management of hydrolysis intermediates, induction periods, seed effects, and competing ferric phases (Asimi et al., 2020; Asimi Neisiani et al., 2023; Buriti et al., 2025b; Dutrizac & Jambor, 2000).

Formation is promoted by acidic sulfate media, oxidized iron, an available A-site cation, suitable temperature, controlled pH, and adequate residence time. Industrial studies show that agitation, neutralant addition, seed history, and cation selection influence iron removal, crystallinity, filtration, impurity capture, and cost. Related applications include As-bearing jarosite precipitation for solution purification and selective iron rejection from complex sulfate liquors, confirming that the optimum is liquor-specific rather than universal (Asimi et al., 2020; Asimi Neisiani et al., 2023; Buriti et al., 2025b; Hazaveh et al., 2020; X. Zhou et al., 2024).

Natural formation in acid mine drainage shares the requirements of acidity, sulfate, and ferric iron but differs from industrial precipitation in mixing, biological mediation, supersaturation history, and temporal variability. Biogenic jarosite properties vary with solution pH, and jarosite precipitation can significantly affect iron balance and passivation in bioleaching systems. These differences must be recognized before natural or biogenic observations are applied to refinery residues (Burton et al., 2021; Oladipo & Ojumu, 2023; Ortiz-Castillo et al., 2021; Z. Wang et al., 2021).

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3.3. Thermodynamic Stability, Kinetics, and Phase Transformation

Jarosite is stable only within a limited chemical range. Acidic, oxidizing sulfate solutions can preserve the phase, whereas neutralization, reduction, complexation, organic ligands, and heating can drive dissolution or conversion to iron oxyhydroxides and oxides. Aluminum substitution, field aging, and associated oxyanions can alter both the rate and pathway of transformation, so an ideal K-jarosite response should not be treated as a universal stability model (Buriti et al., 2024; Cruells & Roca, 2022; Grigg, Notini, et al., 2024; Grigg, Wisawapipat, et al., 2024; Ryu & Kim, 2022; Trueman et al., 2020).

Kinetic interpretation is complicated by polydisperse particles, porosity, nonstoichiometry, changing surface area, product-layer formation, and simultaneous dissolution–reprecipitation. Shrinking-core expressions are useful empirical tools, but a good fit does not prove the existence of a sharp unreacted core. Recent work has compared alternative kinetic descriptions, explicitly treated multiparticle populations, and examined dissolution under acidic and complexing conditions (Buriti et al., 2025a; Calla-Choque & Lapidus, 2021; Islas et al., 2020; Trueman et al., 2020).

For industrial residues, kinetic model selection should be supported by time-resolved data on mineralogy, morphology, solution speciation, and reagent depletion. A changing rate may reflect dissolution of a minor reactive phase, diffusion through a porous layer, passivation, complexant consumption, or secondary precipitation. Studies of hazardous jarosites and silver-bearing jarosite systems show that apparent rate constants must be interpreted alongside solid-phase evolution and particle-size distribution (Buriti et al., 2025a; Islas et al., 2020, 2021; Calla-Choque & Lapidus, 2021).

4. Industrial Applications, Residue Generation, and Alternative Iron-Removal Baselines

4.1. Role of Jarosite in Hydrometallurgical Iron Control

In roast–leach–electrowinning zinc processing, iron dissolves from the calcine and associated minerals and must be reduced before purification and electrowinning. Jarosite precipitation remains attractive because it operates at atmospheric pressure and yields a

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relatively crystalline solid, but it also consumes neutralant, generates acidity, and transfers metals and impurities to the residue. Behavior of iron during pressure leaching, As-bearing jarosite purification, and selective jarosite precipitation from complex leachates illustrate the strong dependence on feed chemistry and upstream process conditions (Asimi et al., 2020; Dutrizac & Jambor, 2000; Hazaveh et al., 2020; Qin et al., 2020; X. Zhou et al., 2024).

Operating variables are strongly coupled. Increasing temperature can accelerate hydrolysis and crystal growth; raising pH can improve iron removal while increasing coprecipitation of valuable metals; seeding can shorten induction but recycle impurities; and increasing residence time can improve maturation while increasing reactor volume and metal capture. Technical and economic comparisons of sodium- and ammonium-based precipitation further show that reagent selection affects both kinetics and plant-level performance (Asimi et al., 2020; Asimi Neisiani et al., 2023; Buriti et al., 2025b; Sun et al., 2025).

Figure 4 places residue generation within the complete industrial circuit. The figure emphasizes that jarosite is not an isolated waste-management issue: its composition is created by upstream leaching and precipitation choices, while its treatment affects downstream water, acid, sulfate, and metal balances.

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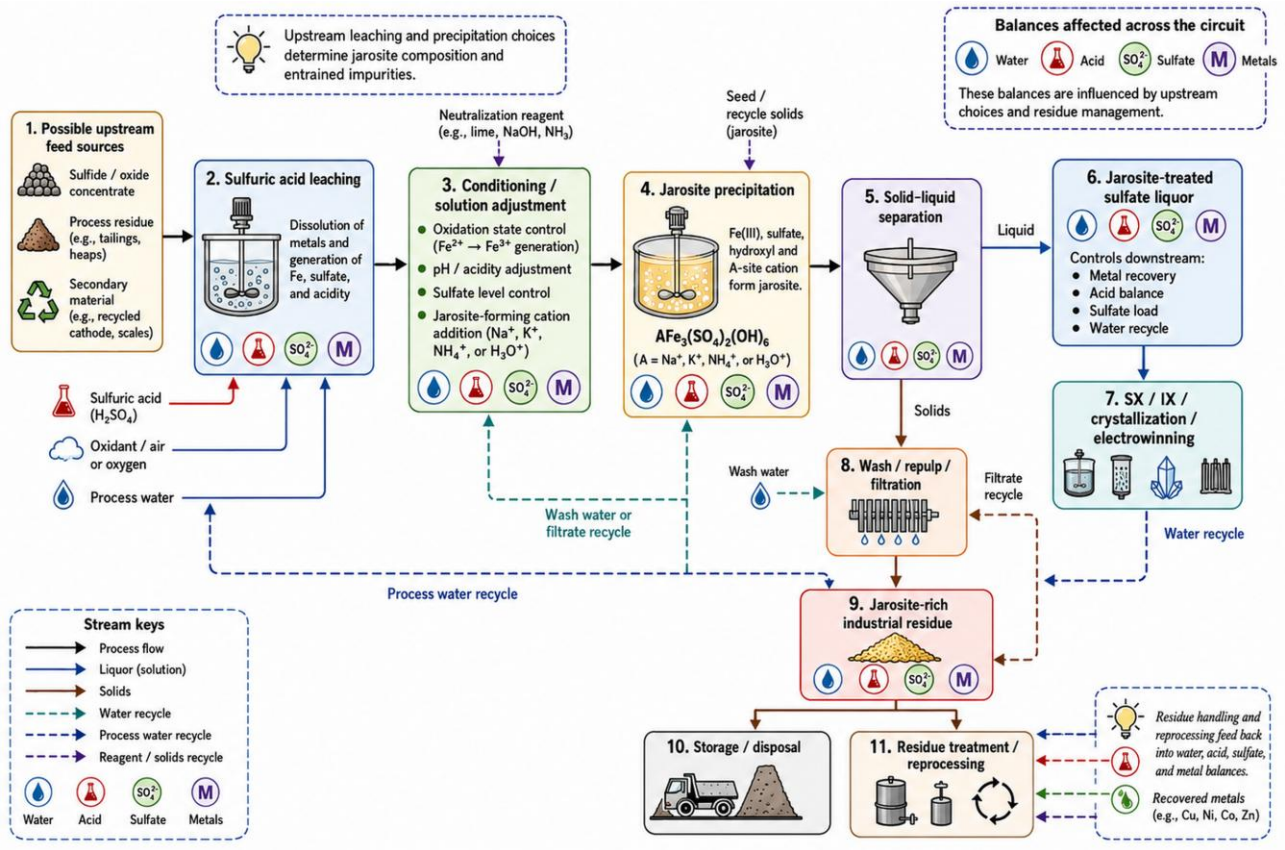

Figure 4. Jarosite precipitation and residue generation within a sulfate hydrometallurgical circuit. Author's elaboration based on Dutrizac and Jambor (2000), Asimi et al. (2020), Asimi Neisiani et al. (2023), Qin et al. (2020), and X. Zhou et al. (2024).

The flowsheet reveals two design points. First, reducing metal loss to jarosite might be cheaper than metal recovery after precipitation, making upstream selectivity part of residue valorization. Second, post-treatment must integrate with plant water and acid circuits; dissolving the cake and returning contaminated sulfate without a clear destination just shifts the problem.

4.2. Operating Variables and Multi-Objective Optimization

The key variables governing industrial jarosite precipitation and their associated trade-offs must be interpreted jointly because the direction and magnitude of each response depend on liquor composition, seed history, and reactor hydrodynamics. Temperature accelerates ferric hydrolysis, nucleation, and crystal growth, but it can also change competing phase stability, evaporation, corrosion, and the residence time needed

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for maturation. Consequently, temperature should be optimized together with phase identity, particle-size distribution, filtration, and valuable-metal coprecipitation rather than treated as an isolated kinetic accelerator (Dutrizac & Jambor, 2000; Asimi et al., 2020; Buriti et al., 2025b).

pH and A-site cation availability control both iron removal and impurity capture. Raising pH generally increases ferric precipitation but can also increase Zn, In, Cu, or other metal losses, whereas inadequate K^+, Na^+, NH_4^+, or H_3O^+ availability can favor poorly crystalline ferric phases or incomplete jarosite formation. Sodium- and ammonium-based routes also differ in reagent cost, solution chemistry, residue composition, and downstream recycle implications, so the selected cation must be evaluated at circuit rather than batch scale (Asimi Neisiani et al., 2023; Sun et al., 2025).

Seed loading, neutralant-addition rate, mixing intensity, and residence time determine supersaturation history and crystal maturation. Seeding can shorten induction and improve filterability, but recycled solids may also return impurities and alter nucleation. Rapid neutralant addition can create local high-pH zones and amorphous precipitates, whereas insufficient agitation can broaden residence-time and supersaturation distributions. Longer residence time may improve crystallinity while increasing reactor volume, metal capture, and operating cost (Asimi et al., 2020; Buriti et al., 2025b).

Operational optimization should therefore be multi-objective. Iron removal, valuable-metal retention, filterability, neutralant consumption, particle-size distribution, residue leachability, water use, and recycle compatibility should be evaluated together. Studies reporting only final dissolved iron cannot determine whether the precipitation step improved the overall process, because an apparent gain in Fe removal may be offset by increased metal loss, poor filtration, higher residue mass, or more difficult sulfate management.

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These coupled responses define the practical operating window and should be reported together when jarosite precipitation is compared with alternative iron-removal routes.

4.3. Comparison with Alternative Iron-Removal Routes

The baseline for jarosite treatment is not limited to disposal of the existing filter cake. In some cases, the key decision is whether to reduce or avoid jarosite formation through controlled ferric precipitation using goethite, hematite, magnetite, or other methods. These alternatives differ in temperature, pressure, acidity, zinc loss, filtration, residue volume, recycle potential, and capital costs. Table 5 offers a qualitative comparison; route choice depends on liquor chemistry, plant configuration, product needs, and environmental factors (Dutrizac & Jambor, 2000; Höber & Steinlechner, 2021; Qin et al., 2020; Xing et al., 2024; X. Zhou et al., 2024).

Table 5. Qualitative comparison of jarosite and alternative iron-removal routes

Route	Typical operating basis	Fe removal and selectivity	Solid handling and residue stability	Acid, sulfate, and recycle implications	Industrial maturity
Jarosite	Atmospheric; typically elevated temperature in acidic sulfate media	High Fe removal with good crystallinity; co-precipitation depends on pH, seed, and A-site cation	Generally filterable but creates high residue mass and captures sulfate/alkali and valuable metals	Generates acidity; mature recycle options for seed and some liquor, but residue treatment remains necessary	High; long-established in zinc hydrometallurgy

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Route	Typical operating basis	Fe removal and selectivity	Solid handling and residue stability	Acid, sulfate, and recycle implications	Industrial maturity
Goethite / paragoethite	Atmospheric; controlled oxidation and neutralization at moderate-to-high temperature	Can reduce alkali/sulfate incorporation; Zn and impurity losses depend strongly on pH and Fe addition	Residue volume may be lower than jarosite, but filterability is sensitive to nucleation and aging	Acid/neutralant balance remains important; potential for seed control and lower sulfate inventory	High to moderate, depending on circuit
Hematite	Pressure/hydrothermal, commonly at substantially higher temperature	Produces dense, high-Fe solids with comparatively low residue volume and potentially lower Zn loss	Usually dense and filterable; requires pressure equipment and corrosion-resistant materials	Lower sulfate incorporation in product but high energy and capital demand; heat integration is decisive	Industrial in selected zinc circuits
Magnetite or alternative ferric phases	Controlled redox, hydrothermal, electrochemical, or precipitation routes	Potentially produces recyclable Fe product and reduces waste mass	Product quality can be attractive, but redox control and impurity partitioning are complex	May enable iron recycle or direct product use; reagent and energy demands remain route-specific	Emerging to moderate

Note. Author-developed conceptual screening tool based on Dutrizac and Jambor (2000), Höber and Steinlechner (2021), Qin et al. (2020), Xing et al. (2024), and X. Zhou et al. (2024). Operating windows are qualitative and should not be treated as universal design values or as a process-design comparison.

Table 5 should be used only to identify comparison variables and data gaps. A defensible industrial comparison should report, at minimum, Fe-removal efficiency, Zn and valuable-metal losses, sulfate capture or release, dry residue mass per tonne of feed,

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filtration rate and cake moisture, neutralant consumption, energy demand, reagent recycle, and site-specific capital and operating implications.

4.4. Composition and Heterogeneity of Jarosite-Rich Industrial Residues

Jarosite-rich industrial residues commonly contain major amounts of Fe and sulfate, along with variable amounts of Zn, Pb, Cu, Ag, In, As, Cd, Ca, Si, alkali ions, soluble salts, and moisture. Their composition depends on the mineralogy of the concentrate, roasting, leaching, iron-removal strategy, seed recycle, washing efficiency, and sampling position. Environmental and physicochemical assessments confirm that nominally similar residues can differ markedly in phase inventory, mobility, and toxicity (M. Chen et al., 2025; Huang et al., 2024; Peng, Liu, et al., 2023; R. Wang et al., 2020).

A defensible characterization must distinguish between dry-solid and as-received wet-cake compositions and separately quantify moisture, soluble salts, and wash history. Mass-balance calculations should reconcile feed solution, neutralant, seed, precipitate, filtrate, and wash liquor. Without this information, apparent enrichment or recovery may reflect removal of water, sulfate, or entrained solution rather than true liberation from the solid matrix (Ahamed et al., 2021; Höber & Steinlechner, 2021; Singh et al., 2023).

A functional classification of residue components by their likely occurrence and treatment relevance provides a framework applicable to any site-specific sample.

This functional classification helps determine whether a treatment should target the jarosite lattice, accessory phases, or entrained solution. It also prevents circular-economy claims based solely on bulk Fe content: a nominally iron-rich residue may still be unsuitable for pigment, cement, or ironmaking applications because of sulfur, alkali, lead, zinc, arsenic, or fine-particle constraints.

The relevant functional categories are matrix phases, discrete valuable-metal phases, reactive Fe phases, gangue, and pore solution.

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5. Dissolution, Detoxification, and Recovery of Valuable Metals

5.1. Acidic and Complexing Leaching

Acidic leaching is inherently challenging because jarosite forms and persists in sulfate media. Higher acidity and temperature can accelerate dissolution but also increase corrosion, reagent consumption, and the amount of dissolved iron that must be separated. Thiourea, oxalate, cyanide, and non-cyanide lixiviants have been investigated to extract silver or mitigate ferric-ion effects, while kinetic studies show that particle population and reagent stability strongly influence apparent performance (Buriti et al., 2025a; Calla-Choque & Lapidus, 2020, 2021; Dávila-Pulido et al., 2025; Islas et al., 2020, 2021; Nolasco et al., 2025).

Calla-Choque and Lapidus (2020) demonstrated that an acidic thiourea–oxalate system could decompose an industrial jarosite and release silver. The reported response depended strongly on temperature, solids loading, and the oxalate inventory required to complex the released Fe and Cu. The study therefore provides proof of selective, complexant-assisted leaching and shows why high recovery at low pulp density cannot be directly extrapolated to an industrial slurry.

The subsequent multiparticle kinetic study clarified that particle-size distribution must be represented rather than replaced by a single ideal radius (Calla-Choque & Lapidus, 2021). Nolasco et al. (2025) extended thiourea leaching to industrial jarosite and identified a surface-reaction contribution under the conditions examined. Islas et al. (2021) compared cyanide and non-cyanide systems, and Dávila-Pulido et al. (2025) examined alkaline decomposition and cyanidation. Together, these studies support staged pretreatment and leaching, but do not eliminate the need for reagent recycling and downstream silver recovery design.

The central design challenge is selectivity. Complete iron dissolution may liberate valuable metals but produces a large Fe- and sulfate-rich liquor. Practical routes must specify the subsequent separation of Ag, In, Zn, Pb, and Cu; the regeneration or destruction of complexants and acids; and the fate of iron and sulfate. Hydrometallurgical utilization, indium recovery, solvometallurgical extraction, and integrated multi-metal

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flowsheets demonstrate several possible sequences, but extraction alone remains an intermediate result rather than a process outcome (Ahamed et al., 2021; De-la-Cruz-Moreno et al., 2021; Kushwaha & Agarwal, 2024; Q. Zhou et al., 2025).

5.2. Reductive Dissolution

Reductive dissolution destabilizes jarosite by converting structural Fe(III) to Fe(II). Ferrous iron, inorganic sulfur compounds, electron shuttles, sulfate-reducing bacteria, iron-reducing microorganisms, and biological–acid pathways have all been examined. These studies show that reduction can accelerate lattice breakdown and metal release, but phosphate, Pb substitution, electron-transfer limitations, secondary precipitation, and redox control can substantially alter the outcome (H.-R. Chen et al., 2022; K. Chen et al., 2021; Fang et al., 2025; Gao et al., 2020, 2021; González et al., 2020; Singh et al., 2025; Yang et al., 2020; Zhang et al., 2025).

5.3. Alkaline and Electrochemical Treatment

Alkaline treatment can decompose jarosite, release sulfate, and generate Fe-rich transformed solids. NaOH-based decomposition of ammonium–sodium arsenic jarosite, suspension electrolysis in an alkaline electrolyte, and thermally modified jarosite adsorbents demonstrate the diversity of alkaline objectives. The route must nevertheless be judged by caustic consumption, sulfate management, impurity partitioning, and product purity rather than solely by the disappearance of jarosite reflections (Ahamed et al., 2021; Flores et al., 2022; Picazo-Rodríguez et al., 2022; Qin & Haarberg, 2022).

5.4. Hydrothermal and Thermal Conversion

Hydrothermal and thermal treatments can convert jarosite into hematite, magnetite, pyrrhotite, reduced iron, or other Fe-rich products. Recent work includes cement-kiln roasting, $Ca(OH)_2$ leaching followed by biomass magnetization, biochar reduction, hydrothermal crystallization, detailed thermal decomposition, toxic-element tracking, and NaCl-assisted phase transformation (Ge et al., 2023, 2024, 2025; Kamberović et al., 2023; Lu et al., 2023; Olcay et al., 2025; X. Peng et al., 2024; Xing et al., 2024; Zeng et al., 2023).

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Additional pyrometallurgical studies encompass CaO–SiO_2–CaSi treatment, Pb–Ag recovery, self-reducing briquetting, chloride volatilization, non-fossil reductants, and comprehensive reduction–recycling schemes. These routes can concentrate metals or produce metallurgical feedstocks, but they require explicit control of SOx, volatile Pb/As/Cd species, dust, refractory demand, and the specification of every solid product (Jiménez-Lugos et al., 2024a, 2024b; Kamberović et al., 2021; Mombelli et al., 2021; Rämä et al., 2023; Sanchez Vite et al., 2025; H. B. Wang et al., 2020; Y. Wang et al., 2020; Xu et al., 2021; S. Zhou et al., 2024; Zulhan et al., 2023).

5.5. Biological Treatment

Biological routes include reductive dissolution, bioleaching, biomineralization, and biologically mediated transformation. They may operate under milder conditions but are generally slower and sensitive to pulp density, toxicity, nutrients, gas transfer, and passivation. Studies using biogenic jarosite, electron shuttles, sulfur-oxidizing or sulfate-reducing microorganisms, and iron-reducing bacteria demonstrate mechanistic potential and show that secondary minerals and associated oxyanions control mobility and recovery (Fang et al., 2025; Gao et al., 2020, 2021; González et al., 2020; Lee et al., 2025; Oladipo & Ojumu, 2023; Ortiz-Castillo et al., 2021; Singh et al., 2025; Yang et al., 2020; Zhang et al., 2025).

Figure 5 compares the principal routes proposed to destabilize jarosite-rich residues and highlights the process streams and operational constraints for each alternative. Acid, alkaline, thermal, and biological treatments differ substantially in reagent and utility requirements, phase transformations, metal-recovery opportunities, and downstream handling needs. The figure therefore places route selection in a plant-wide context, emphasizing the importance of integrating residue treatment with existing water, gas, and solid–liquid separation and recycle systems.

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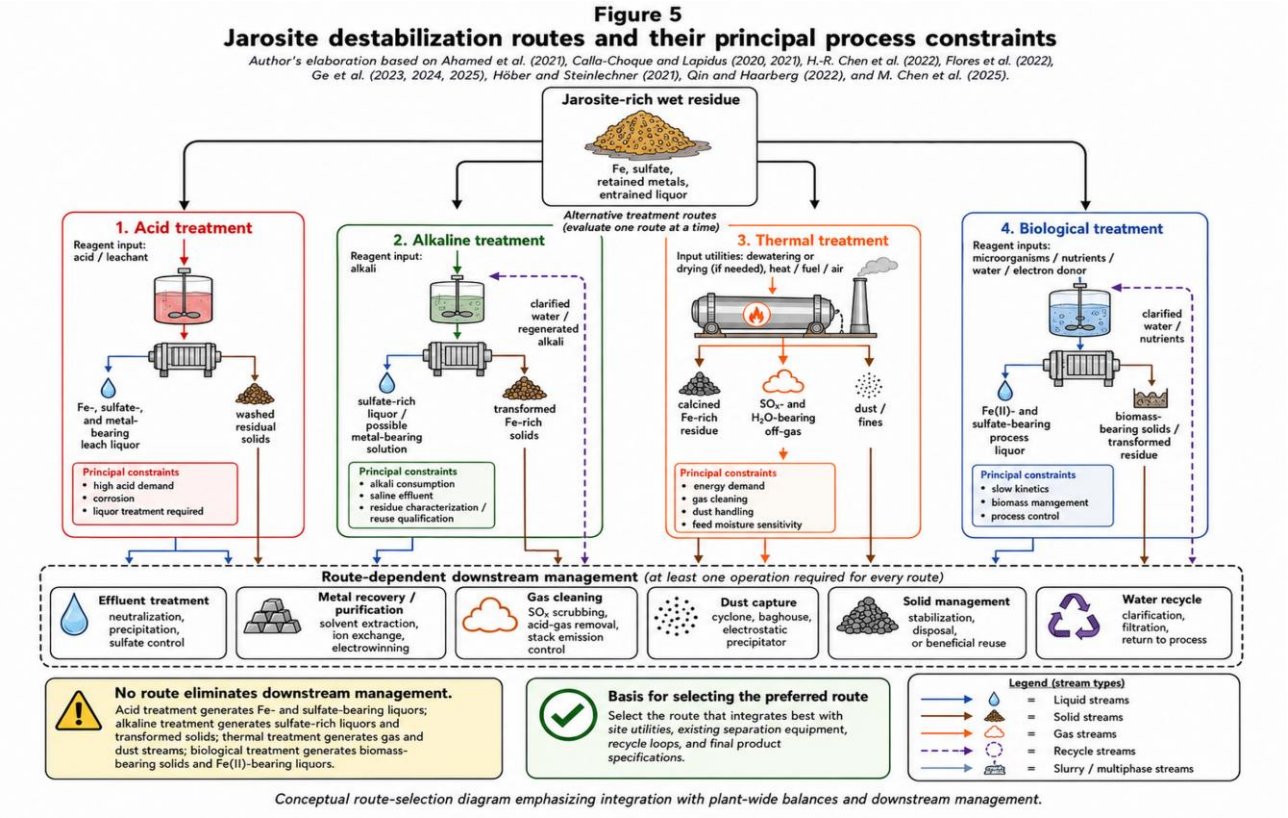

Figure 5. Jarosite destabilization routes and their principal process constraints. Author's elaboration based on Ahamed et al. (2021), Calla-Choque and Lapidus (2020, 2021), H.-R. Chen et al. (2022), Flores et al. (2022), Ge et al. (2023, 2024, 2025), Höber and Steinlechner (2021), Qin and Haarberg (2022), and M. Chen et al. (2025).

Figure 5 shows that no route eliminates the need for downstream management. Acid treatment produces Fe- and sulfate-bearing liquors; alkaline treatment produces sulfate-rich solutions and transformed solids; thermal treatment produces gas and dust streams; and biological treatment produces biomass-bearing solids, transformed residues, and Fe(II)-bearing liquors. The preferred route is therefore the one that integrates most effectively with site utilities, existing separation equipment, and final product specifications.

5.6. Comparative Evidence and Route-Level Confidence

The main comparison separates primary experimental evidence from prior reviews. Table 6 summarizes the dominant evidence classes, typical evidence, confidence levels,

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and principal limitations. The counts reflect one dominant-topic code per reference and are not a substitute for full-text quality scores.

Table 6. Route-level evidence support, limitations, and single-reviewer-assessed confidence

Evidence class (records; reviewer-assessed confidence)	Evidence supporting confidence	Evidence limiting confidence	Minimum evidence needed to upgrade confidence
Formation / precipitation (n = 12; moderate to high)	Industrial operating evidence, controlled kinetic studies, and convergent chemistry–mineralogy relationships.	Liquor, seed, cation, hydrodynamic, and impurity effects are strongly site-specific.	Multi-site continuous campaigns reporting Fe removal, valuable-metal loss, filterability, residue mass, and full acid/sulfate balance.
Hydrometallurgical recovery (n = 23; moderate)	Numerous real-residue studies and diverse acidic, complexing, alkaline, chlorination, and staged flowsheets.	Reagent regeneration, sulfate closure, solid–liquid separation, and sustained operation are usually incomplete.	Integrated recycle campaigns with closed multi-element balances, product recovery, effluent treatment, and realistic pulp density.
Reductive / biological (n = 9; low to moderate)	Credible mechanistic evidence for Fe(III) reduction, lattice destabilization, and associated contaminant redistribution.	Low rates, toxicity, carbon/electron-donor demand, pulp-density constraints, and scale-up uncertainty.	Continuous or semicontinuous tests on industrial residues with kinetics, microbial resilience, recycle, and secondary-phase control.
Hydrothermal / thermal (n = 19; moderate)	Repeated demonstration of conversion to hematite, magnetite, pyrrhotite, reduced iron, or alloy products.	Energy, SOx, volatile metals, dust capture, impurity removal, and product qualification are often incomplete.	Pilot heat and gas balances, quantified emissions/capture, consistent product specification, and integration with downstream users.
Environmental behavior (n = 17; moderate to high for mechanisms; moderate for industrial transfer)	Strong pH/redox, spectroscopic, mineral-transformation, toxicity, and field-oriented evidence.	Synthetic and natural systems do not always represent heterogeneous industrial filter cakes or engineered products.	Scenario-based aging of representative industrial residues and products with mineralogical tracking and exposure-specific tests.
Product / material reuse (n = 5;	Promising performance for adsorbents,	Small evidence base, variable feed, limited	Recognized specification testing,

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Evidence class (records; reviewer-assessed confidence)	Evidence supporting confidence	Evidence limiting confidence	Minimum evidence needed to upgrade confidence
exploratory to moderate)	concrete, whiskers, and electrochemical or functional materials.	durability, end-of-life testing, market scale, and displacement evidence.	long-term service and end-of-life performance, customer qualification, and realistic market-volume analysis.
System assessment (n = 1; low)	Demonstrates the importance of system boundaries, resource efficiency, and baseline comparison.	Too few comparable TEA/LCA datasets for route-level generalization.	Multiple site-specific TEA–LCA studies using common boundaries, uncertainty analysis, qualified products, and actual recycle data.

Note. Author's synthesis from the verified evidence classifications and reconstructed inventory. Six prior reviews and three foundational or methodological sources are not included in the seven primary-route rows. Confidence levels are single-reviewer-assessed qualitative judgments, not inter-rater consensus scores.

5.7. Metal-Specific Recovery Considerations

Silver may be structurally incorporated, occluded, or associated with Pb-bearing phases. Thiourea can achieve high dissolution under specific acidic conditions, but ferric iron accelerates reagent degradation and increases the demand for complexants. Oxalate can mitigate Fe-related effects, while alkaline decomposition, cyanide or non-cyanide leaching, and thermal pretreatment offer alternative routes for liberation. A credible silver flowsheet must therefore include redox control, reagent accounting, solid-loading optimization, and a defined recovery step (Calla-Choque & Lapidus, 2020, 2021; Dávila-Pulido et al., 2025; Islas et al., 2021; Jiménez-Lugos et al., 2024b; Nolasco et al., 2025; Picazo-Rodríguez et al., 2023).

Indium is attractive because jarosite-rich industrial residues can concentrate a critical metal from zinc circuits. Hydrometallurgical recovery, roasting–water-leaching sequences, and lead-jarosite precipitation studies indicate that In deportment is linked to both jarosite formation and subsequent phase conversion. The industrial value of these routes depends on feed-grade variability, the concentration of In in the product liquor, impurity control, losses from volatilization or coprecipitation, and the quality of the

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remaining Fe-rich solid (De-la-Cruz-Moreno et al., 2021; Dong et al., 2025; Janošević et al., 2023; Sun et al., 2025; Q. Zhou et al., 2025).

Zn, Cu, Pb, and Ag may occur as soluble salts, in substitutional sites, in anglesite, as sulfides, oxides, or in discrete inclusions. Early washing or mild leaching can recover soluble fractions, whereas structurally bound and phase-hosted metals may require roasting, chlorination, hydrothermal conversion, or staged hydrometallurgy. Pb and Ag must be evaluated together because thermal and chloridizing conditions can produce volatile, soluble, or alloy products (Conić et al., 2024; Höber et al., 2022; Jiménez-Lugos et al., 2024a, 2024b; Kamberović et al., 2021; Sanchez Vite et al., 2025; Shi, Min, Tian, et al., 2022; Shi, Min, Zhang, et al., 2023; Steinlechner & Höber, 2022; Steinlechner & Witt, 2023; H. B. Wang et al., 2020; Zeng et al., 2023).

Iron is the dominant mass component and therefore governs the flowsheet. Conversion routes have produced or targeted hematite, magnetite, reduced iron, pyrrhotite, briquettes, and electrochemically recoverable iron. Product claims must be supported by specifications for sulfur, alkali, Zn, Pb, As, phase, particle size, color, reducibility, and mechanical properties appropriate to the intended market (Ge et al., 2023, 2024, 2025; Lu et al., 2023; Mombelli et al., 2021; Qin & Haarberg, 2022; Rämä et al., 2023; Thibault et al., 2020; R. Wang et al., 2025; Y. Wang et al., 2020; Xing et al., 2024; Xu et al., 2021; S. Zhou et al., 2024; Zulhan et al., 2023).

6. Environmental Behavior and Risk

6.1. Jarosite as Both a Sink and a Source

Jarosite can attenuate dissolved contaminants by incorporating or sorbing them during precipitation, and this function may be beneficial while the phase remains stable. However, pH, redox potential, ionic strength, organic matter, microbial activity, and mineralogical transformation can release sulfate, acidity, Fe, and trace elements. Laboratory toxicity and field-oriented assessments therefore describe jarosite as both a contaminant sink and a potential delayed source (Burton et al., 2021; Huang et al., 2024; Peng, He, et al., 2023; Peng, Liu, et al., 2023; R. Wang et al., 2020).

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Oxyanion-bearing jarosites do not share one transformation pathway. Ryu and Kim (2022) showed that pH and oxyanion identity strongly influenced dissolution and conversion, while Al substitution and soil aging altered the rates and products of Fe(II)-mediated transformation (Grigg, Notini, et al., 2024; Grigg, Wisawapipat, et al., 2024). Studies of arsenic-bearing jarosite further show that oxalic or gallic acid can redistribute As during redox-driven transformation (Jin, Li, et al., 2020; Tang et al., 2020).

Industrial-residue assessment should combine standardized short-term tests with scenario-based aging. Various processes like carbonation, wet–dry and freeze–thaw cycling, reducing burial, organic ligands, microbial reduction, abrasion, and saline or acidic exposure can produce release patterns that single compliance extraction might miss. Studies on reductive dissolution, organic-matter effects, simulated remediation, and mixed-oxyanion systems show that temporary readsorption or reprecipitation can mask longer-term mobility (Gao et al., 2021; Jin, Huang, et al., 2023; Jin, Guo, Huang, et al., 2024; Kölbl et al., 2021; Lee et al., 2025; Trueman et al., 2020; Zhang et al., 2025).

Table 7 summarizes the principal environmental controls and the evidence required to support a claim of detoxification or safe reuse.

Table 7. Environmental controls governing jarosite stability and contaminant release

Control	Expected effect	Risk pathway	Evidence needed	Interpretive limitation
pH	Acidic conditions may preserve jarosite; neutral/alkaline conditions may transform it.	Release of sulfate, Fe, and substituted/adsorbed contaminants.	pH-dependent leaching and mineralogy after testing.	One short-term regulatory leaching test cannot represent all disposal or reuse conditions.
Redox potential	Reduction of Fe(III) destabilizes the lattice.	Mobilization of As, Pb, Sb, or other associated elements.	Controlled redox experiments and Fe(II)/Fe(total) measurements.	Open-air batch tests may miss reducing field conditions.

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Control	Expected effect	Risk pathway	Evidence needed	Interpretive limitation
Mineralogical transformation	Jarosite can convert to goethite, hematite, or amorphous phases.	Contaminants may be released, readsorbed, or re-encapsulated.	Time-resolved XRD, spectroscopy, and solution analysis.	Lower dissolved concentration may reflect temporary readsorption.
Aging and weathering	Carbonation, wet–dry cycling, freeze–thaw, and abrasion alter reactivity.	Cracking of stabilized products and renewed leaching.	Accelerated aging plus post-aging performance tests.	Short curing periods overstate long-term stability.
Particle size and dust	Fine dry residues are dispersible and reactive.	Inhalable dust and off-site transport.	Dustiness, particle-size, and handling controls.	Chemical stabilization does not automatically control dust.
Secondary streams	Leachate, wash water, filter cake, gas-cleaning dust, and spent adsorbent.	Transfer of pollution to another phase.	Complete stream inventory and hazardous-property testing.	Detoxification of the original cake is insufficient if new wastes are created.

Note. Author's elaboration based on Burton et al. (2021), Gao et al. (2021), Grigg, Notini, et al. (2024), Grigg, Wisawapipat, et al. (2024), Huang et al. (2024), Jin, Huang, et al. (2023), Jin, Guo, Huang, et al. (2024), Kölbl et al. (2021), Lee et al. (2025), Ryu and Kim (2022), Tang et al. (2020), Trueman et al. (2020), and Zhang et al. (2025).

The table reinforces a central conclusion: detoxification is a performance claim, not a treatment label. Neutralization, roasting, encapsulation, or adsorption may reduce one leachable fraction while increasing another risk, such as dust, sulfate-rich effluent, or volatile-metal capture dust. A complete environmental assessment must follow all elements through the treatment system and evaluate the final products under realistic aging conditions.

Because environmental performance depends on the management scenario, Table 8 separates the principal exposure pathways and minimum tests for storage, treatment, reuse, and product routes.

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Table 8. Scenario-specific environmental-risk matrix for jarosite-rich residues and derived products

Scenario	Dominant exposure or transfer pathways	Principal concerns	Minimum evidence and tests	Decision boundary
Storage or disposal	Seepage, acidic drainage, reducing burial, wet–dry weathering, windblown fines.	Sulfate/acidity release; As, Pb, Zn, Cd, or Sb mobility; dust; long-term phase change.	Representative sampling; pH-dependent and redox leaching; column/percolation testing; dustiness; mineralogy before and after aging.	Site-specific disposal classification and containment/closure design.
Hydrometallurgical treatment	Leach liquors, wash waters, bleed streams, neutralization solids, spent reagents.	Transfer of contaminants to solution or secondary precipitates; high sulfate and reagent load.	Complete liquid/solid balance; speciation; recycle and purge tests; effluent treatability; secondary-solid leaching and aging.	The original cake is not detoxified unless all secondary streams have controlled destinations.
Thermal or hydrothermal treatment	SOx, steam, volatile Pb/As/Cd species, dust, gas-cleaning residues, transformed solids.	Air emissions, volatile-metal capture, residual sulfur, off-specification Fe product.	Mass and energy balance; off-gas composition; capture efficiency; dust characterization; product leaching; post-treatment phase analysis.	Conversion is acceptable only with quantified gas cleaning and qualified solid products.
Construction or geotechnical reuse	Service-water contact, carbonation, cracking, abrasion, demolition, end-of-life crushing.	Distributed long-term release, expansion, efflorescence, sulfate attack, contaminated fines.	Strength/soundness; wet–dry and freeze–thaw; carbonation; abrasion; leaching before and after damage; demolition scenario.	Mechanical performance and environmental durability must both meet the applicable product/use requirements.
Adsorbent or reactive-media use	Contact with real waters, competing ions, regeneration liquor, spent	Breakthrough, desorption, contaminant remobilization, spent-media liability.	Column breakthrough; competition; regeneration cycles; attrition; spent-media leaching and	Use is circular only when spent media and regeneration streams are safer and controllable.

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Scenario	Dominant exposure or transfer pathways	Principal concerns	Minimum evidence and tests	Decision boundary
	media disposal.		aging; mass balance of captured contaminants.	
Metallurgical, pigment, or functional-product use	Handling dust, process emissions, impurity transfer to slag/off-gas, service and end-of-life exposure.	Deleterious impurities, inconsistent product, emissions displaced downstream.	Product specification; dust/emission assessment; downstream process trial; impurity deportment; end-of-life route.	A saleable name is insufficient; the product must be accepted against a real specification and use case.

Note. Author-developed scenario matrix based on the environmental mechanisms and process evidence synthesized in Section 6. The matrix is a decision tool rather than a universal regulatory protocol; jurisdiction-specific methods and acceptance criteria remain controlling.

The matrix shows why one test cannot support all management claims. Disposal requires field-relevant seepage and redox evidence; hydrometallurgical and thermal routes require complete secondary-stream accounting; and product uses require service and end-of-life testing in addition to initial chemical compliance.

6.2. Regulatory Scope and Responsible Claims

Legal classification varies by jurisdiction, waste origin, composition, acidity, and test method, and is outside this review's scope. The manuscript does not universally classify jarosite-rich residues as hazardous or inert. Conclusions are limited to tested material and scenario, and compliance relies on official waste code, sampling, and leaching or reuse methods for the jurisdiction. Generic references to leaching tests are avoided since standardized methods and acceptance criteria differ.

Terms like harmless, detoxified, inert, green, and near-zero waste are considered performance claims. A residue might pass short-term tests but become unstable during processing; metals may be recovered while producing sulfate-rich effluent or dust; and a material might have useful strength or adsorption capacity but lack long-term stability or a credible outlet. Responsible claims need defined boundaries, quantified streams,

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realistic aging, and baseline comparison (M. Chen et al., 2025; Cruz-Hernández et al., 2025; Pandiyan & Solaiyan, 2024; Singh et al., 2023).

7. Circular Valorization and Waste-to-Product Routes

7.1. Iron Oxides, Pigments, and Metallurgical Feedstocks

Conversion of jarosite to hematite, magnetite, reduced iron, or related Fe-rich products is attractive because iron dominates the residue mass. Hydrothermal, oxidizing, reducing, biomass-assisted, and integrated pyrometallurgical routes have been investigated, with markedly different implications for energy, sulfur capture, volatilization, and impurity control (Ge et al., 2023, 2024, 2025; Lu et al., 2023; Mombelli et al., 2021; Rämä et al., 2023; Thibault et al., 2020; Y. Wang et al., 2020; Xing et al., 2024; S. Zhou et al., 2024; Zulhan et al., 2023).

The target product determines the required purification and qualification. Pigments require controlled color, morphology, particle size, and low soluble salt content; ironmaking feeds require Fe grade, low deleterious elements, strength, and predictable reduction; calcium sulfate whiskers and electrochemical materials require even more specific phase and structural control. A route should not be described as high-value utilization until the product is evaluated against a recognized specification and a credible market volume (Ge et al., 2025; Pandiyan & Solaiyan, 2024; Tan et al., 2021; W. Xu et al., 2025).

7.2. Adsorbents and Environmental Functional Materials

Jarosite and jarosite-derived iron materials can adsorb or immobilize arsenic, chromium, phosphate, and other species through reactive Fe–OH groups, structural substitution, and coprecipitation. Industrial jarosite waste, thermally modified jarosite, Pb-substituted natrojarosite, and synthetic jarosite systems have all shown adsorption or immobilization potential (Cruz-Hernández et al., 2025; Hu et al., 2025; Karimian et al., 2023; Picazo-Rodríguez et al., 2022; Sowers et al., 2023).

A complete adsorption assessment includes concentration ranges, competing ions, pH, kinetics, column behavior, regeneration, stability, and leaching. Using hazardous residue for water treatment is circular if the spent material is more manageable

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and contaminants remain controlled during use and disposal (Cruz-Hernández et al., 2025; Hu et al., 2025; Peng, He, et al., 2023; Picazo-Rodríguez et al., 2022; Sowers et al., 2023).

7.3. Cementitious, Composite, Ceramic, and Geotechnical Uses

Jarosite residues are proposed for cementitious products, briquettes, calcium sulfate whiskers, composites, ceramics, roads, and stabilized materials. These methods may use more material than metal recovery but risk dispersing metals and sulfate across many products. Material performance must consider contaminant stability and recoverable metals' fate (Ahamed et al., 2021; Ge et al., 2023; Mombelli et al., 2021; Pandiyan & Solaiyan, 2024; Tan et al., 2021).

Mechanical performance alone is insufficient. Strength at early curing ages does not demonstrate resistance to sulfate attack, acid exposure, freeze–thaw, abrasion, fire, or end-of-life crushing. Residue addition can also affect setting, expansion, efflorescence, and corrosion through soluble salts and sulfate. Product-specific durability and leaching tests are therefore essential before bulk utilization is described as sustainable (Pandiyan & Solaiyan, 2024).

A defensible circular hierarchy prevents metal loss during precipitation, recovers valuable elements, converts the Fe-rich fraction into a qualified product, and stabilizes only the final non-recoverable fraction. Integrated processes and multi-metal flowsheets support this, as bulk incorporation can hinder recovery and disperse long-term liability (M. Chen et al., 2025; Höber & Steinlechner, 2021; Singh et al., 2023; Q. Zhou et al., 2025).

7.4. Operational Criteria for Near-Zero Waste

Near-zero waste is used here as a decision criterion and measurable system aspiration, not as an outcome established for most routes in the reviewed evidence. It is not demonstrated by disappearance of the original filter cake or by a single high recovery value. Table 9 proposes indicators that can be reported without imposing universal acceptance limits. Project-specific targets should be justified against feed variability, legal requirements, product specifications, market displacement, and a defined baseline such as secure stabilization and disposal or an alternative iron-removal flowsheet.

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Table 9. Author-developed operational indicators for evaluating near-zero-waste claims

Indicator	Calculation or reporting basis	Minimum evidence
Element closure	Reconcile Fe, sulfate/S, target metals, hazardous elements, and major reagents across all solids, liquors, washes, gases, and products	Report closure for each element; a 95–105% target range may be used as a diagnostic, with justified deviations
Secondary-residue intensity	Dry mass of all secondary solids and gas-cleaning dust per tonne of dry feed	Compare with untreated residue and alternative iron-removal baseline
Water recovery and recycle	Fresh water, wash water, evaporation, purge, and recycled water per tonne	Report net consumption and internal recycle percentage
Sulfate recovery or controlled disposition	Sulfate in product, recycle liquor, purge, gypsum/other solid, and gas phase	No unassigned sulfate stream; identify saleable, recyclable, or treated destination
Reagent intensity and regeneration	Net acid, alkali, reductant, complexant, chloride, and neutralant make-up	Report make-up after recycle, not only gross laboratory dose
Gaseous and dust emissions	SOx, CO_2, NH_3, volatile Pb/As/Cd species, and particulate capture	Quantify generation and treatment efficiency for thermal routes
Qualified product fraction	Mass converted into products meeting defined chemical, physical, and environmental specifications	Do not count off-specification material or experimental intermediates as product
Primary-material substitution	Actual quantity of primary iron, cementitious, adsorbent, or battery material displaced	Use market-compatible quality and realistic substitution ratio
Aging stability	Leaching and physical performance after pH/redox cycling, carbonation, wet–dry, freeze–thaw, abrasion, or service exposure	Report post-aging mineralogy and release, not only initial compliance
Economic and life-cycle advantage	Cost, revenue, energy, emissions, and avoided disposal versus a defined baseline	Use the same system boundary and recovery assumptions for TEA and LCA

Note. Author-developed decision criteria based on Abadías Llamas et al. (2020), Ahamed et al. (2021), Asimi Neisiani et al. (2023), M. Chen et al. (2025), Höber and Steinlechner (2021), Singh et al. (2023), and Q. Zhou et al. (2025). The suggested closure range is a diagnostic target rather than a universal regulatory threshold.

Table 10 maps the principal valorization and management classes to specification-driven qualification parameters. The examples are intentionally product-specific—such as Fe grade, sulfur, and deleterious elements for metallurgical products; color coordinates for pigments; strength and durability for construction products; column and regeneration

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performance for adsorbents; and cycling stability for electrochemical materials. Final acceptance values remain product-, customer-, and jurisdiction-specific.

Table 10. Author-developed product-qualification matrix for jarosite valorization routes

Product or management class	Illustrative outlet	Specification-driven qualification parameters	Environmental and end-of-life evidence	Principal barrier
Iron oxides, pigments, or metallurgical feed	Hematite, magnetite, pigment, sinter/pellet feed, reduced iron.	Fe grade and phase purity; total S/sulfate; Na/K; Zn, Pb, As, Cd, Cu; particle-size distribution; surface area; color L*a*b* for pigments; reducibility/metallization and strength for ironmaking.	Dustiness; off-gas and volatile-metal accounting; leaching after weathering; downstream slag/off-gas impurity deportment.	Energy and impurity removal; consistency with a recognized customer or internal specification.
Recovered metals, salts, or concentrates	Ag, In, Zn, Pb, Cu products or purified solutions.	Recovery and selectivity; grade/purity; target concentration; impurity envelope; downstream precipitation, crystallization, electrowinning, or refinery acceptance.	Full element and reagent balance; wash and bleed streams; residue and effluent testing; reagent recycle and purge.	Low grades, complex separation, secondary liquors, and uncertain product acceptance.
Adsorbent or reactive medium	As, Cr, phosphate, or mixed-contaminant treatment media.	Equilibrium capacity; selectivity; kinetics; hydraulic properties; column breakthrough; attrition; regeneration efficiency over repeated cycles.	Real-water competition; desorption; regeneration-liquor treatment; spent-media leaching, aging, and final disposal.	Capacity loss in real waters and end-of-life liability.
Cementitious or geotechnical product	Binder component, aggregate, brick, road material, or soil stabilizer.	Setting time; soundness/expansion; compressive and flexural strength at relevant ages; sulfate/chloride resistance; permeability; freeze–thaw and abrasion performance.	Leaching before and after carbonation, cracking, abrasion, and end-of-life crushing; dust and demolition management.	Sulfur and metal release, variable feed, and dispersed long-term liability.

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Product or management class	Illustrative outlet	Specification-driven qualification parameters	Environmental and end-of-life evidence	Principal barrier
Whisker, ceramic, polymer, or composite product	Calcium sulfate whisker, ceramic precursor, filler, pigment, or functional additive.	Phase purity; crystal morphology/aspect ratio; dispersion; interface compatibility; thermal and fire behavior; dimensional and mechanical performance.	Machining dust; leaching during service and disposal; recyclability of the host product.	Small market relative to residue generation and sensitivity to feed variability.
Electrochemical material	$FePO_4$-based cathode precursor or other functional iron material.	Crystallinity/phase; purity; conductivity; specific capacity; rate capability; coulombic efficiency; cycle life; batch consistency.	Impurity release during manufacture; electrolyte compatibility; end-of-life recovery or leaching.	High purification burden, stringent consistency, and small specialty-market scale.
Secure stabilization or disposal	Engineered monolith, conditioned residue, or lined storage.	Physical integrity; permeability; compressive strength where relevant; moisture and water balance; closure and monitoring criteria.	pH/redox-dependent leaching; long-term weathering; dust; seepage; post-closure stability.	Permanent liability, land use, and loss of recoverable resources.

Note. Author-developed qualification matrix based on Ahamed et al. (2021), M. Chen et al. (2025), Conić et al. (2024), Cruz-Hernández et al. (2025), Ge et al. (2023, 2024, 2025), Höber and Steinlechner (2021), Janošević et al. (2023), Mombelli et al. (2021), Pandiyan and Solaiyan (2024), Picazo-Rodríguez et al. (2022), Tan et al. (2021), and W. Xu et al. (2025). Parameters are illustrative; controlling values must come from the intended product specification and jurisdiction.

Table 10 shows that valorization is not equivalent to dilution into a product. The final material must perform a technically required function, satisfy a recognized customer or internal specification, remain environmentally stable through service and end of life, and be produced at a scale compatible with residue generation. Otherwise, the route is better described as experimental reuse than as established circularity.

Figure 6 integrates the technical and environmental gates to be examined before a jarosite route is considered circular. The framework begins with characterization because every subsequent decision depends on the actual mineral and impurity

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inventory. It is a proposed authorial decision framework, not evidence that the reviewed routes have already achieved circularity.

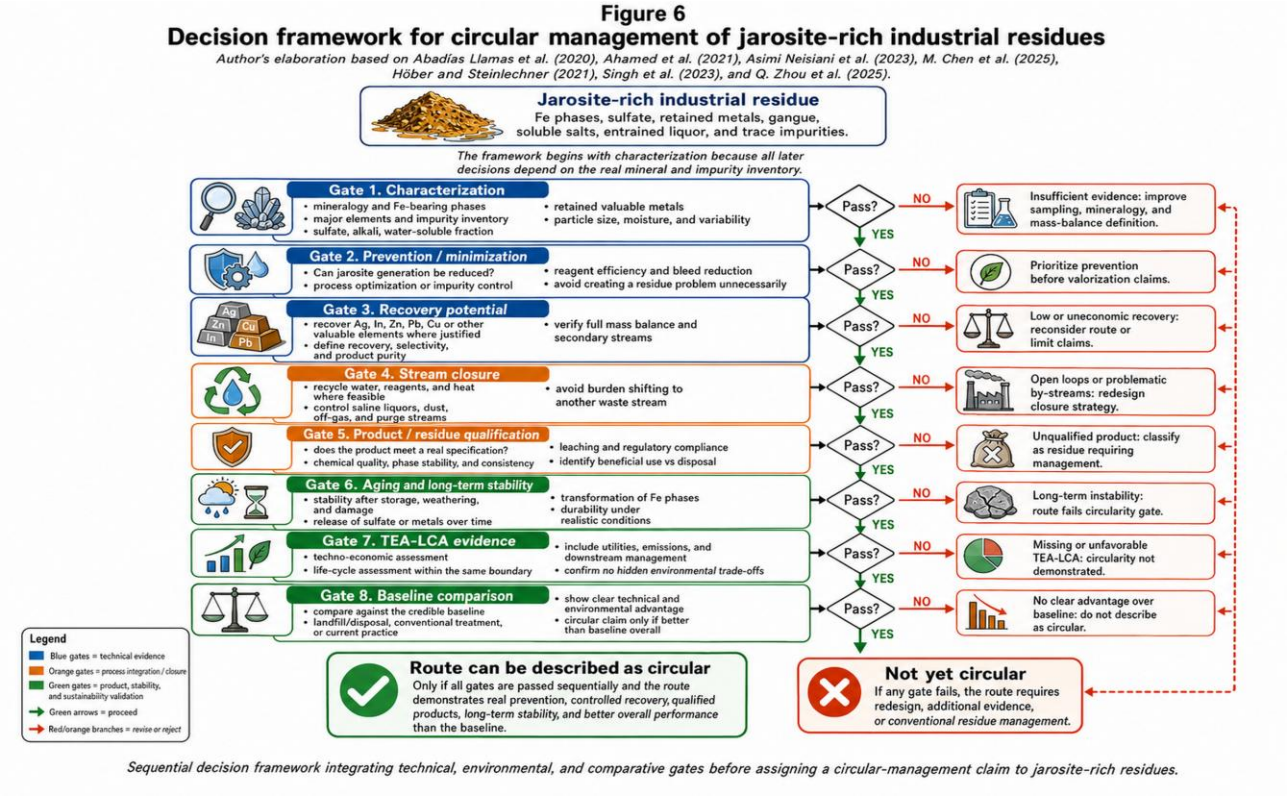

Figure 6. Author-developed decision framework for circular management of jarosite-rich industrial residues. Synthesis based on Abadías Llamas et al. (2020), Ahamed et al. (2021), Asimi Neisiani et al. (2023), M. Chen et al. (2025), Höber and Steinlechner (2021), Singh et al. (2023), and Q. Zhou et al. (2025). The figure is a proposed decision tool, not an extracted empirical result.

The framework treats near-zero waste as a system-level decision criterion. The original filter cake can disappear while its sulfate becomes wastewater, its metals become gas-cleaning dust, and its iron becomes an off-specification product. A circular claim is justified only when the complete material and energy flows are quantified, products are qualified, aging and end-of-life behavior are acceptable, and performance is superior to a realistic baseline. The available literature rarely demonstrates all of these conditions simultaneously.

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8. Critical Synthesis of Advances, Contradictions, and Scale-Up Gaps

8.1. What Advanced Most Clearly from 2020 to 2025

The clearest scientific advance is the recognition that jarosite reactivity depends on composition, particle population, solution chemistry, redox state, and transformation history rather than on pH or temperature alone. Recent studies compare kinetic models, represent multiparticle systems, quantify low- and moderate-temperature precipitation, and link substituted oxyanions or Al to distinct transformation pathways (Buriti et al., 2024, 2025a, 2025b; Calla-Choque & Lapidus, 2021; Grigg, Notini, et al., 2024; Islas et al., 2020; Ryu & Kim, 2022).

A second advance is the shift from single-step extraction to integrated sequences. Roasting followed by water leaching, selective precipitation, staged Cu–Zn–Pb–Ag recovery, hydrometallurgical In recovery, and comprehensive multi-metal separation demonstrate how phase conversion can create selectivity. The strongest studies follow element partitioning after each stage rather than reporting one final extraction value (Conić et al., 2024; De-la-Cruz-Moreno et al., 2021; Dong et al., 2025; Janošević et al., 2023; Kamberović et al., 2021; Sun et al., 2025; Y. Wang et al., 2020; Q. Zhou et al., 2025).

A third advance is the widening of the product concept. Research now includes reduced iron, hematite, briquettes, adsorbents, concrete, calcium sulfate whiskers, and electrochemical materials. This broadens potential outlets but also introduces product-quality, market-volume, and end-of-life requirements that are not captured by conventional extraction testing (Cruz-Hernández et al., 2025; Ge et al., 2025; Mombelli et al., 2021; Pandiyan & Solaiyan, 2024; Picazo-Rodríguez et al., 2022; Tan et al., 2021; W. Xu et al., 2025).

8.2. Why Published Results Diverge

Published results diverge because samples differ in A-site occupancy, substitutions, crystallinity, particle size, porosity, associated phases, wash history, and entrained liquor. Nominal pH does not capture sulfate activity, ionic strength, complexation, redox potential, or reagent depletion. Industrial precipitation, biogenic

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jarosite, synthetic kinetic powders, and real filter cakes therefore represent different reacting systems and should not be compared without explicit normalization (Asimi et al., 2020; Buriti et al., 2024, 2025a, 2025b; Grigg, Wisawapipat, et al., 2024; Oladipo & Ojumu, 2023; Peng, Liu, et al., 2023).

Analytical definitions create further divergence. Solution-based extraction can be biased by evaporation, sampling dilution, wash water, or reprecipitation; thermal studies may identify hematite without closing sulfur and volatile-metal balances; and leaching tests may not distinguish adsorption, precipitation, and structural incorporation. Kinetic, thermal, and toxicity studies illustrate the need to reconcile analytical response with mineralogical change and complete mass balance (Islas et al., 2020; Kamberović et al., 2023; Lu et al., 2023; Olcay et al., 2025; R. Wang et al., 2020).

8.3. Scale-Up, Economics, and Life-Cycle Evidence

Most treatment concepts remain below sustained pilot scale. Increasing vessel volume does not preserve mixing, heat transfer, reagent distribution, gas evolution, abrasion, filtration, or residence-time distribution. Fine cakes can blind filters, entrain valuable liquor, and create dust during drying. Industrial precipitation studies, economic comparisons, and processing reviews consistently show that hydrodynamics, solid–liquid separation, and feed variability can dominate viability even when bench chemistry is favorable (Asimi et al., 2020; Asimi Neisiani et al., 2023; M. Chen et al., 2025; Höber & Steinlechner, 2021; Singh et al., 2023).

Techno-economic and life-cycle assessment should use the same flowsheet boundary and include feed variability, reagent make-up and regeneration, energy source, corrosion-resistant equipment, washing, filtration, gas cleaning, wastewater treatment, product finishing, analytical quality control, storage, and discounted product revenue. Avoided primary production should be credited only when the recovered product meets a real specification and displaces a market product (Abadías Llamas et al., 2020; Asimi Neisiani et al., 2023; M. Chen et al., 2025; Höber & Steinlechner, 2021; Singh et al., 2023).

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Table 11 translates these observations into minimum evidence requirements for progressively higher technology-readiness levels.

Table 11. Author-developed minimum evidence gates for industrial implementation

Development stage	Minimum technical evidence	Minimum environmental evidence	Minimum economic evidence	Go/no-go question
Laboratory proof of concept	Representative feed characterization; controls; complete solid/liquid balance; reproducibility.	All secondary solids and liquors identified; preliminary leaching.	Reagent and energy inventory at test scale.	Is the observed response chemically real and selective?
Bench integrated flowsheet	Sequential separation; recycle tests; filtration and washing; product analysis.	pH/redox scenarios; preliminary aging; effluent treatment.	Equipment concept; reagent recycle; sensitivity to feed grade.	Does integration preserve the laboratory advantage?
Pilot continuous operation	Residence-time distribution; hydrodynamics; heat/mass transfer; campaign variability.	Continuous effluent, gas, dust, and product monitoring.	CAPEX/OPEX estimate with uncertainty and contingency.	Can the route operate reliably for a sustained campaign?
Demonstration/qualification	Product consistency; customer or internal-use qualification; maintenance data.	Long-duration aging and regulatory acceptance.	Contracted or credible market; comparison with disposal and alternatives.	Is there a durable business and compliance case?
Commercial decision	Site-integrated balances and operating procedures.	Closure, liability, and end-of-life plan.	Bankable economics and risk allocation.	Does the complete system create more value and lower risk than the baseline?

Note. Author-developed implementation gates based on Abadías Llamas et al. (2020), Asimi et al. (2020), Asimi Neisiani et al. (2023), M. Chen et al. (2025), Höber and Steinlechner (2021), Singh et al. (2023),

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and Y. Wang et al. (2020). These gates are proposed decision criteria, not empirical results extracted from a single study.

The go/no-go questions in Table 11 are deliberately conservative. They prevent a common progression error in which a high laboratory extraction is treated as evidence that only engineering scale-up remains. In many cases, the unresolved issue is not reactor size but chemical selectivity, secondary-stream treatment, or product quality.

9. Research Agenda for 2026 and Beyond

Future research should begin with representative sampling across operating campaigns, feed blends, seasons, and cake-washing conditions. Variability should be treated as an experimental factor rather than analytical noise. A minimum dataset should include moisture, soluble salts, bulk chemistry, quantitative mineralogy, particle-size distribution, surface area, microscopy, and phase-specific deportment of valuable and hazardous elements (Huang et al., 2024; Peng, Liu, et al., 2023; R. Wang et al., 2020).

Kinetic studies should report particle-size distributions, solids loading, hydrodynamic conditions, reagent depletion, solution speciation, and intermediate solids. Competing models should be evaluated through physically interpretable parameters, residual analysis, and validation outside the fitted range. For heterogeneous industrial residues, distributed-reactivity or population-based approaches may be more defensible than a single idealized shrinking-core model (Buriti et al., 2024, 2025a; Calla-Choque & Lapidus, 2021; Islas et al., 2020; Trueman et al., 2020).

Integrated flowsheets should be designed around element closure. Every test should track Fe, sulfate, water, acid or alkali, target metals, hazardous elements, and carbon- or sulfur-containing reagents. The objective function should combine recovery, selectivity, reagent intensity, filtration, product quality, and residue stability, with recycle explicitly tested rather than assumed (Ahamed et al., 2021; Ge et al., 2024; Y. Wang et al., 2020; Q. Zhou et al., 2025).

Environmental testing should progress from short compliance extractions to scenario-based aging under pH cycling, oxidizing and reducing conditions, organic ligands, carbonation, wet–dry and freeze–thaw cycles, abrasion, and realistic waters. For

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adsorbents and construction products, service conditions and end-of-life crushing should be included. Release functions should be linked to mineral transformations rather than reported as isolated pass/fail concentrations (Grigg, Wisawapipat, et al., 2024; Jin, Li, et al., 2020; Jin, Huang, et al., 2023; Jin, Guo, Huang, et al., 2024; Kölbl et al., 2021; Lee et al., 2025; Ryu & Kim, 2022; Tang et al., 2020; Zhang et al., 2025).

Pilot programs should include at least one sustained continuous campaign with recycle. Batch repetition is not equivalent because sulfate, alkali, organics, fine solids, and impurities can accumulate. Pilot data should quantify uptime, scaling, corrosion, gas transfer, filtration cycle, wash ratio, product variability, and off-gas or effluent treatment (Asimi et al., 2020; Oladipo & Ojumu, 2023; Z. Wang et al., 2021).

Finally, techno-economic and life-cycle studies should be performed together using the same recovery assumptions, utilities, product specifications, and system boundary. Sensitivity analysis should include metal prices, residue grade, reagent recovery, energy source, carbon intensity, product discount, disposal cost, and environmental liability. This integration is necessary to distinguish genuine circularity from costly transfer of contaminants between phases (Abadías Llamas et al., 2020; Asimi Neisiani et al., 2023; M. Chen et al., 2025; Höber & Steinlechner, 2021; Singh et al., 2023).

Table 12 prioritizes the principal research gaps and proposes measurable outputs. These outputs are framed for inclusion in research proposals, pilot test plans, or decision protocols.

Table 12. Author-developed research priorities and measurable decision outputs

Priority gap	Recommended study	Minimum measurable output	Decision enabled
Feed variability	Multi-campaign sampling and mineralogical deportment.	Variability envelope for phases, soluble salts, and target metals.	Whether one flowsheet can treat the full residue population.
Mechanistic kinetics	Time-resolved dissolution/transformation with competing models.	Validated rate expression linked to mineralogical change and solids loading.	Reactor concept and residence-time basis.

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Priority gap	Recommended study	Minimum measurable output	Decision enabled
Selective separation	Integrated recovery of Ag/In/Zn/Pb/Cu with Fe and sulfate control.	Product purity, recovery, reagent recycle, and complete element balance.	Whether valuable-metal revenue can support treatment.
Solid–liquid separation	Filtration, washing, thickening, and rheology at realistic pulp density.	Cycle time, cake moisture, wash efficiency, filtrate clarity, power demand.	Equipment sizing and water balance.
Product qualification	Target-specific testing of oxide, adsorbent, cement, composite, or iron feed.	Compliance with recognized performance and impurity specifications.	Whether a real market or internal use exists.
Long-term stability	Accelerated and scenario-based aging with mineralogical tracking.	Release functions after carbonation, redox cycling, abrasion, and weathering.	Environmental acceptance and liability.
System sustainability	Integrated TEA and LCA with uncertainty.	Cost, energy, water, emissions, avoided burden, and sensitivity ranges.	Whether the route outperforms disposal and alternative iron removal.

Note. Author-developed research agenda based on Abadías Llamas et al. (2020), Aromataris and Munn (2020), Buriti et al. (2024, 2025a, 2025b), M. Chen et al. (2025), Höber and Steinlechner (2021), Page et al. (2021), and Singh et al. (2023). The outputs are proposed decision-oriented reporting targets.

The decision-oriented structure of Table 12 is important. Research should be designed to reduce a specific uncertainty—feed compatibility, reactor basis, separation viability, equipment sizing, market acceptance, environmental stability, or overall sustainability. Additional characterization that does not change a decision may be scientifically interesting but will not necessarily advance industrial implementation.

10. Conclusions

Jarosite precipitation remains an important atmospheric-pressure route for ferric-iron control in sulfate hydrometallurgy, but its process benefit is inseparable from the generation of a fine, acidic, multiphase residue. The decisive distinction is between an ideal jarosite phase and a jarosite-rich industrial residue in which valuable and hazardous elements may be structurally incorporated, sorbed, occluded, hosted by accessory phases, or retained in pore solution. Treatment must therefore be matched to actual mineralogy and element deportment.

Research published from 2020 to 2025 strengthened understanding of precipitation and dissolution kinetics, redox and pH-driven transformation mechanisms,

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selective recovery of silver and indium, multi-metal flowsheets, hydrothermal and thermal conversion, biological treatment, and waste-to-product concepts. The single-reviewer assessment indicates the strongest confidence in mechanisms and laboratory proof of concept, moderate confidence in integrated treatment of representative residues, and the lowest confidence in sustained pilot operation, closed reagent and sulfate recycle, long-term product performance, durable markets, and comparable TEA–LCA.

No single universal treatment is supported. Credible management requires comparison with alternative iron-removal routes, closure of element, water, sulfate, reagent, gas, and secondary-solid balances, qualification of every claimed product, and stability testing after realistic aging. Circularity and near-zero waste should therefore be treated as decision criteria and research objectives for most routes, not as outcomes already demonstrated by the current evidence base.

The review was conducted by one reviewer; the early retrieval records and original coding file were not retained in audit-ready form, and no inter-rater reliability coefficient can be reported. Accordingly, route classifications and confidence statements should be interpreted as transparent reviewer-assessed judgments supported by the reconstructed evidence inventory, not as formally validated consensus ratings.

Finally, this review does not assign a universal regulatory classification to jarosite or jarosite-rich residues. Hazardousness, reuse eligibility, and acceptance criteria must be determined through representative sampling, jurisdiction-specific waste codes and test methods, product standards, and scenario-appropriate environmental evaluation.

Supplementary Material

Supplementary Appendix S1 provides the reconstructed database-specific search strings and clarifies the limitations of the historical search log. Supplementary Table S1 provides the reconstructed evidence inventory for the 95-reference set, including evidence type, material basis, dominant route, scale, key process, environmental testing, product qualification, mass-balance reporting, and principal limitation.

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Conflicts of Interest

The author declares no conflict of interest.

Data Availability

All information analyzed in this review was obtained from the published sources cited in the article. Supplementary Appendix S1 provides reconstructed database-specific search strings, and Supplementary Table S1 provides a reconstructed evidence inventory for the 95 references. The earliest raw database exports, original retrieval counts, original study-level coding and quality-scoring files, the exclusion register, and any independent-reviewer data were not retained or do not exist; therefore, the supplement should not be interpreted as a restored systematic-review audit trail or as a basis for calculating inter-rater reliability.

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