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Thermal Decomposition of Iron Chlorides in Chloride-Based Metallurgy: Mechanisms, Kinetics, Gas–Solid Coupling, and Process Implications—A Critical Review

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Abstract

Iron chlorides are reactive hubs in chloride-based metallurgy rather than passive intermediates because their thermal behavior governs acid regeneration, oxide-product quality, chlorine closure, corrosion, gas treatment, and chlorination-route selectivity. This critical review evaluates a curated evidence base of 75 publications spanning 2016 through September 2026 and integrates $FeCl_2$/$FeCl_3$ hydrolysis and decomposition with phase evolution, gas–solid transport, reactor hydrodynamics, impurity effects, corrosion, and recycle. The central finding is that no universal decomposition temperature exists. Local temperature, interfacial steam partial pressure or water activity, oxygen partial pressure, HCl/Cl_2 chemical potential, hydration state, particle or droplet history, and multicomponent salt chemistry jointly determine whether FeOCl, oxyhydroxides, hematite, magnetite, volatile chlorides, HCl, or Cl_2 dominate. Quantitative literature anchors demonstrate the scale dependence of reported behavior: FeOCl can form from $FeCl_3 \cdot 6H_2O$ at 140 °C under reduced pressure; near-complete $FeCl_2 \cdot 4H_2O$ hydrolysis has been reported at 803–903 K after 40 min; and $FeCl_3 \cdot 6H_2O$ chlorination of nickel matte yielded an apparent activation energy of 77.8 kJ mol^{-1} under feed-specific thermal-analysis conditions. These values are treated as system-specific anchors rather than transferable constants. The review introduces an author-developed conceptual reaction–transport–recycle (RTR) framework that separates local chemistry, particle/droplet transport, and process-loop performance; it is not presented as a prospectively validated quantitative scoring system. The paper compares thermal, hybrid, and membrane routes using chlorine accounting closure, reusable-HCl quality, iron-product specification, net energy, purge, corrosion, and emissions as decision metrics. Research priorities are activity-based multicomponent thermodynamics, in situ phase/speciation measurement, intrinsic kinetics

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separated from transport, complete chlorine mass balances, real-feed continuous pilots, corrosion-aware design, and harmonized techno-economic/life-cycle assessment.

Keywords: iron chlorides; pyrohydrolysis; FeOCl; HCl regeneration; gas–solid reactions; chloride metallurgy.

Highlights

- $FeCl_2$/$FeCl_3$ transformation is a coupled Fe–Cl–O–H reaction network rather than a single decomposition-temperature event.
- Reported temperature windows and activation energies are system-specific because phase evolution, heat and mass transfer, and gas chemistry are coupled.
- The author-developed conceptual reaction–transport–recycle (RTR) framework translates mechanistic evidence into explicit scale-up decision gates without claiming a validated quantitative score.
- Route selection should be based on chlorine closure, reusable-HCl quality, specified iron product, net energy, corrosion, purge, and emissions.

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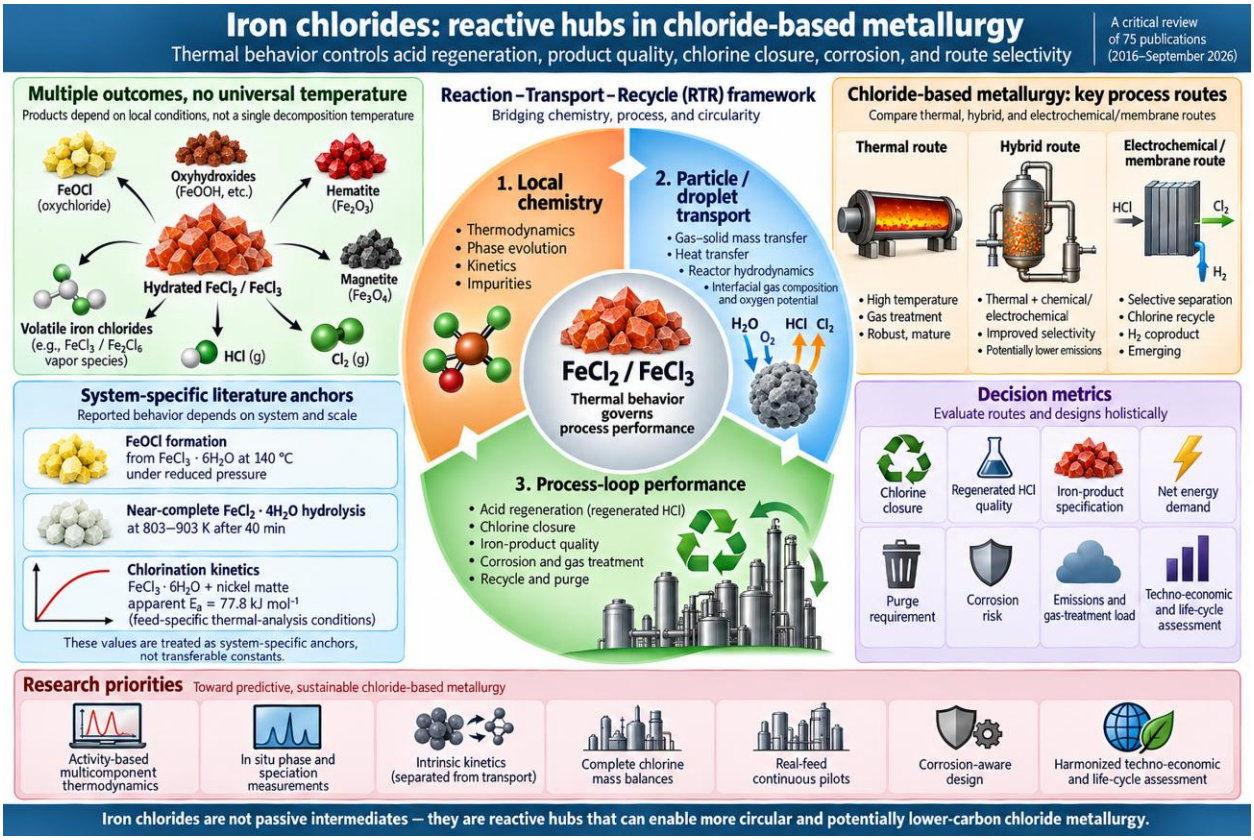
Graphical abstract



1. Introduction

Hydrochloric-acid pickling, chloride leaching, chlorination roasting, chloride refining, and several waste-valorization processes generate streams in which iron occurs predominantly as $FeCl_2$, $FeCl_3$, hydrated chlorides, chloride complexes, or mixed iron–chloride solids. In such systems, iron chloride is often treated operationally as a reagent, impurity, or recyclable salt; however, at elevated temperatures it becomes a reaction hub that redistributes chlorine, oxygen, hydrogen, and iron among condensed and gaseous phases. The practical consequence is that acid recovery, iron-oxide formation, chlorine emissions, corrosion, and downstream product quality are

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controlled by the same underlying Fe–Cl–O–H chemistry. This coupling is evident in industrial pickling and acid-regeneration studies, where the value of the process is determined not merely by chloride destruction but by simultaneous HCl recovery, iron-product management, and gas cleanup (Anderez et al., 2022; Bascone et al., 2016; Gao et al., 2021; Gueccia et al., 2021).

The most familiar industrial example is pyrohydrolysis of spent hydrochloric pickling liquor. In spray-roasting and related high-temperature systems, aqueous iron chlorides are concentrated, atomized, heated, hydrolyzed, and converted to iron oxides while HCl is recovered from the off-gas. Process simulations and industrially oriented studies report very high acid-recovery potential when gas–solid separation and absorption are properly integrated, but they also show that the reactor cannot be isolated from upstream liquor composition or downstream scrubbing and absorption (Bascone et al., 2016; Gao et al., 2021). Alternative closed-loop routes based on diffusion dialysis, membrane distillation, solvent extraction, electrowinning, and reactive precipitation further demonstrate that thermal decomposition is one option within a broader decision space for chloride management rather than an automatically superior endpoint (Arguillarena et al., 2022, 2023; Gueccia et al., 2021, 2022; Lorenz et al., 2023).

At the mechanistic scale, a second body of literature has developed around FeOCl, akaganeite, hematite, magnetite, and other iron phases prepared from ferric or ferrous chloride precursors. Thermal decomposition of $FeCl_3 \cdot 6H_2O$ can produce FeOCl before hematite, while hydrothermal or forced-hydrolysis conditions can route ferric chloride through β-FeOOH or other intermediates whose persistence depends on phosphate, chromium, pH, and temperature (Agarwal et al., 2021; Chen et al., 2017; Robić et al., 2021, 2022; Yu et al., 2023). Ferrous chloride behaves differently: high-temperature hydrolysis can be topochemical and diffusion-controlled, and oxide products may contain magnetite and hematite rather than a single ferric oxide phase (Motovilov & Luganov, 2016; Motovilov et al., 2018; Yamamoto et al., 2023). These observations caution against representing iron chloride decomposition with a single universal reaction or threshold temperature.

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A third body of evidence comes from chloride metallurgy itself. $FeCl_3 \cdot 6H_2O$ has been used as a chlorinating reagent for nickel matte, nickel concentrates, low-grade sulfide ores, and iron-rich residues; iron chloride vapor has also been exploited in precious-metal treatment. In these cases, the decomposition and volatilization of the iron chloride reagent compete with the intended chloride-transfer reaction, so selectivity depends on temperature, gas transport, mineralogy, and the relative stability or volatility of product chlorides (Höber et al., 2022; Mu et al., 2021; Steinlechner & Witt, 2023; Taninouchi & Okabe, 2018; Taninouchi et al., 2024; Wei et al., 2025; Zhong et al., 2022). Recent reviews of chlorination agents and chlorination roasting reinforce that reagent selection should be evaluated together with reaction mechanism, chloride volatility, downstream separability, and environmental control (Dou et al., 2026; Fan et al., 2025; Xing et al., 2020).

Despite this breadth, the literature remains fragmented. Materials papers commonly emphasize crystal morphology or functional performance; kinetic studies often report apparent rates without separating chemical reaction from diffusion and heat transfer; process studies optimize acid or metal recovery without resolving local phase evolution; and sustainability analyses may compare flowsheets without explicitly linking impacts to chlorine closure, oxide-product quality, or corrosion. This critical review therefore integrates thermodynamic stability, phase evolution, intrinsic and apparent kinetics, gas–solid transport, atmosphere and moisture effects, multicomponent chemistry, reactor design, corrosion, circularity, and industrial deployment. The central thesis is that useful scale-up requires a reaction–transport–recycle description: chemistry establishes what can happen, transport and hydrodynamics determine what actually happens locally, and recycle/off-gas design determines whether that chemistry becomes an economically and environmentally useful process. To translate this synthesis into a decision structure, the review proposes an author-developed conceptual RTR framework and tests its

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internal consistency against quantitative operating anchors; the framework is not presented as a prospectively validated quantitative scale-up score.

2. Review Methodology, Evidence Classes, and Critical Analysis Framework

2.1. Search strategy, eligibility, and scope

The evidence base was delimited to publications from 2016 through 20 September 2026 using structured keyword combinations centered on iron-chloride chemistry and its process consequences. Literature identification used scholarly web discovery and backward/forward citation chaining, while Crossref/DOI records and publisher journal platforms were used for bibliographic verification. No subscription bibliographic database (Scopus or Web of Science) was directly searched or exported, and no separately logged Google Scholar result set was retained; accordingly, the review does not claim database-specific coverage from those platforms. A Scopus-compatible TITLE-ABS-KEY Boolean string was used only as a reproducible syntax template: TITLE-ABS-KEY(("iron chloride*" OR "ferrous chloride" OR "ferric chloride" OR FeCl2 OR FeCl3) AND (decomposition OR hydrolysis OR pyrohydrolysis OR pyrolysis OR roasting OR FeOCl OR "HCl regeneration" OR "acid regeneration")). Complementary searches added chlorination/selective metal recovery, spent pickling liquor, molten chlorides/corrosion, gas–solid kinetics, circularity, techno-economic analysis (TEA), and life-cycle assessment (LCA). Exact-title and DOI verification used Crossref and publisher pages, including journal platforms operated by Elsevier, Springer Nature, Wiley, ACS, RSC, MDPI, and journal-specific publishers. The review is a structured critical narrative synthesis, not a statistical meta-analysis, and does not claim PRISMA compliance or exhaustive systematic coverage.

Because the early scoping and citation-chaining stages were iterative and we did not retain database-export logs, we cannot reconstruct exact counts for the initial search universe, deduplication, title/abstract screening, or full-text screening without retrospective estimation. No

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PRISMA-style flow diagram or fabricated screening counts are therefore presented. The auditable endpoint is the curated corpus of 75 peer-reviewed studies. Principal exclusion categories during curation were duplicate records, unverifiable bibliographic entries, preprints or other non-peer-reviewed items, and application papers that did not provide transferable mechanistic, process, or system-level evidence.

The final reviewed corpus contains 75 peer-reviewed publications. Inclusion required direct $FeCl_2$/$FeCl_3$ evidence or a clearly defined mechanistic/process role in one of six evidence classes: (i) direct decomposition, hydrolysis, pyrolysis, or phase transformation; (ii) FeOCl/oxyhydroxide/oxide synthesis used only to establish accessible phases or transformation sequences; (iii) spent-pickling-liquor treatment and HCl regeneration; (iv) chlorination roasting, chloride transfer, or metal recovery; (v) molten-salt, multicomponent-property, and corrosion studies; and (vi) circularity, techno-economic, or life-cycle analyses. We retained functional-material and carbonaceous studies only when they exposed a competing Fe–Cl reaction channel or a methodological limitation relevant to metallurgy. Duplicate records, unverifiable bibliographic entries, and application papers with no transferable mechanistic or process evidence were excluded. This scope preserves mechanistic breadth while making the limits of transfer for indirect evidence explicit.

2.2. Evidence classes, question relevance, and transferability limits

Evidence was coded by feed state, iron oxidation state, hydration state, temperature window, atmosphere, residence time, analytical response, likely controlling resistance, product phase, and process scale. Reactor simulations, pilot plants, and real pickling liquors provide the strongest evidence for flowsheet integration and operability but usually weak resolution of short-lived intermediates. Controlled powder, hydrothermal, and in situ diffraction studies provide stronger phase-pathway evidence but can differ substantially from industrial operation in heating rate, water

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activity, sample dimensions, and gas renewal. Functional FeOCl materials therefore provide phase-stability evidence only, not direct kinetic analogs of spray roasting (Cao et al., 2021; Chen et al., 2019, 2021; Dumbre et al., 2016; Li et al., 2026; Yu et al., 2017).

Carbonaceous and waste-pyrolysis systems are treated as boundary evidence rather than process analogs. $FeCl_3$ can promote reduction, graphitization, dechlorination, pore development, and sulfur/chlorine redistribution in complex carbon/mineral matrices (Feng et al., 2024; Gomez-Martin et al., 2021; Kim et al., 2026; Liu et al., 2026; Tao et al., 2026; Yin et al., 2024). These studies are retained because they demonstrate reaction channels that may become relevant when metallurgical residues contain carbon or organics, but they are not used to infer intrinsic $FeCl_x$ pyrohydrolysis rates.

Table 1 summarizes the evidence classes used throughout this review. The classification is not a ranking of scientific quality; it identifies the question each source type best answers and makes transferability limits visible. Direct evidence is distinguished from mechanistic analogs, process/materials analogs, and system-level comparators. A phase-identification study may be the strongest source for an intermediate, while a plant study is the strongest source for acid concentration, gas-handling configuration, operability, and scale. Draw critical conclusions only when the evidence role matches the claim.

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Table 1. Evidence classes, question relevance, and transferability limits for iron-chloride thermal processing

Evidence class/role	Primary question answered	Strength	Main transfer limitation
Direct evidence — $FeCl_2$/$FeCl_3$ hydrolysis or decomposition	Which phases and gases form, and at what apparent rate?	Direct chemical relevance	Often simplified feeds, small particles, or long residence times
Mechanistic analog — FeOCl/oxide materials synthesis	Can FeOCl, β-FeOOH, hematite, or magnetite be stabilized?	Strong phase identification and characterization	Preparation windows may not represent industrial heating, gas flow, or concentration
Direct process evidence — spray-roasting / HCl-regeneration studies	Can chlorine be closed as reusable HCl at process scale?	Reactor and flowsheet relevance	Limited resolution of transient microscopic intermediates
Process analog — chlorination metallurgy with direct $FeCl_3$ chemistry	How does $FeCl_3$ transfer chlorine to valuable metals?	Selectivity and kinetic relevance for reactive solids	Feed mineralogy strongly system-specific
Process/materials analog — molten-salt and corrosion studies	How do mixed chlorides alter activity, transport, and materials compatibility?	High-temperature multicomponent relevance	May operate outside aqueous-pyrohydrolysis regime
System-level comparator — LCA/TEA/circularity studies	Does closure of acid, metals, water, and heat create net value?	System-level decision relevance	Results depend on boundary conditions, energy mix, and local logistics

Note. Developed by the author from the reviewed 75-publication corpus and the contrasting evidence types represented by Bascone et al. (2016), Chen et al. (2017), Gueccia et al. (2021), Xu et al. (2025), and Arguillarena et al. (2022).

2.3. Critical-synthesis framework

The synthesis follows five linked questions. First, what iron/chlorine species enter the hot zone? Second, what local temperature and gas-phase chemical potentials exist around a droplet or particle? Third, which condensed phases and gases are thermodynamically and kinetically accessible? Fourth, which resistance—surface reaction, gas-film transfer, product-layer diffusion,

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heat transfer, evaporation, or residence-time distribution—controls the measured response? Fifth, where do chlorine, iron, water, energy, and impurities leave the unit operation, and can they be recycled without shifting burdens to corrosion, purge, dust, or gas treatment? This sequence prevents the common error of treating decomposition efficiency as an isolated reactor metric and provides the evidence structure later formalized in the RTR framework.

3. Thermodynamic Stability and Phase Relations in the Fe–Cl–O–H System

3.1. Why a single decomposition temperature is inadequate

Iron-chloride decomposition is a multicomponent equilibrium and reaction-network problem. Temperature changes equilibrium constants, vapor pressures, hydration states, diffusion coefficients, droplet evaporation, and the residence time needed to form product layers. The relevant variables are therefore temperature T, interfacial steam partial pressure $p(H_2O)$ (or water activity where a condensed solution or melt exists), oxygen partial pressure $p(O_2)$, and chlorine-bearing gas potentials represented by p(HCl) and $p(Cl_2)$. Water promotes hydrolysis; oxygen shifts Fe(II)/Fe(III) and magnetite/hematite stability; HCl and Cl_2 can suppress net hydrolysis or enable backward chlorination; and additional chlorides modify activities and transport properties. Consequently, a reported onset temperature from thermogravimetry, hydrothermal synthesis, or a particular roaster is not transferable unless feed state, gas composition, pressure, sample geometry, and heating history are also specified.

Ferric chloride hydrate illustrates this point. Partial thermal decomposition can yield FeOCl with HCl and water release, and FeOCl can then hydrolyze or oxidize toward hematite. Controlled synthesis studies report crystalline FeOCl at relatively low temperatures under reduced pressure and rotation, whereas other protocols use higher-temperature partial decomposition of $FeCl_3 \cdot 6H_2O$ to generate FeOCl before further conversion (Agarwal et al., 2021; Li et al., 2026; Yu et al., 2023). Forced hydrolysis in liquid water accesses a different pathway through β-FeOOH and hematite,

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with phosphate or Cr^{3+} modifying nucleation, phase persistence, crystallite size, and morphology (Chen et al., 2017; Robić et al., 2021, 2022). These studies do not imply identical industrial mechanisms, but collectively establish that FeOCl and oxyhydroxide intermediates are chemically credible across a range of water activities.

Ferrous chloride introduces a different redox constraint because Fe(II) must remain divalent, oxidize, or undergo coupled hydrolysis reactions that can produce magnetite and hydrogen. High-temperature hydrolysis studies of $FeCl_2 \cdot 4H_2O$ report topochemical behavior and mixed magnetite/hematite products, while solid-state investigations of the Schikorr-type route from ferrous chloride to magnetite highlight hydrogen evolution as a kinetic bottleneck (Motovilov & Luganov, 2016; Motovilov et al., 2018; Yamamoto et al., 2023). Thus, $FeCl_2$-rich pickling liquors should not be modeled simply as diluted $FeCl_3$ feeds: oxidation state changes can alter both chlorine release and oxide product specification.

3.2. Representative reaction set

A minimal reaction set useful for process reasoning is given in Equations 1–5. The equations are stoichiometric envelopes rather than elementary steps or universal phase boundaries. Their net direction depends on local activities and partial pressures. For any candidate reaction j, the appropriate equilibrium test is the reaction Gibbs energy in Equation 6; therefore, increasing T alone does not establish the path if Q changes simultaneously because of evaporation, gas removal, oxidation, or salt non-ideality.

$$FeCl_3 \cdot 6H_2O \rightarrow FeOCl + 2HCl + 5H_2O \quad (1)$$

$$2FeOCl + H_2O \rightarrow Fe_2O_3 + 2HCl \quad (2)$$

$$2FeCl_3 + 3H_2O \rightarrow Fe_2O_3 + 6HCl \quad (3)$$

$$3FeCl_2 + 4H_2O \rightarrow Fe_3O_4 + 6HCl + H_2 \quad (4)$$

$$4FeCl_2 + 3O_2 \rightarrow 2Fe_2O_3 + 4Cl_2 \quad (5)$$

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$$\Delta_r G_j(T,\{a_i,p_i\}) = \Delta_r G^\circ_j(T) + RT \ln Q_j \quad (6)$$

Equation 1 represents partial ferric-chloride-hydrate conversion to FeOCl, while Equations 2 and 3 represent hydrolytic progression toward ferric oxide under steam-containing conditions (Li et al., 2026; Yu et al., 2023). Equation 4 expresses the stoichiometric possibility of magnetite plus H_2 formation from ferrous chloride and water, consistent with the solid-state Schikorr-reaction perspective of Yamamoto et al. (2023). Equation 5 is retained only as an oxidative chlorine-release limit: it should not be read as the default pathway in wet regeneration service, because steam-rich conditions favor HCl-forming hydrolysis. Its relevance increases as the environment becomes comparatively dry and oxygen-rich. Equation 6 makes the main thermodynamic point explicit: R is the universal gas constant, T is absolute temperature, and Q_j is the reaction quotient for reaction j. Q_j changes with local gas removal, evaporation, activities in concentrated or molten salts, and product-phase activity, so equilibrium direction must be evaluated for the actual local state rather than inferred from furnace temperature alone.

Table 2 compares $FeCl_2$ and $FeCl_3$ from a process standpoint. The contrast is especially important for spent pickling solutions because steel pickling commonly generates Fe(II)-rich liquors, whereas oxidative steps, chloride-transfer processes, or reagent preparation may introduce substantial Fe(III). Alcaraz et al. (2021) demonstrated recovery and characterization of $FeCl_2 \cdot 4H_2O$ from pickling liquor, while Yang et al. (2020) showed that ferrous ions modify HCl volatilization behavior in solution. These upstream effects change the feed delivered to a thermal unit before decomposition begins.

Table 2. *Process-relevant comparison of $FeCl_2$- and $FeCl_3$-dominated feeds*

Attribute	$FeCl_2$-rich feed	$FeCl_3$-rich feed	Process implication
Dominant iron state	Fe(II)	Fe(III)	Oxidation potential and oxide product distribution differ

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Attribute	$FeCl_2$-rich feed	$FeCl_3$-rich feed	Process implication
Hydrated feed behavior	Strongly coupled to water release and oxidation	Can access FeOCl during partial hydrolysis/decomposition	Feed drying history can precondition later phase evolution
Representative oxide products	Magnetite and/or hematite depending on redox conditions	FeOCl intermediate, then hematite under hydrolytic/oxidizing conditions	Product specification requires gas-potential control
Gas products	HCl; possible H_2 in coupled Fe(II) hydrolysis; Cl_2 under oxidation	HCl from hydrolysis; chlorine-bearing vapors under severe or chloride-rich conditions	Off-gas train must handle variable speciation
Key evidence	Motovilov et al. (2018); Yamamoto et al. (2023)	Agarwal et al. (2021); Yu et al. (2023); Li et al. (2026)	Do not apply one kinetic model to both oxidation states

Note. Developed by the author based on Alcaraz et al. (2021), Motovilov et al. (2018), Yamamoto et al. (2023), Yu et al. (2023), and Li et al. (2026).

3.3. Quantitative operating anchors and transfer limits

The reviewed literature provides useful quantitative anchors, but not a single transferable equilibrium boundary. Yu et al. (2023) formed crystalline FeOCl from $FeCl_3 \cdot 6H_2O$ at 140 °C under reduced pressure and rotation, with reaction times from 10 min to 2 h. The source reports approximately −0.1 MPa gauge vacuum; if referenced to 101.3 kPa atmospheric pressure, this corresponds to a near-vacuum absolute pressure of roughly 1.3 kPa, but the conversion is necessarily approximate because the reported gauge value is rounded. The metallurgical significance is therefore not the low temperature itself, but the demonstration that water removal and pressure history can stabilize FeOCl before complete oxide formation. Motovilov et al. (2018) reported practically complete hydrolysis of $FeCl_2 \cdot 4H_2O$ at 803–903 K (530–630 °C) after 40 min, producing an ultrafine magnetite/hematite mixture and describing the process as topochemical within a diffusion zone. These two datasets occupy fundamentally different hydration, pressure,

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oxidation-state, and transport regimes; they should therefore not be reconciled by a single "decomposition temperature."

Phase-transformation kinetics provide another quantitative boundary. Peterson et al. (2016) monitored $FeCl_3$-derived akaganeite/hematite evolution from 80 to 200 °C by time-resolved synchrotron diffraction. Reported activation energies include 129 ± 15 kJ mol^{-1} for akaganeite nucleation in the 80–100 °C regime, 74 ± 8 kJ mol^{-1} for akaganeite crystal growth, 125 ± 7 kJ mol^{-1} for akaganeite dissolution, 80 ± 13 kJ mol^{-1} for hematite nucleation, and 110 ± 21 kJ mol^{-1} for hematite crystal growth. These values quantify solid-phase transformation steps, not intrinsic gas–solid $FeCl_x$ hydrolysis, and illustrate why a global Arrhenius fit can merge distinct barriers.

Chlorination studies provide process-specific kinetic anchors. Mu et al. (2021) reported 93.6% Ni, 91.7% Cu, and 88.2% Co extraction from nickel matte after $FeCl_3 \cdot 6H_2O$ roasting at 350 °C for 2 h using 75–80 μm particles and a chlorinating-agent-to-matte mass ratio of 2:1; Kissinger and Flynn–Wall–Ozawa analysis gave an average apparent activation energy of 77.8 kJ mol^{-1}. Wei et al. (2025) achieved 95.5% Ni, 94.4% Cu, and 92.1% Co after preroasting at 300 °C for 2 h followed by $FeCl_3 \cdot 6H_2O$ chlorination at 200 °C for 120 min with 75–80 μm ore and a 2:1 reagent-to-ore ratio, and identified internal diffusion as the primary rate control. These values are valuable for defining experimental windows, but they describe coupled chlorination/mineral conversion and must not be transferred directly to clean $FeCl_2$/$FeCl_3$ pyrohydrolysis.

Figure 1 integrates the principal pathways into a single Fe–Cl–O–H reaction network. The value of Figure 1 is not its stoichiometric completeness but its explicit recognition of reversibility and branching: $FeCl_3$ can hydrolyze through FeOCl, $FeCl_2$ can hydrolyze through Fe(II)-bearing oxide routes, and oxide products remain exposed to HCl/Cl_2 capable of re-establishing chlorinated surface or vapor species. This is the fundamental reason that gas removal and gas renewal belong inside the kinetic description rather than downstream of it.

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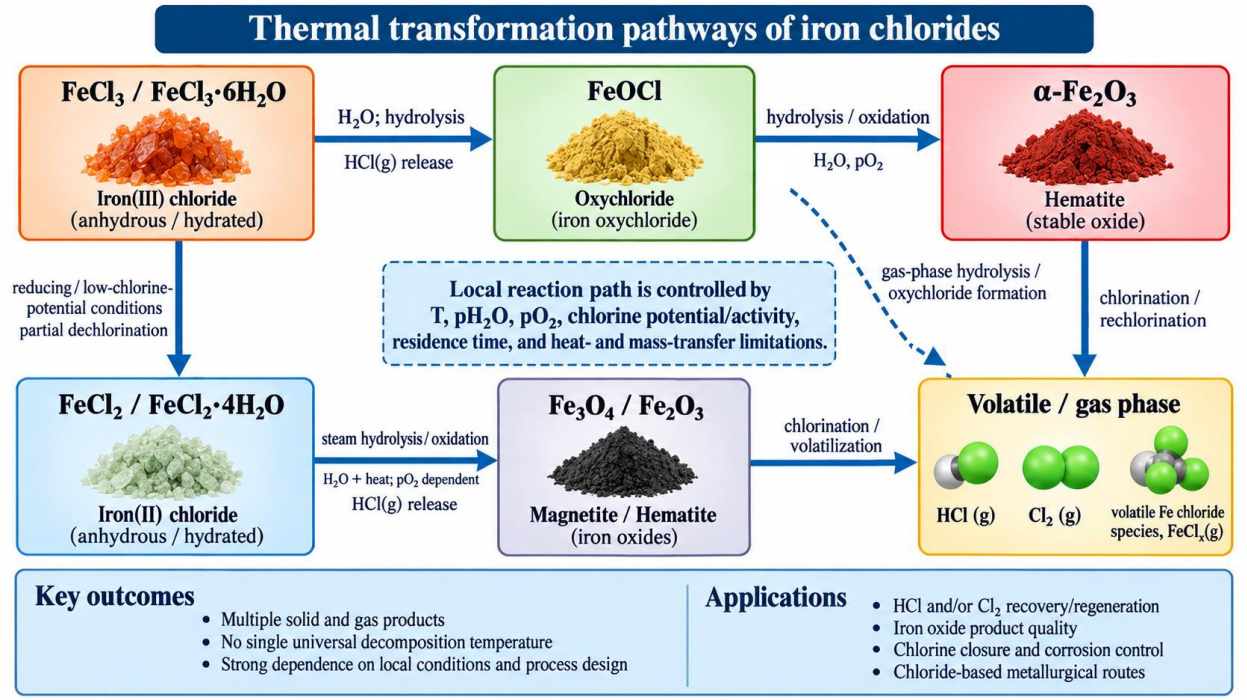

Figure 1. *Conceptual Fe–Cl–O–H reaction network linking iron chlorides, FeOCl, iron oxides, and chlorine-bearing gases.*

Note. Developed by the author based on Motovilov et al. (2018), Yamamoto et al. (2023), Yu et al. (2023), Li et al. (2026), and Gao et al. (2021).

The network also explains why oxide powder characteristics are sensitive to processing history. Studies focused on hematite nano-octahedra, FeOCl-derived hematite, hydrothermal hematite/boehmite, and industrially relevant pigment production all report strong links between precursor chemistry, thermal treatment, and product morphology or phase assemblage (Agarwal & Bora, 2021; Batygina et al., 2016; Chepushtanova et al., 2025; Stefenon et al., 2026). For acid-regeneration plants, this matters because iron oxide is not merely waste: if particle size, phase, chloride content, and morphology are controlled, the solid can contribute to process economics; if they are uncontrolled, dust handling and disposal become additional liabilities.

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4. Reaction Mechanisms and Phase Evolution

4.1. Hydrolysis-driven formation of FeOCl, oxyhydroxides, and oxides

Ferric chloride hydrolysis proceeds through progressively hydrolyzed coordination environments, condensation, nucleation, and solid-state phase transformation. Under hydrothermal conditions, β-FeOOH can appear before α-Fe_2O_3, and additives such as phosphate can retard or redirect the transformation by adsorbing on growing surfaces or stabilizing alternative iron-phosphate structures (Chen et al., 2017; Robić et al., 2022). Cr^{3+} similarly changes crystallite size and morphology and can inhibit hematite crystallization without necessarily entering the hematite or akaganeite unit cell in a simple manner (Robić et al., 2021). These results are particularly relevant to industrial liquors containing alloying elements or treatment additives: "impurity" is not merely a mass fraction to be tolerated; it can alter nucleation and the time required to reach a low-chloride oxide product.

FeOCl deserves special attention because it can be both an intermediate and a deliberately synthesized material. Thermal-decomposition studies produce FeOCl nanoparticles under reduced pressure at approximately 140 °C, and broader FeOCl materials literature describes partial decomposition of ferric chloride hydrate as a scalable synthesis route (Li et al., 2026; Yu et al., 2023). FeOCl has also been used or investigated as a catalyst and electrochemical material (Cao et al., 2021; Chen et al., 2019, 2021; Dumbre et al., 2016; Yu et al., 2017; Zhang et al., 2017). The critical process inference is not that industrial roasters should reproduce these syntheses, but that FeOCl can persist when water release is sufficient to hydrolyze $FeCl_3$ but insufficient—thermodynamically or kinetically—to complete conversion to oxide. A roaster operating with local cold spots, inadequate steam contact, or short residence time may therefore discharge a chemically different solid from one operating at the same nominal outlet temperature with better mixing.

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The FeOCl-to-hematite transition also illustrates a more general feature of chloride-derived oxide formation: the product layer may not be inert. As an oxychloride converts, porosity, cracking, sintering, and crystallite growth change the effective diffusivity of water and HCl. Consequently, a shrinking-core or topochemical description may fit conversion data over one interval but fail after a morphology transition. This is consistent with the diffusion-zone behavior reported for ferrous-chloride hydrolysis and with time-resolved transformation studies of akaganeite to hematite, which show that phase transformation kinetics can have their own temperature and structural dependence (Motovilov et al., 2018; Peterson et al., 2016).

4.2. Reduction, oxidation, and carbonaceous competing pathways

Under reducing or carbon-rich environments, iron chlorides and oxides can undergo reduction, carburization, dechlorination, or redistribution into metallic iron and iron-carbide/oxide populations. Fe-catalyzed graphitization and $FeCl_3$-derived biochar studies show that the chloride precursor and carbon matrix co-evolve during heating (Feng et al., 2024; Gomez-Martin et al., 2021; Gonzalez-Aguirre et al., 2026; Kim et al., 2026). These systems are included only as mechanistic boundary evidence: they demonstrate that carbon activity can consume or transform an $FeCl_3$ reagent before the nominal hydrolysis/decomposition endpoint is reached.

Complex wastes reinforce the same boundary condition. $FeCl_3$ addition during textile-sludge pyrolysis changes sulfur/chlorine retention and metal stabilization or volatilization, and the result depends strongly on gas atmosphere (Liu et al., 2026; Tao et al., 2026). Related carbon/mineral systems show that chloride-derived iron may become structurally incorporated rather than simply release chlorine-bearing gas (Sun et al., 2024; Yin et al., 2024; Yan et al., 2018). Accordingly, carbon activity and organics should be treated as explicit variables for secondary-resource feeds, but these studies do not use them as direct kinetic proxies for clean $FeCl_x$ pyrohydrolysis.

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4.3. Chloride transfer to other metals

When $FeCl_3 \cdot 6H_2O$ is intentionally used as a chlorinating agent, decomposition competes with chloride transfer. Nickel-matte and nickel-concentrate studies show high simultaneous extraction of Ni, Cu, and Co after $FeCl_3 \cdot 6H_2O$ roasting and water leaching, while kinetic analyses identify particle size, reagent ratio, temperature, time, and internal diffusion as important variables (Mu et al., 2021; Wei et al., 2025; Zhong et al., 2022). Selective chlorination of iron-rich residues exploits differences in chloride stability or volatility to remove valuable metals while retaining much of the iron matrix (Höber et al., 2022; Steinlechner & Witt, 2023). The useful reaction therefore occurs in a window where $FeCl_3$ remains sufficiently reactive to donate chlorine but does not become so volatile or hydrolyzed that chlorine is lost before contacting the target phase.

This competition is general to chlorination metallurgy. Reviews by Xing et al. (2020), Fan et al. (2025), and Dou et al. (2026) emphasize differences in gas generation, thermodynamic driving force, selectivity, handling, and environmental implications among chlorinating agents. Iron chloride vapor treatment has been used for platinum alloying and platinum-group metal recovery from spent catalysts, showing gaseous chloride transport can be exploited rather than just treated as waste (Taninouchi & Okabe, 2018; Taninouchi et al., 2024). Dry-aqua-regia concepts for neodymium recovery demonstrate how chloride volatility and selective transport can be engineered for recycling (Yoshimura et al., 2026). Iron-chloride decomposition chemistry determines the available chlorine chemical potential and must be included in the selectivity model.

Figure 2 is a conceptual operating-regime map using physically interpretable axes: increasing temperature/thermal history and increasing interfacial steam partial pressure $p(H_2O)$ (or water activity where a condensed solution or melt exists). The boxes are explicitly not equilibrium phase fields. Their boundaries can shift with $p(O_2)$, $p(HCl)$, $p(Cl_2)$, precursor hydration, pressure, particle size, impurities, and gas renewal. Quantitative literature anchors are shown only to demonstrate

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that experimentally reported windows belong to different local environments and therefore cannot be collapsed into a universal threshold temperature.

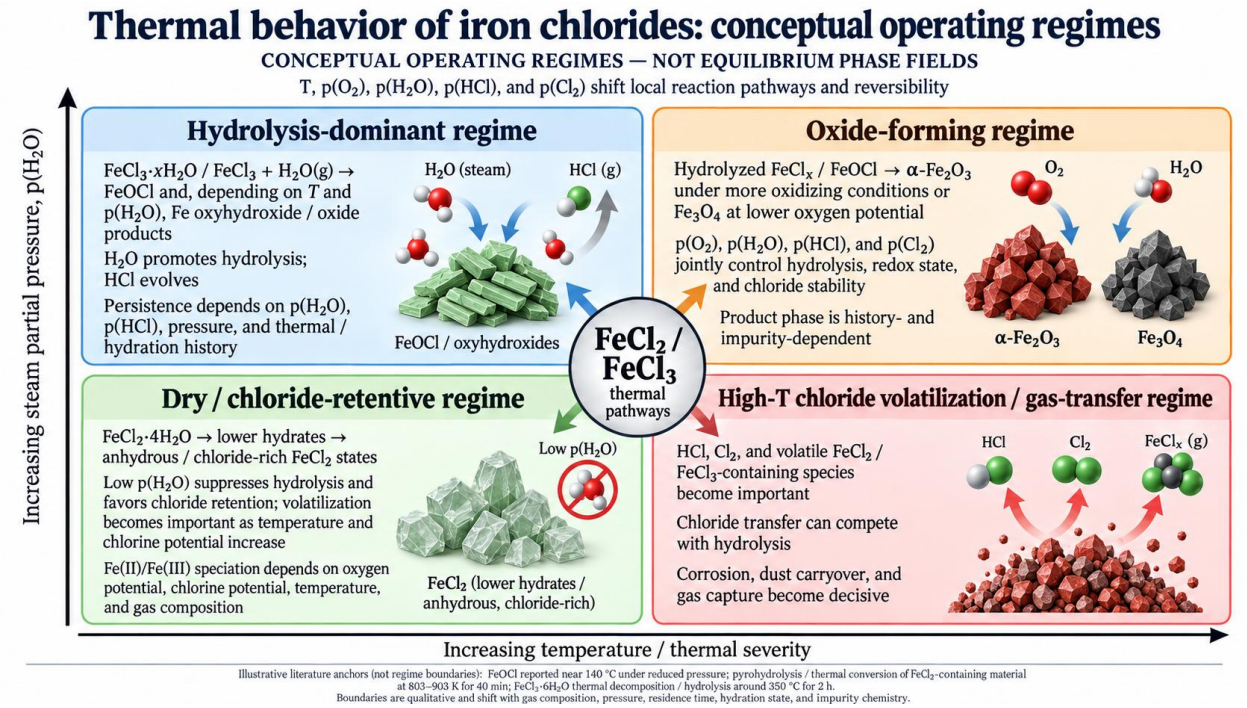

Figure 2. Conceptual operating-regime map for iron-chloride transformation as temperature/thermal history and interfacial steam potential change.

Note. Developed by the author based on Chen et al. (2017), Motovilov et al. (2018), Yu et al. (2023), Mu et al. (2021), Fan et al. (2025), and Li et al. (2026). The colored boxes are conceptual regimes—not equilibrium phase fields—and the quantitative anchors are illustrative rather than transferable boundaries.

The map clarifies why process control cannot be reduced to furnace temperature. Increasing temperature can accelerate hydrolysis and oxide crystallization while simultaneously increasing chloride volatility, wall heat flux, sintering, and corrosion. Increasing interfacial steam potential can drive HCl-forming hydrolysis but also changes droplet evaporation and gas capacity. The

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useful operating window is therefore the intersection of product specification, chlorine closure, transport adequacy, and materials compatibility.

5. Decomposition Kinetics and Coupled Heat and Mass Transfer

5.1. Intrinsic versus apparent kinetics

The central kinetic problem in iron-chloride decomposition is identifiability. Conversion measured by thermogravimetry, off-gas HCl, oxide mass change, residual chloride, or metal extraction is generally an apparent response of chemistry plus transport. A fitted Arrhenius parameter is intrinsic only if temperature gradients, gas-film resistance, evaporation, product-layer diffusion, changing phase fraction, and residence-time effects are negligible or independently modeled. The quantitative examples in Section 3.3 show why this distinction matters: 77.8 kJ mol^{-1} from thermal analysis of $FeCl_3$-assisted nickel-matte chlorination is a valid apparent descriptor for that reacting feed, but it is not a universal $FeCl_3$ decomposition activation energy.

Direct evidence for transport control appears in the ferrous-chloride hydrolysis literature. Motovilov et al. (2018) reported near-complete $FeCl_2 \cdot 4H_2O$ hydrolysis after 40 min at 803–903 K and interpreted the transformation as topochemical in a diffusion zone. In $FeCl_3 \cdot 6H_2O$ chlorination of nickel systems, particle size, reagent ratio, temperature, and time strongly affect conversion; Wei et al. (2025) specifically identified internal diffusion as the primary rate control after preroasting. These results are more transferable when reported with geometry, conversion range, gas flow, phase evolution, and morphology than when condensed to a single global rate constant.

Phase transformation can itself become rate-limiting. Peterson et al. (2016) separated nucleation, growth, and dissolution contributions during akaganeite-to-hematite evolution and reported distinct activation energies for each step. For $FeCl_3$-derived solids, chloride-rich precursor → FeOCl/oxyhydroxide → hematite conversion can therefore involve sequential barriers. A global

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reaction model may reproduce overall chlorine removal while failing to predict residual chloride, particle strength, surface area, or phase purity.

5.2. Droplet and particle histories in spray pyrolysis and roasting

Spray-based processes add a distinct sequence: atomization, sensible heating, water evaporation, solute concentration, possible crystallization, hydrolysis/decomposition, oxide nucleation, particle densification, and gas–solid disengagement. Gao et al. (2021) used extraction plus spray pyrolysis to reduce the thermal treatment load while producing high-purity Fe_2O_3 and recycling HCl. Lv et al. (2021) studied Fe_2O_3 particle preparation from simulated pickling liquor in a Venturi reactor and showed that pyrolysis conditions affect particle formation. Bascone et al. (2016) modeled a spray-roasting regeneration flowsheet including gas/solid separation, concentration, absorption, and final scrubbing. Taken together, these studies show that "reaction time" in a roaster is actually a thermal and compositional trajectory through several unit phenomena.

The trajectory is sensitive to atomization. Small droplets heat and dry rapidly but can produce fine particles that are difficult to recover; larger droplets may leave incompletely decomposed cores or wall deposits. Solute concentration affects boiling-point elevation, viscosity, and crystallization; iron valence and impurity salts alter solution activity and subsequent solids. Yang et al. (2020), for example, showed that ferrous ions stabilize HCl in aqueous pickling solutions and suppress HCl volatilization, implying that feed concentration and iron loading change the amount of free/volatile acid delivered to the thermal stage. Thus, upstream liquor chemistry influences both the heat duty and the roaster's initial gas composition.

Figure 3 separates two levels that should not be represented as five resistances in simple series. Gas-film transfer, heating/evaporation, surface reaction, and product-layer transport occur at the particle/droplet scale. Atomization, mixing, residence-time distribution (RTD), entrainment, wall

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interaction, and the bulk heat- and mass-transfer field occur at the reactor scale and impose the local histories particles experience. The plant outlet is therefore a convolution of a distribution of local histories with intrinsic chemistry and particle-scale transport.

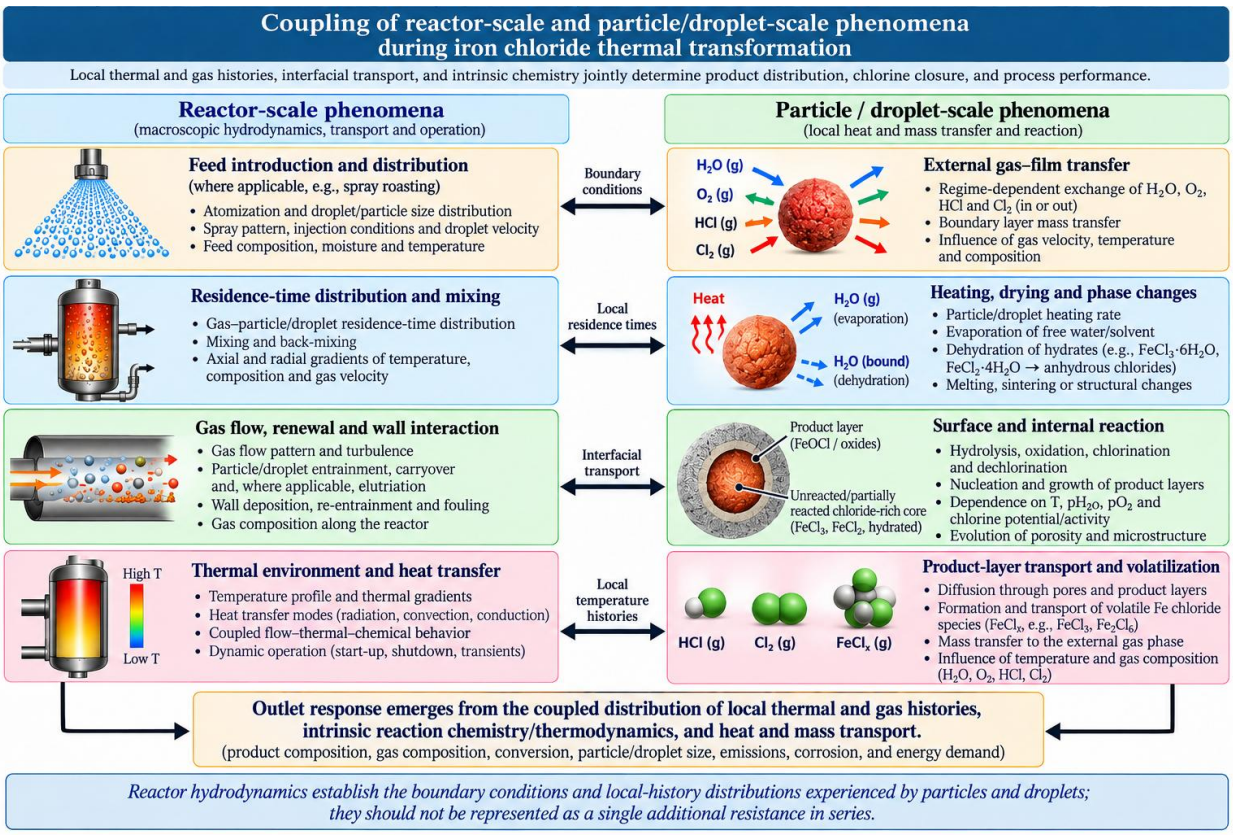

Figure 3. Two-scale coupling between reactor hydrodynamics and particle/droplet kinetics in iron-chloride thermal conversion.

Note. Developed by the author based on Motovilov et al. (2018), Bascone et al. (2016), Lv et al. (2021), Mu et al. (2021), and Wei et al. (2025). Reactor hydrodynamics are shown as boundary conditions on local histories rather than as a single resistance in series.

Table 3 now consolidates quantitative kinetic and operating evidence. The comparison distinguishes temperature/time windows and reported activation-energy information from the

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physical resistance embedded in the measurement, thereby avoiding the misleading interpretation that all reported kinetic parameters describe the same elementary $FeCl_x$ reaction.

Table 3. Quantitative kinetic/operating evidence and its scale-up interpretation

Study/system	Operating window/feed	Quantitative descriptor	Measurement basis	Embedded control	Scale-up interpretation
Yu et al. (2023), $FeCl_3 \cdot 6H_2O \rightarrow FeOCl$	140 °C; ~−0.1 MPa gauge (≈1.3 kPa absolute if referenced to 101.3 kPa atm; source value rounded); 150 rpm; 10 min–2 h	Crystalline FeOCl formed; no intrinsic Ea reported	X-ray diffraction (XRD) / particle growth under reduced pressure	Evaporation + decomposition + crystal growth	Low-T FeOCl stability depends strongly on pressure/water removal; not a roaster kinetic constant
Motovilov et al. (2018), $FeCl_2 \cdot 4H_2O$ hydrolysis	803–903 K; 40 min	Practically complete hydrolysis; no intrinsic Ea reported	High-T hydrolysis; oxide characterization	Topochemical reaction in a diffusion zone	Time cannot be extrapolated by temperature alone; product-layer transport is embedded
Peterson et al. (2016), akaganeite → hematite	80–200 °C hydrothermal	Ea: akaganeite nucleation 129 ± 15; growth 74 ± 8; dissolution 125 ± 7; hematite nucleation 80 ± 13; growth 110 ± 21 kJ mol^{-1}	Time-resolved synchrotron X-ray diffraction (XRD) / Johnson–Mehl–Avrami–Kolmogorov (JMAK) analysis	Nucleation, dissolution, and crystal growth	Quantifies solid-phase transformation barriers, not intrinsic gas–solid $FeCl_x$ hydrolysis

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Study/system	Operating window/feed	Quantitative descriptor	Measurement basis	Embedded control	Scale-up interpretation
Mu et al. (2021), $FeCl_3 \cdot 6H_2O$ chlorination of nickel matte	350 °C; 2 h; 75–80 µm; reagent:matte = 2:1	Average apparent Ea = 77.8 kJ mol^{-1}; Ni/Cu/Co extraction 93.6/91.7/88.2%	Differential thermal/thermogravimetric analysis (DTA–TG) + Kissinger/Flynn–Wall–Ozawa (FWO); roasting/leaching	Coupled chlorination, phase evolution, and diffusion	Ea is feed- and method-specific; useful as an apparent process descriptor
Wei et al. (2025), low-grade nickel sulfide ore	Preroast 300 °C, 2 h; chlorination 200 °C, 120 min; 75–80 µm; 2:1	Ni/Cu/Co extraction 95.5/94.4/92.1%; internal diffusion identified as primary control	Thermodynamics + phase analysis + kinetic fitting	Internal pore/product-layer diffusion	Pretreatment and porosity can dominate over nominal furnace temperature
Bascone et al. (2016), spray-roasting flowsheet	Integrated roaster + gas/solid separation + absorber + scrubber	Acid recovery >99% under integrated conditions; no intrinsic Ea	Process simulation / flowsheet balance	Droplet history, RTD, capture, and absorption	Reactor performance cannot be evaluated independently of downstream gas capture

Note. Quantitative data synthesized from Yu et al. (2023), Motovilov et al. (2018), Peterson et al. (2016), Mu et al. (2021), Wei et al. (2025), and Bascone et al. (2016). Activation energies are reported values for the stated measurement/model and should not be interpreted as universal $FeCl_x$ decomposition constants.

A practical consequence is that kinetic studies intended for reactor design should report conversion simultaneously with phase fraction, residual chloride, particle-size evolution, and off-gas composition. Experiments at multiple sample masses and gas velocities are especially valuable because they can reveal external transfer limitations. Where possible, estimate intrinsic kinetics from thin layers or small particles under differential conversion, then embed them in a separate transport model. Without this separation, computational fluid dynamics (CFD) or process simulators may reproduce one reactor while failing under different scale, nozzle design, or feed concentration.

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6. Atmosphere, Moisture, and Gas–Solid Interactions

6.1. Steam activity as a reaction variable

Moisture is a reactant, not a background condition. In a dry chloride-rich environment, $FeCl_x$ can remain stable, melt, volatilize, or transfer chloride; as interfacial steam potential increases, hydrolysis becomes thermodynamically and kinetically accessible and HCl generation accelerates. Bulk humidity does not equal $p(H_2O)$ at the reacting interface. A rapidly evaporating droplet can be water-rich early in its trajectory and comparatively dry after crust formation, while an HCl-rich boundary layer can suppress net hydrolysis even when the bulk gas contains steam. Reactor reporting should therefore distinguish inlet/outlet humidity from the local steam potential inferred or modeled at the particle surface.

The FeOCl literature provides a useful mechanistic anchor. Crystalline FeOCl can be isolated when ferric chloride is only partially hydrolyzed/decomposed, while further water exposure and thermal treatment promote oxide formation (Li et al., 2026; Yu et al., 2023). Forced-hydrolysis studies show that solution chemistry and additives change the route through oxyhydroxide and hematite (Chen et al., 2017; Robić et al., 2021, 2022). Industrially, this implies that residual FeOCl is a diagnostic of an intermediate water/chlorine potential and/or insufficient residence time, not simply an indicator that the furnace was “too cold.”

6.2. Oxygen, chlorine potential, and reversible gas chemistry

Oxygen potential determines whether Fe(II) persists, magnetite forms, or the system is driven toward ferric oxide. It also affects whether chlorine exits mainly as HCl under steam-rich hydrolysis or as more oxidized chlorine-bearing gas under dry oxidative conditions. In high-temperature equipment, this redox control interacts with wall materials: chloride corrosion depends on the Fe–O–Cl chemical environment, and thermodynamic corrosion analyses demonstrate that chlorine-containing atmospheres can destabilize protective oxides or generate

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volatile/low-melting chlorides (Kaczmarczyk & Gurgul, 2024; Kaczmarczyk & Mlonka-Mędrala, 2016). The gas composition required for product chemistry therefore has to be compatible with the alloy or refractory envelope.

Fe–Cl thermochemical hydrogen cycles provide boundary evidence for reversibility rather than a direct model of acid-regeneration roasting. Their main contribution here is thermodynamic: $Fe/FeCl_2/HCl/H_2O$ chemistry can be circulated through staged chemical-potential windows when heat and reagent regeneration are deliberately integrated (Safari & Dincer, 2020; Özkaya et al., 2023; Valant & Luin, 2024). This reinforces the broader design principle that iron chloride should be treated as a recyclable chemical carrier where the full loop is favorable, not as a species that must always be destroyed thermally.

Organic chlorine is a secondary boundary condition for carbonaceous feeds. Iron oxides can catalyze dechlorination of PVC-derived products (Ahmed et al., 2017, 2019), and inappropriate combinations of chlorine, carbon, catalytic metals, oxygen, and temperature history can create conditions associated with PCDD/F formation (Pereira, 2026). For clean pickling-liquor service, this pathway is peripheral; for organics-bearing wastes, it justifies extending chlorine closure beyond HCl and Cl_2 to credible secondary chlorine products and the gas-cleaning train.

A useful operational rule follows: specify atmosphere control by measurable gas composition and dew point/steam fraction at the reactor inlet and outlet, not by qualitative labels such as “air,” “inert,” or “humid.” When possible, include HCl, Cl_2, O_2, H_2O, and relevant volatile metal chlorides in the online or campaign-based analytical plan. This is essential for distinguishing true decomposition from simple chloride volatilization.

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7. Impurities, Multicomponent Chlorides, Molten Salts, and Materials Compatibility

7.1. Impurities as phase and activity modifiers

Real chloride feeds contain Na, K, Mg, Ca, Zn, Al, Cr, sulfate, phosphate, silica, organics, and suspended solids. These species can change water activity, chloride activity, melting behavior, viscosity, nucleation, gas evolution, and corrosion. Hydrothermal studies show directly that Al- and Fe-chloride mixtures can yield coupled boehmite/hematite products, while phosphate and Cr^{3+} change ferric-hydrolysis phase selection and morphology (Batygina et al., 2016; Chen et al., 2017; Robić et al., 2021, 2022). Therefore, the assumption that impurities merely "dilute" $FeCl_x$ is generally unsafe.

The same issue appears in pickling-liquor valorization. Hot-dip galvanizing acids may contain substantial Zn in addition to Fe, motivating selective solvent extraction or membrane routes before reuse or further processing (Arguillarena et al., 2023; Gueccia et al., 2021). If such mixed liquors are thermally treated without pre-separation, Zn chloride volatility and corrosion can alter solids and gas treatment. Feed purification can thus be justified not only by product purity but also by stabilizing the decomposition chemistry itself.

7.2. Mixed molten chlorides and transport properties

At higher salt loadings or in deliberately molten systems, non-ideal chloride interactions become dominant. Molecular-dynamics and experimental work on NaCl–$MgCl_2$–$CaCl_2$–$FeCl_2$/$FeCl_3$ mixtures shows that iron chlorides influence local structure, ionic transport, viscosity, and density (Xu et al., 2025). Studies of molten-salt chlorination systems likewise report strong composition effects on physical properties relevant to mixing and mass transfer (He et al., 2024). Thermochemical measurements of $FeCl_2$ in LiCl show that electrochemical or thermodynamic models for mixed melts need activity data rather than pure-component assumptions (Gesualdi et al., 2025).

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These findings matter even when a nominal process is not designed as a molten-salt reactor. During drying of concentrated chloride liquors, transient eutectic or low-melting phases can form on particle surfaces or walls. Such films can accelerate ion transport, agglomeration, wall sticking, and corrosion, while also changing the effective contact between steam and iron chloride. This can explain abrupt changes in apparent kinetics that would otherwise be attributed to a new elementary reaction.

7.3. Corrosion as a chemistry constraint

$FeCl_3$ is particularly aggressive toward many structural alloys because it can participate in active oxidation/chlorination cycles. Experiments with 316 stainless steel in NaCl–$MgCl_2$ melts and vapors show that $FeCl_3$ concentration alters corrosion behavior, and related work on NaCl–KCl–$FeCl_3$ systems reports both thermophysical-property design and corrosion mechanisms at lower temperatures (Li et al., 2025; Lu et al., 2023; Yang et al., 2023, 2024). High-temperature chloride corrosion studies of advanced alloys and Fe–O–Cl thermodynamic analyses reach the same engineering conclusion: materials selection cannot be separated from chloride speciation and oxygen potential (Bai et al., 2021; Kaczmarczyk & Gurgul, 2024).

Electrochemical removal of impurity metals from molten chloride mixtures provides a complementary strategy for controlling salt composition (Niazi et al., 2022). Although such electrochemical purification is not a standard component of HCl regeneration, it highlights a broader design option: rather than accepting multicomponent chloride accumulation and compensating with purge, a process can selectively remove problematic metals and preserve the salt/acid loop. This principle becomes more attractive as chloride-based metallurgy moves toward tighter water and reagent closure.

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Table 4 summarizes the principal impurity and multicomponent effects to incorporate into pilot testing. The table is introduced here because these effects cut across thermodynamics, kinetics, and mechanical design rather than belonging to a single unit operation.

Table 4. Impurity and multicomponent effects relevant to iron-chloride thermal processing

Component/condition	Observed or expected effect	Evidence base	Design response
Phosphate / Cr^{3+}	Changes nucleation, oxyhydroxide/hematite transformation, and particle morphology	Chen et al. (2017). Robić et al. (2021, 2022)	Characterize feed impurities; do not calibrate kinetics on pure $FeCl_3$ only
Al-bearing chloride systems	Coupled hydrolysis and mixed oxide/hydroxide formation	Batygina et al. (2016)	Track co-precipitation and product purity
NaCl–$MgCl_2$–$CaCl_2$ with $FeCl_2$/$FeCl_3$	Changes local structure, viscosity, density, and ionic transport	Xu et al. (2025); He et al. (2024)	Use activity/property models for concentrated or molten regimes
$FeCl_3$ in molten chloride contact with steel	Accelerated chloride corrosion; protective-scale instability	Lu et al. (2023); Li et al. (2025); Yang et al. (2024)	Couple gas/salt chemistry with alloy selection and temperature limits
Zn/Cu/Mn and other metals	Volatility, selective chloride formation, contamination, or electrochemical separability	Arguillarena et al. (2023). Niazi et al. (2022)	Consider upstream separation, controlled purge, or selective recovery

Note. Developed by the author from the studies cited in the Evidence base column.

The overarching implication is that real-feed validation is indispensable. A decomposition mechanism established in high-purity $FeCl_3 \cdot 6H_2O$ may remain chemically correct but become process-irrelevant when a concentrated industrial liquor forms a multicomponent salt film, when zinc chloride enters the vapor phase, or when corrosion products recycle iron and nickel/chromium back into the solids. Continuous pilot campaigns should therefore include impurity mass balances and corrosion coupons or probes alongside conversion measurements.

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8. Industrial and Emerging Applications

8.1. HCl regeneration from spent pickling liquors

HCl regeneration is the clearest industrial application of iron-chloride pyrohydrolysis. Carbon-steel pickling progressively consumes free acid and accumulates ferrous chloride; the spent liquor can either be treated as hazardous waste, purified and reused, or thermally regenerated (Anderez et al., 2022; Alcaraz et al., 2021). Spray roasting converts iron chlorides to iron oxides and recovers HCl from the gas phase. Bascone et al. (2016) reported that pyrohydrolysis technologies can achieve acid recoveries above 99% under appropriate integrated conditions and modeled a small-scale plant including a cyclone, Venturi scrubber, absorber, and final scrubbing, with a sub-azeotropic HCl product. Their work also makes an important scale-up point: economics and operability depend on the full gas-cleaning and absorption train, not only the roaster.

Gao et al. (2021) proposed extraction of ferric chloride from concentrated HCl followed by spray pyrolysis of the iron-rich stripping liquor. By removing much of the reusable acid before thermal treatment, the approach reduces the mass load entering the hot stage and produces high-purity Fe_2O_3 while returning HCl to pickling. The process illustrates a recurring opportunity: hybrid flowsheets can allocate each separation to the unit operation that handles it most efficiently. Thermal conversion need not perform acid separation, metal separation, solids formation, and concentration at the same time.

Membrane-based approaches provide a useful benchmark. Gueccia et al. (2021) demonstrated a pilot-scale integrated system based on diffusion dialysis, membrane distillation, and reactive precipitation with real industrial solutions; later economic analysis evaluated the value of onsite waste-pickling-solution valorization (Gueccia et al., 2022). Arguillarena et al. (2023) demonstrated pilot-scale non-dispersive solvent extraction for selective zinc removal and production of a reusable iron-chloride solution. These alternatives do not eliminate the relevance

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of thermal decomposition; rather, they define situations in which thermal treatment should be preceded by selective separation or avoided if direct acid recovery and metal valorization are more favorable.

8.2. Iron-oxide and pigment production

Iron oxide is the principal solid coproduct of many regeneration routes, and its value depends on phase purity, particle size, morphology, residual chloride, and color. Reviews and experiments on oxide production from chloride pickling solutions show continuing interest in transforming an acid-treatment liability into a saleable or usable material (Riabik & Amosov, 2025). Motovilov et al. (2018) produced ultrafine magnetite/hematite mixtures from ferrous chloride hydrate under high-temperature hydrolysis, whereas $FeCl_3$-derived routes can produce hematite with morphology strongly dependent on precursor and thermal history (Agarwal & Bora, 2021; Agarwal et al., 2021).

Pigment-oriented studies extend this concept. Chepushtanova et al. (2025) developed a process for converting pyrite–cobalt concentrates into Fe_2O_3/Fe_3O_4 pigment products, and Stefenon et al. (2026) investigated calcination-temperature effects on iron-oxide synthesis and pigment performance. Kargin et al. (2025) examined thermal reduction and oxidation of iron-oxide slags from the rolling-mill steel industry, reinforcing that redox history governs oxide phase and properties. For HCl regeneration, these studies suggest that product valorization should begin with a target specification—hematite versus magnetite, particle size, color, trace metals—then work backward to liquor purification, gas atmosphere, and temperature profile.

8.3. Selective chlorination and valuable-metal recovery

$FeCl_3$ is also a reagent platform for selective chlorination. In nickel systems, $FeCl_3 \cdot 6H_2O$ roasting followed by water leaching has achieved high extraction of Ni, Cu, and Co, with phase-evolution and kinetic studies clarifying how chlorination proceeds through the solid (Mu et al.,

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2021; Zhong et al., 2022; Wei et al., 2025). Selective chlorination of iron-precipitation residues can preferentially volatilize or extract valuable metals while leaving much of the iron matrix behind, offering a route for secondary-resource upgrading (Höber et al., 2022; Steinlechner & Witt, 2023). Reviews of polymetallic chlorination emphasize that the useful separation derives from differences in chloride stability, volatility, and downstream solubility—not simply from high total chlorination conversion (Fan et al., 2025; Xing et al., 2020).

Precious and critical metals broaden the application range. Iron chloride vapor has been used to alloy platinum and to assist leaching/recovery of platinum-group metals from spent catalysts (Taninouchi & Okabe, 2018; Taninouchi et al., 2024). Yoshimura et al. (2026) applied a dry-aqua-regia concept to neodymium recovery from spent magnets, illustrating the continued evolution of chlorine-mediated recycling. These examples support a selectivity-first interpretation of iron-chloride decomposition: the optimal condition is not necessarily the one that decomposes $FeCl_3$ fastest, but the one that delivers chlorine to the target phase, generates a separable product, and allows chlorine to be recovered with minimal corrosion and emissions.

8.4. Fe–Cl thermochemical cycles and other functional systems

The Fe–Cl thermochemical water-splitting literature demonstrates closed chemical cycling of iron chlorides and is included as boundary evidence for recycle design. Safari and Dincer (2020), Özkaya et al. (2023), and Valant and Luin (2024) show that $Fe/FeCl_2/HCl/H_2O$ chemistry can be staged around heat availability and reagent regeneration. The transferable lesson for chloride metallurgy is cyclic reagent management and heat matching, not direct equivalence with spray roasting.

Functional FeOCl studies are retained only to establish phase accessibility and methodological caution. FeOCl can be synthesized as a catalyst or electrochemical material (Cao et al., 2021; Chen et al., 2019, 2021; Dumbre et al., 2016; Yu et al., 2017; Zhang et al., 2017), but those optimized

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syntheses are not industrial kinetic analogs. Chen et al. (2021) further showed that apparent FeOCl catalytic performance can be overestimated if adsorption and homogeneous dissolved-iron reactions are not separated; the analogous metallurgical lesson is to separate true solid-state chemistry from parallel gas-phase and transport phenomena.

9. Reactor Selection, Flowsheet Integration, and Scale-Up

9.1. Reactor selection as a reaction–transport choice

Reactor selection should begin with the feed's physical form and the desired solid product. Spray roasting is naturally compatible with aqueous pickling liquors because atomization creates high surface area and integrates concentration, drying, and reaction; it is also the thermal configuration with the clearest direct $FeCl_x$ process evidence in the reviewed corpus. Its disadvantages are fine-particle entrainment, sensitivity to nozzle/droplet distribution, wall deposition, and the need for efficient gas–solid separation. Fluidized-bed pyrohydrolysis and rotary/mechanically mixed thermal reactors are retained in Table 5 as engineering extrapolations/design alternatives based on general gas–solid reaction engineering rather than as directly validated $FeCl_x$ industrial routes within this corpus. Fluidized beds can offer strong gas–solid heat and mass transfer when feed conditioning prevents agglomeration, whereas rotary or mixed reactors may better tolerate coarse heterogeneous solids but generally broaden residence-time and gas-contact distributions. These alternatives require direct $FeCl_x$ validation before inferring performance. The critical choice is therefore not which reactor reaches the highest temperature, but which configuration delivers the required local $p(H_2O)$, $p(O_2)$, $p(HCl)$, and $p(Cl_2)$ conditions and residence-time history to every relevant particle or droplet.

For spent-pickling liquor, Bascone et al. (2016) showed why the roaster must be modeled together with the cyclone, scrubber, absorber, and tail-gas washing. Gas cooling and dust recovery affect chlorine capture; absorber water balance controls product acid concentration; and recycle

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streams influence feed concentration. Gao et al. (2021) demonstrate another integration path in which solvent extraction reduces the iron-rich stream sent to spray pyrolysis. Gueccia et al. (2021) show that non-thermal units can recover acid before metal precipitation. The common principle is process intensification through load allocation: the thermal reactor should perform only transformations that genuinely benefit from high temperature.

9.2. Control variables and scale-up measurements

A scale-up dataset should contain more than furnace temperature and nominal residence time. For liquid feeds, it should include free HCl, Fe(II)/Fe(III), total chloride, major impurity ions, solids, density, viscosity, and feed temperature. Atomization data should include nozzle type, pressure, droplet distribution, and turndown. Gas data should include flow, O_2, H_2O/dew point, HCl, Cl_2 where relevant, and dust loading. Solid data should include residual chloride, phase fractions, particle-size distribution, morphology, bulk density, and key impurities. Materials-of-construction data should record corrosion rate and deposit chemistry. These measurements allow a mass and chlorine balance to diagnose whether poor “decomposition” is actually poor reaction, volatile chloride loss, entrainment, or incomplete gas absorption.

Online control can then be organized around leading indicators. Dew point and O_2 influence the chemical path; outlet HCl and dust loading indicate conversion and separation; roaster pressure drop and wall temperature can indicate deposition; residual chloride in product is a lagging quality metric. When multicomponent salts matter, viscosity or melting behavior can change suddenly with composition, making model-based soft sensors valuable. Binnemans and Jones (2023) identify real-time analysis and digital process control as principles of circular hydrometallurgy; iron-chloride regeneration is an especially suitable application because reagent loss, water balance, and product quality are tightly coupled.

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Figure 4 is revised to distinguish material, chlorine-gas, energy, and control/purge loops. The central reactor can represent spray roasting, a fluidized bed, or another thermal unit, but the closure logic remains the same: solids must meet an iron-product specification; off-gas must be separated and absorbed to produce reusable HCl; recovered heat must displace a real process duty; and impurities/corrosion products require an explicit purge or recovery strategy.

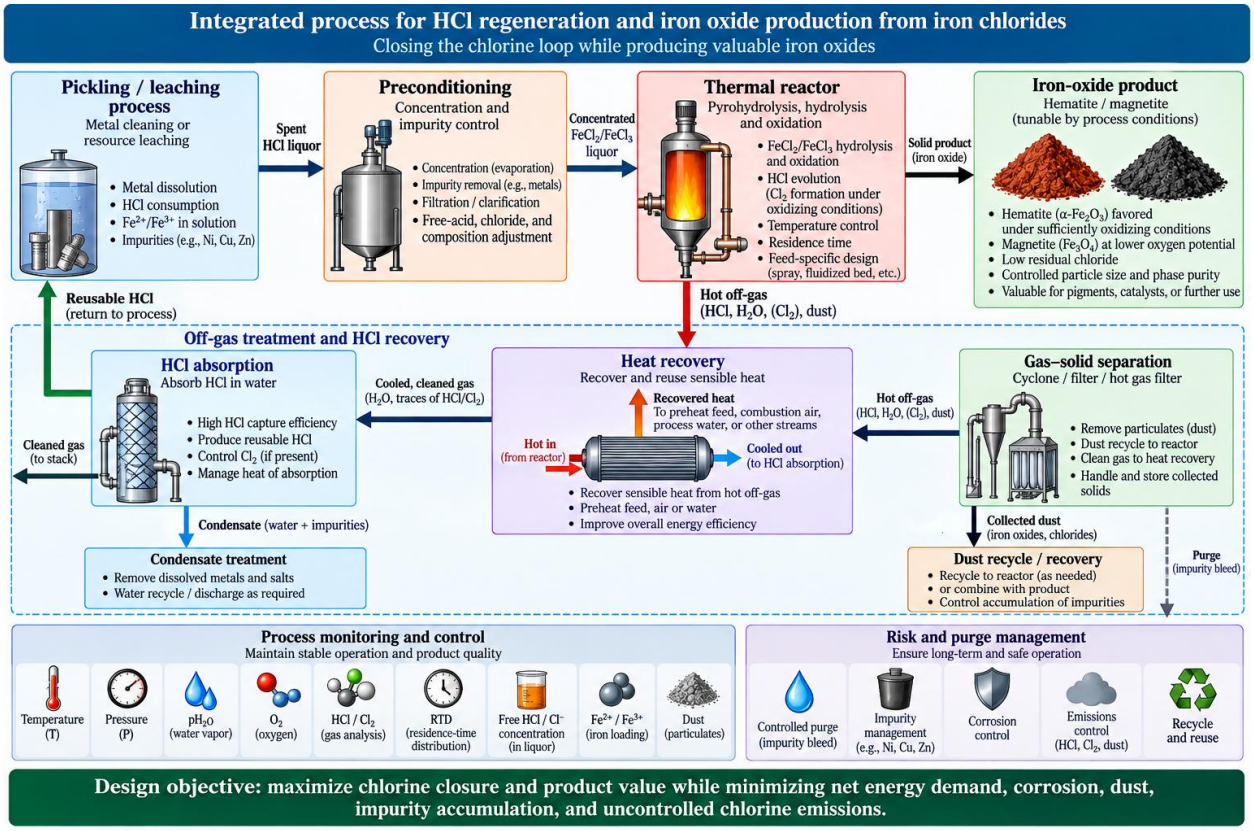

Figure 4. Integrated flowsheet for thermal iron-chloride conversion showing separate material, gas/recovery, energy, and control/purge loops.

Note. Developed by the author based on Bascone et al. (2016), Gao et al. (2021), Gueccia et al. (2021), and Liu et al. (2023). Dashed connections denote energy integration or control/purge functions rather than primary material flow.

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The post-figure interpretation is decisive: the acid loop closes only if chlorine captured as HCl is reusable at the required concentration and purity; the iron loop is valorized only if the oxide meets a use specification; and the energy loop improves only if recovered heat displaces a real duty elsewhere. Otherwise, nominal recycling can simply convert one waste stream into another. Scale-up reviews should therefore report closure efficiencies for chlorine, iron, water, and energy separately rather than one global "recovery" number.

Table 5 compares the principal reactor/flowsheet options from this perspective. It also includes non-thermal routes because they are legitimate competitors when the purpose is acid recovery rather than oxide production.

Table 5. *Reactor and flowsheet options for iron-chloride-bearing streams*

Option	Best-suited feed/objective	Strengths	Principal constraints
Spray roasting / spray pyrolysis	Aqueous $FeCl_x$ liquors; HCl regeneration plus oxide production	Fast heat/mass transfer; integrated drying; established acid-regeneration concept	Droplet/RTD control, fines, wall deposition, gas cleanup, corrosion
Fluidized-bed pyrohydrolysis — engineering extrapolation/design alternative	Concentrated chloride solids/slurries compatible with fluidization	Excellent gas–solid contact and heat transfer	Agglomeration, feed conditioning, attrition, and dust
Rotary/mixed thermal reactor — engineering extrapolation/design alternative	Heterogeneous residues or coarse solids	Feed tolerance and longer residence time	Broader RTD, larger gas inventory, possible lower transfer intensity
Hybrid extraction + thermal conversion	Liquors where acid can be recovered before iron conversion	Reduces hot-stage mass/energy duty; improves product purity	Additional solvent/separation circuit and recycle management
Membrane/precipitation route	Liquors where direct acid/metal recovery is preferred	Lower-temperature separation; modularity and potential onsite use	Membrane fouling/salting effects, concentration limits, downstream metal product handling

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Note. Developed by the author based on Bascone et al. (2016), Gao et al. (2021), Gueccia et al. (2021), and Lorenz et al. (2023). Spray roasting, hybrid extraction–thermal conversion, and membrane-based routes are supported directly by the reviewed process literature. The fluidized-bed and rotary/mixed-reactor rows are engineering extrapolations/design alternatives; they are not presented as directly validated $FeCl_x$ industrial evidence in this corpus.

10. Environmental Performance, Circularity, and Techno-Economic Trade-Offs

10.1. Acid regeneration as a circularity problem

Regenerating HCl can reduce fresh-acid demand and hazardous-liquid disposal, but regeneration is not automatically circular. A thermally intensive process may recover chlorine while consuming fuel, generating CO_2, producing a low-value iron oxide, and accelerating corrosion. Conversely, a membrane process may reduce thermal duty but require electricity, replacement membranes, chemicals, and a concentrated residual stream. Circular performance must therefore be evaluated by closed mass and energy balances rather than by the presence of a recycle arrow. Agarwal and Pandey (2023) review acid remediation and recycling across industrial processes, while Binnemans and Jones (2023) formalize circular hydrometallurgy around reagent regeneration, water closure, waste prevention, energy efficiency, safe handling of harmful elements, and real-time control. These principles provide an appropriate system boundary for iron-chloride regeneration.

For clarity, five system terms are distinguished here. Internal recycle is the return of a stream to an upstream or same-process unit, irrespective of whether it reduces virgin input. Reagent regeneration is the conversion of a spent chemical form into a specification suitable for reuse. Material recovery is the capture of a material in a potentially usable form. Functional displacement occurs only when the recovered material or energy actually replaces a defined quantity of fresh reagent, raw material, utility, or external treatment. A circular-system benefit requires that this

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displacement remains favorable after accounting for purification, energy, water, purge, corrosion, emissions, and residual-waste burdens. Thus, an internal recycle can exist without a meaningful circularity benefit.

Life-cycle studies of spent-pickling-acid recovery demonstrate that system configuration matters. Arguillarena et al. (2022) found that membrane-based solvent extraction and electrowinning could substantially reduce several environmental impacts relative to the reference treatment, although zinc electrowinning energy demand remained important. Lorenz et al. (2023) reported broad impact reductions for an integrated diffusion-dialysis/membrane-distillation/zero-brine approach compared with linear hazardous-waste management, especially where long-distance transport of waste acid was avoided. These results should not be transferred numerically to thermal regeneration, but they establish the appropriate comparison: onsite closure can create value through avoided transport, avoided fresh acid, recovered metal products, and reduced waste treatment, not only through direct reagent savings.

Economic analysis reaches a similar conclusion. Gueccia et al. (2022) evaluated the benefits of waste-pickling-solution valorization, whereas Liu et al. (2023) modeled CO_2-capture-coupled pyrohydrolysis of $CaCl_2$ waste and explicitly linked energy, acid regeneration, water recycle, capital cost, and operating cost. Calcium chloride chemistry is not directly transferable to $FeCl_x$, but the assessment structure is. A thermal $FeCl_x$ process should report specific energy per kilogram of reusable HCl and per kilogram of specified iron product, together with purge, corrosion, gas-treatment, and avoided-disposal burdens.

To make route comparison transparent without fabricating numerical normalization across incompatible system boundaries, this review proposes—not standardizes—a common reporting basis. Results should be normalized to 1.00 kg of reusable HCl on a 100%-HCl-equivalent basis, while separately reporting the delivered acid-solution concentration (wt%), impurity limits required by the receiving process, and water content/handling in the water and energy balances.

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The co-produced iron material should be reported separately by mass, phase specification, residual chloride, and relevant impurity limits rather than being hidden in the denominator. For TEA/LCA comparisons, the treatment of coproducts must be explicit: system expansion or substitution credit is preferred when a credible displaced product is identifiable, while mass- and economic-allocation sensitivities should be reported when substitution is uncertain. Table 6 therefore uses this basis as an author-proposed reporting framework, not as an established LCA functional unit. Where the reviewed literature does not provide a common numerical basis, the table identifies the evidence qualitatively rather than forcing a false quantitative ranking.

Table 6. Decision matrix for thermal, hybrid, and membrane routes under a proposed common reporting basis

Route	Proposed reporting product basis	Representative evidence	Primary benefit	Primary burdens / penalties	Decision metric under common basis
Spray roasting / thermal pyrohydrolysis	1.00 kg HCl equivalent at receiving-process specification + specified Fe oxide	Bascone et al. (2016); Motovilov et al. (2018)	Integrated drying/reaction; high acid-recovery potential; oxide coproduct	Fuel/heat duty; fines; wall deposition; gas cleanup; corrosion	kg reusable HCl; oxide specification/yield; net MJ; Cl closure; purge/emissions
Hybrid extraction + thermal conversion	1.00 kg HCl equivalent at receiving-process specification + higher-purity Fe oxide	Gao et al. (2021)	Removes reusable acid before hot stage; reduces thermal mass load	Additional solvent/separation loop; solvent/reagent recycle	Same functional unit plus solvent loss, recycle duty, and hot-stage mass reduction
Integrated membrane/precipitation	1.00 kg HCl equivalent at receiving-process specification + recovered metals / controlled brine	Gueccia et al. (2021, 2022); Lorenz et al. (2023)	Lower-temperature onsite closure; modular acid/metal recovery	Electricity; membrane fouling/salting; replacement; residual concentrate	kg reusable HCl; electricity; membrane replacement; metal recovery; residual brine
Selective metal removal before reuse	Reusable $FeCl_x$/HCl stream + recovered Zn/other metal	Arguillarena et al. (2022, 2023)	Avoids unnecessary decomposition; preserves useful chloride chemistry	Extraction/electrowinning duty; chemical inventory; impurity management	Fresh-acid displacement; preserved $FeCl_x$ value; metal coproduct; net energy

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Note. Developed by the author from Bascone et al. (2016), Gao et al. (2021), Gueccia et al. (2021, 2022), Arguillarena et al. (2022, 2023), Lorenz et al. (2023), and the decision variables synthesized in this review. The proposed basis is 1.00 kg HCl equivalent meeting the receiving-process concentration and impurity specification, with solution water and the iron coproduct reported separately. Coproduct substitution/credit or allocation assumptions must be stated explicitly. This is a reporting framework, not a standardized LCA functional unit, and the cited studies do not share identical system boundaries.

10.2. Emissions, chlorine closure, and secondary risk

The principal environmental risk is incomplete chlorine closure. HCl and Cl_2 emissions are corrosive and toxic; volatile metal chlorides can transfer metals to downstream dust; chloride-rich solids can complicate disposal or reuse; and purge streams can accumulate salts. In organic-containing feeds, chlorine can drive undesirable secondary chemistry, including conditions associated with PCDD/F formation when carbon, catalytic metals, oxygen, and inappropriate temperature histories coexist (Pereira, 2026). High-efficiency gas capture therefore serves both resource recovery and emission control.

Report chlorine performance with two complementary metrics. The first is analytical chlorine-accounting closure, CCl, which tests whether the measured outputs reconcile with the chlorine entering the defined system boundary:

$$CCl = (\Sigma k\ nCl,k,out,measured) / nCl,in \quad (7)$$

where k includes reusable HCl or Cl_2, specified products, residual solid chloride, dust, condensates, liquid purges, volatile metal chlorides, and quantified controlled emissions. A value near unity indicates a complete analytical mass balance; it does not, by itself, demonstrate circularity. A second metric, the reusable-chlorine fraction, ηCl,reuse, should therefore be reported:

ηCl,reuse = nCl,in specification-compliant streams that displace virgin chlorine input / nCl,in (8)

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Equations 7 and 8 separate mass-balance completeness from useful reagent regeneration. They also prevent a process with fully measured but environmentally undesirable chlorine losses from being described as highly circular merely because the analytical balance closes.

Corrosion is an environmental and economic burden because metal loss creates maintenance demand, contamination, unplanned shutdowns, and secondary waste. The corrosion literature for $FeCl_3$-containing molten salts and Fe–O–Cl atmospheres shows that chloride chemistry can defeat otherwise protective alloy scales (Bai et al., 2021; Kaczmarczyk & Gurgul, 2024; Li et al., 2025; Lu et al., 2023; Yang et al., 2024). Corrosion allowance, alloy choice, refractory design, and cold-spot elimination should therefore be part of the environmental inventory rather than treated solely as mechanical reliability issues.

10.3. Product valorization and the value of avoiding overprocessing

Circularity improves when the solid product has a defined use. High-purity hematite can have pigment or raw-material value; magnetite-rich products may suit other applications; iron chloride itself may be reusable after impurity removal, as demonstrated by pilot valorization of purified pickling acid (Arguillarena et al., 2023). In some cases, therefore, decomposing $FeCl_2$ to oxide would destroy a useful intermediate and consume unnecessary energy. The preferred route depends on local demand for acid, iron chloride, iron oxide, zinc, or other recovered metals.

The same argument applies to catalyst/reagent loops in carbon processing. Gonzalez-Aguirre et al. (2026) and Kim et al. (2026) address recovery/reuse of iron catalyst and process acid in catalytic graphitization systems. Their specific economics do not transfer to pickling, but the design principle is to recycle the reagent in the chemical form that minimizes total separation and reconversion work. This principle favors a decision tree rather than a universal “decompose and regenerate” policy.

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11. Integrated Critical Framework and Research Priorities

11.1. The reaction–transport–recycle (RTR) framework

The evidence reviewed here supports an author-developed conceptual reaction–transport–recycle (RTR) framework for iron-chloride processes. It is intended as a structured decision aid and has not yet been prospectively validated as a formal quantitative scale-up scoring system. R1—Reaction asks what phases and gas species are accessible at the local T–p(H_2O)–p(O_2)–p(HCl)/p(Cl_2) state, with outputs such as conversion, selectivity, phase fraction, and residual chloride. R2—Transport asks whether heat and reactive gases reach the interface and products leave it fast enough, with outputs such as characteristic times, particle/droplet history, residence-time distribution (RTD), entrainment, and morphology. R3—Recycle asks whether the resulting HCl, iron product, water, heat, impurities, and purge streams have sufficient quality and value to close an industrial loop. Two types of gate failure must be distinguished: evidence failure means that available data are insufficient to justify scale-up, whereas technical failure means that the requirement has been tested and demonstrably cannot be met under the specified design. Accordingly, inadequate evidence should lead to the conclusion that scale-up cannot yet be justified, not that the underlying process is intrinsically invalid.

The framework reconciles apparently contradictory literature by assigning each observation to the correct gate. A low-temperature FeOCl synthesis and a high-temperature hematite roaster can both be valid because their pressure, steam potential, dimensions, and gas renewal differ at R1 and R2. A chlorination study can achieve high Ni/Cu/Co extraction even while $FeCl_3$ is thermally unstable because useful chloride transfer occurs before or alongside decomposition. A membrane route can outperform thermal regeneration for acid recovery at R3 but is unsuitable when producing a specified iron oxide is itself valuable. The useful question is therefore not "What is

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the decomposition temperature?" but "Which pathway dominates locally, what transport resistance controls its realization, and which recycle structure creates the highest system value?"

11.2. Applying RTR to route selection

For spray roasting, R1 requires $FeCl_x$-to-oxide/HCl chemistry with acceptable residual chloride and phase specification; R2 requires droplet-size/RTD control, adequate gas renewal, limited wall deposition, and recoverable fines; R3 requires HCl at reusable concentration, saleable or usable oxide, meaningful heat recovery, and manageable corrosion/purge. For hybrid extraction plus thermal treatment, R1 shifts upstream by recovering reusable acid before the hot stage, R2 benefits from lower hot-stage mass loading, and R3 must include solvent/reagent recovery as well as the HCl/oxide loop. For membrane-centered routes, the dominant R2 constraints become membrane mass transfer, fouling, and concentration limits, while R3 is judged by acid quality, recovered metals, residual brine, electricity, and replacement burden. Figure 5 summarizes these gates as a route-selection tool rather than a purely descriptive framework.

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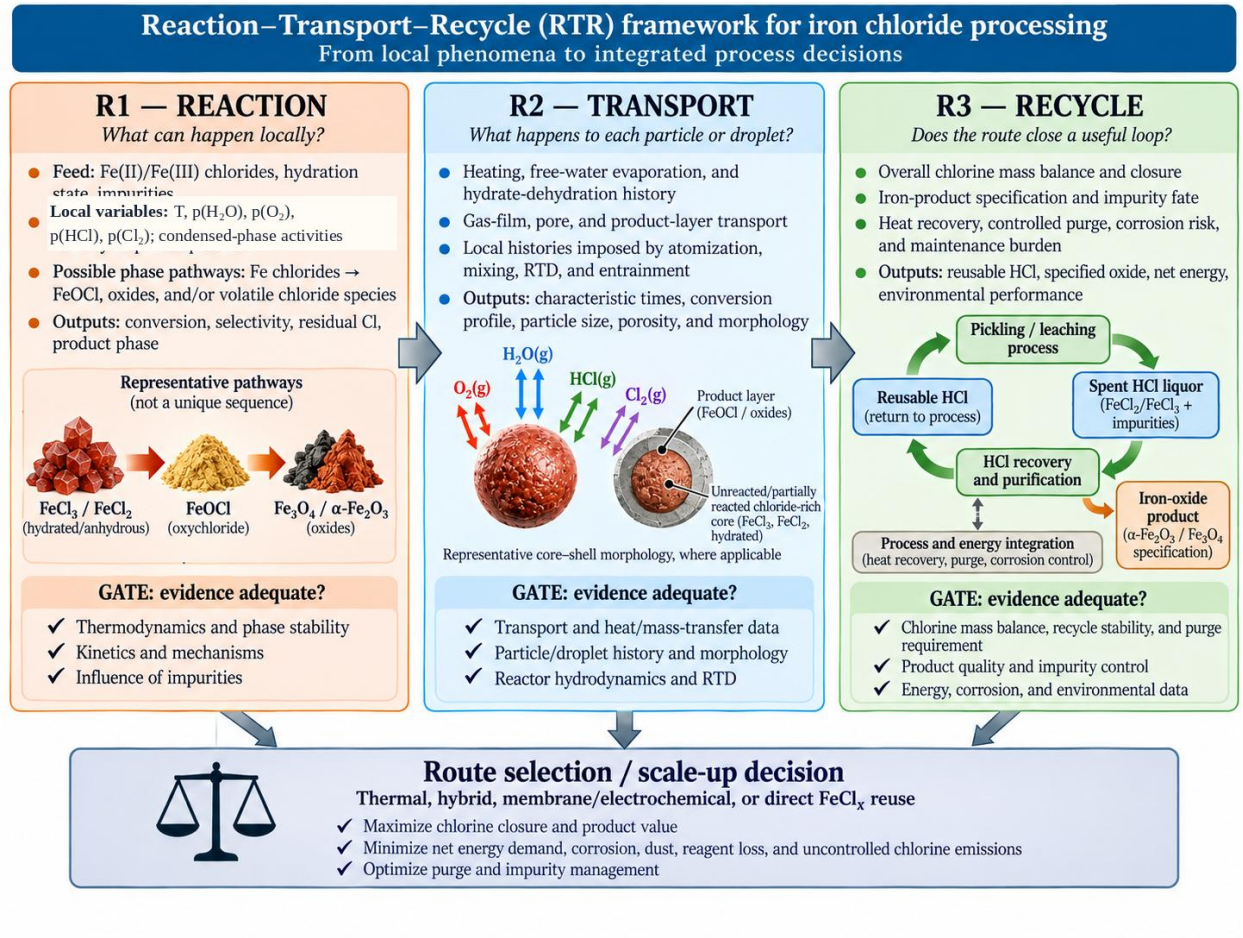

Figure 5. Operational reaction–transport–recycle (RTR) framework for route selection and scale-up.

Note. Developed by the author from the evidence classes and scale-up variables synthesized in this review. RTR is an author-developed conceptual decision framework and has not yet been prospectively validated as a quantitative scoring system. Each gate requires evidence appropriate to its physical scale. Evidence failure means that scale-up cannot yet be justified; technical failure means that a tested requirement is not met. The two should not be conflated.

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The operational form of RTR is intended to prevent category errors in both experiments and process comparison. Reaction evidence should not be used to infer plant performance without transport characterization; reactor conversion should not be reported as chlorine closure without the downstream gas/acid balance; and a recycle arrow should not be counted as circularity unless the recovered stream meets a defined quality and displaces a real fresh-material or energy duty.

11.3. Priority research gaps

Table 7 lists the research priorities emerging from the evidence base. The revised agenda links each gap to a specific decision that the available literature cannot yet support. Evidence density is strongest for qualitative phase/process behavior and weakest for complete multicomponent thermodynamics, intrinsic gas–solid kinetics, full chlorine closure, and long-duration closed-loop pilot operation.

Table 7. Priority research agenda for iron-chloride thermal processing

Priority	Specific gap	Recommended approach	Decision enabled
1. Multicomponent thermodynamics	Limited activity-based Fe–Cl–O–H–M databases for concentrated/mixed chlorides	Calorimetry/electrochemistry + assessed thermodynamic models; validate against Xu et al. (2025)-type property data	Predict hydrolysis, volatilization, melting, and corrosion windows
2. In situ phase/speciation	Transient FeOCl/oxyhydroxide/chloride phases are often inferred after quenching	High-temperature X-ray diffraction (XRD), X-ray absorption spectroscopy (XAS), Raman spectroscopy, and mass spectrometry (MS) with controlled steam/O_2/HCl	Identify actual sequence and bypass reactions
3. Intrinsic kinetics	Apparent kinetics confound reaction and diffusion	Differential-conversion experiments, multiple particle sizes and gas velocities, coupled microkinetic/transport fitting	Transfer rate law across scale and reactor type

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Priority	Specific gap	Recommended approach	Decision enabled
4. Chlorine mass-balance closure	HCl, Cl_2, volatile metal chlorides, and residual solid chloride not always measured together	Full gas/solid/liquid Cl balance with online HCl/Cl_2 and condensate analysis; report CCl and ηCl,reuse using Equations 7–8	Separate conversion from volatilization and capture loss
5. Real-feed impurity effects	Pure $FeCl_x$ data underrepresent Zn/Mg/Ca/Na/Al/Cr/P and organics	Designed impurity matrix plus real industrial campaigns	Define feed acceptance and pretreatment specifications
6. Corrosion-aware process design	Chemistry optimization and materials selection often separate	Simultaneous corrosion coupons/probes, deposit analysis, and process chemistry modeling	Set safe temperature/gas windows and realistic maintenance cost
7. Integrated TEA–LCA	Energy, acid quality, oxide value, emissions, and avoided transport are inconsistently bounded	Common functional unit: kg reusable HCl + specified iron product; scenario/sensitivity analysis	Choose thermal, hybrid, or membrane route transparently
8. Continuous pilot validation	Short batch tests underresolve fouling, salt accumulation, and recycle drift	Weeks-to-months campaigns with closed water/acid loops and impurity purge control	Establish industrial readiness and control strategy

Note. Developed by the author from Bascone et al. (2016), Motovilov et al. (2018), Yang et al. (2020), Gueccia et al. (2021), Zhou et al. (2021), Arguillarena et al. (2022, 2023), Liu et al. (2023), Xu et al. (2025), and Wei et al. (2025).

The first priority is thermodynamic non-ideality. Xu et al. (2025), He et al. (2024), and Gesualdi et al. (2025) show that multicomponent molten-chloride properties and $FeCl_2$ activity cannot be inferred reliably from ideal mixing. Comparable assessed activity models are still needed for the concentrated-aqueous-to-molten transition encountered during liquor drying. Without them, equilibrium diagrams can misplace boundaries for hydrolysis, volatilization, melting, and corrosion.

The second and third priorities are mechanistic observability and kinetic separation. Within the reviewed corpus, Zhou et al. (2021) provide a rare direct in situ view of chlorine evolution during chloride pyrohydrolysis, while Peterson et al. (2016) demonstrate the value of time-resolved phase tracking. Equivalent high-temperature measurements focused directly on

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$FeCl_2/FeCl_3$ under controlled steam, oxygen, and HCl/Cl_2 are needed to distinguish FeOCl, oxyhydroxide, molten chloride, and oxide stages. These measurements should be paired with particle-size and gas-velocity variation so that gas-film and product-layer resistance are not folded into nominally intrinsic rate constants.

The fourth priority is chlorine closure. Many studies quantify metal extraction, oxide formation, or acid recovery but do not report HCl, Cl_2, volatile metal chlorides, condensates, dust, and residual solid chloride together. This prevents a rigorous distinction between chemical conversion, volatilization, entrainment, absorption loss, and true reagent recycle. Full chlorine closure should therefore become a standard performance metric analogous to metal recovery.

The fifth through eighth priorities move from chemistry to industrial readiness. Real feeds must be tested because impurity-controlled phase behavior is well documented; corrosion must be measured concurrently because $FeCl_3$-containing salts and vapors can be materials-limiting; TEA and LCA must use comparable functional units; and continuous recycle campaigns are required to reveal impurity build-up, purge requirements, membrane/absorber drift, and deposit formation. In this sense, the next advances are less likely to come from another isolated decomposition curve than from integrated experiments that connect local chemistry to plant mass balance and materials performance. For broader context on emerging iron technologies, see Oarga-Mulec et al. (2024).

11.4. Limitations and boundary conditions

A principal limitation of the available literature is the scarcity of full-scale studies that simultaneously quantify reactor conversion, transient phase evolution, gas speciation, transport or RTD, corrosion, and complete chlorine mass balances. Most evidence resolves only part of that coupled problem. Consequently, the proposed RTR framework should be interpreted as a conceptual structure for identifying evidence requirements, not as an independently validated predictive model. Continuous real-feed pilot campaigns that measure chemistry, transport,

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corrosion, and recycle performance together remain a priority (Bascone et al., 2016; Gao et al., 2021; Gueccia et al., 2021).

The breadth of applications reviewed also creates transferability limits. Direct $FeCl_2$/$FeCl_3$ hydrolysis and spray-roasting studies support the core thermal-processing conclusions, whereas functional FeOCl synthesis, carbonaceous pyrolysis, $CaCl_2$/$MgCl_2$ pyrohydrolysis, thermochemical hydrogen cycles, and selected molten-salt systems are used only as mechanistic analogs, process/materials analogs, or system-level comparators. Such boundary evidence establishes plausible pathways, measurement strategies, or design constraints, but it is not used to define intrinsic industrial $FeCl_x$ kinetics or universal operating windows.

12. Conclusions

Iron-chloride thermal processing is best understood as a coupled Fe–Cl–O–H reaction network operating within transport- and recycle-constrained equipment. $FeCl_2$ and $FeCl_3$ do not share a universal decomposition temperature or kinetic constant. Hydrolysis, oxidation, reduction, volatilization, FeOCl formation, oxyhydroxide transformation, hematite/magnetite formation, chloride transfer, and re-chlorination can overlap, and their relative importance changes with hydration state, local steam and oxygen partial pressures, chlorine-bearing gas activity, pressure, heating history, particle or droplet size, and impurities. Quantitative literature values are therefore most useful as operating anchors tied to fully described experimental conditions rather than as transferable thresholds. Apparent rates can embed heat transfer, evaporation, gas-film transport, product-layer diffusion, phase transformation, and residence-time distribution; industrial scale-up should separate intrinsic chemistry from transport wherever possible and should close the chlorine balance across gases, solids, condensates, dust, and recovered acid. HCl regeneration is compelling when the recovered acid is reusable and the iron product meets a defined specification, whereas hybrid or membrane routes may be preferable when thermal conversion adds unnecessary energy

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demand or destroys a valuable chloride stream. The author-developed RTR framework is the principal conceptual design outcome of this review, but it is not yet a validated quantitative scoring system. Scale-up can be justified only when evidence is adequate across reaction, transport, and recycle requirements; insufficient evidence should be distinguished from demonstrated technical failure. Future progress therefore depends less on additional isolated decomposition curves than on multicomponent activity models, in situ phase/speciation measurements, transport-separated kinetics, real-feed continuous pilots, corrosion-aware reactor design, complete chlorine accounting, and harmonized techno-economic/life-cycle assessment under a clearly specified reporting basis.

Declarations

Funding

This review received no specific external funding.

Conflict of Interest

The author declares no conflict of interest.

Data Availability

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

Author Contributions

The author was responsible for conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

References

Agarwal, C., & Pandey, A. K. (2023). Remediation and recycling of inorganic acids and their green alternatives for sustainable industrial chemical processes. *Environmental Science: Advances, 2*, 1306–1339. https://doi.org/10.1039/D3VA00112A

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/08/2026 - **Accepted:** 21/09/2026
Vol: 01.05
DOI: 10.66104/a1p8y062
Pages: 1-57

Agarwal, P., & Bora, D. K. (2021). Quasicrystal symmetry in single-crystalline hematite nano octahedron grown from FeOCl nanoparticles. *Materials Science in Semiconductor Processing, 131*, Article 105873. https://doi.org/10.1016/j.mssp.2021.105873

Agarwal, P., Preethi, J. B., & Bora, D. K. (2021). Direct thermal decomposition of $FeCl_3 \cdot 6H_2O$ in oleic acid forms hematite cube and nano-octahedron structures with quasicrystalline and supercell symmetries for enhanced photoelectrochemical functionality. *Materials Chemistry and Physics, 273*, Article 124977. https://doi.org/10.1016/j.matchemphys.2021.124977

Ahmed, O. H., Altarawneh, M., Al-Harahsheh, M., Jiang, Z.-T., & Dlugogorski, B. Z. (2019). Catalytic de-chlorination of products from PVC degradation by magnetite (Fe_3O_4). *Applied Surface Science, 480*, 792–801. https://doi.org/10.1016/j.apsusc.2019.03.017

Ahmed, O. H., Altarawneh, M., Jiang, Z.-T., Al-Harahsheh, M., & Dlugogorski, B. Z. (2017). Reactions of products from thermal degradation of PVC with nanoclusters of α-Fe_2O_3 (hematite). *Chemical Engineering Journal, 323*, 396–405. https://doi.org/10.1016/j.cej.2017.04.047

Alcaraz, L., Sotillo, B., Marco, J. F., Alguacil, F. J., Fernández, P., & López, F. A. (2021). Obtention and characterization of ferrous chloride $FeCl_2 \cdot 4H_2O$ from water pickling liquors. *Materials, 14*(17), Article 4840. https://doi.org/10.3390/ma14174840

Anderez, A., Alguacil, F. J., & López, F. A. (2022). Acid pickling of carbon steel. *Revista de Metalurgia, 58*(3), e226. https://doi.org/10.3989/revmetalm.226

Arguillarena, A., Margallo, M., Arruti-Fernández, A., Pinedo, J., Gómez, P., Ortiz, I., & Urtiaga, A. (2023). Circular economy in hot-dip galvanizing with zinc and iron recovery from spent pickling acids. *RSC Advances, 13*, 6481–6489. https://doi.org/10.1039/D2RA08195D

Arguillarena, A., Margallo, M., Irabien, Á., & Urtiaga, A. (2022). Life cycle assessment of zinc and iron recovery from spent pickling acids by membrane-based solvent extraction and electrowinning. *Journal of Environmental Management, 318*, Article 115567. https://doi.org/10.1016/j.jenvman.2022.115567

Bai, L., Peng, W., Men, D., Zhu, J., Wu, X., Shi, X., Xiang, J., Deng, X., Wang, Y., Sun, Z., Yu, S., & Wei, X. (2021). High temperature chloride corrosion behavior of 904L:AlFeNiMoNb high-entropy alloy. *Frontiers in Materials, 8*, Article 764928. https://doi.org/10.3389/fmats.2021.764928

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/08/2026 - **Accepted:** 21/09/2026
Vol: 01.05
DOI: 10.66104/a1p8y062
Pages: 1-57

Bascone, D., Cipollina, A., Morreale, M., Randazzo, S., Santoro, F., & Micale, G. (2016). Simulation of a regeneration plant for spent pickling solutions via spray roasting. *Desalination and Water Treatment, 57*, 23405–23419. https://doi.org/10.1080/19443994.2015.1137146

Batygina, M. V., Dobrynkin, N. M., & Noskov, A. S. (2016). Synthesis of boehmite and hematite by joint hydrolysis of carbamide, aluminum chloride, and iron(III) chloride under hydrothermal conditions. *Russian Journal of Applied Chemistry, 89*(11), 1763–1768. https://doi.org/10.1134/S1070427216110057

Binnemans, K., & Jones, P. T. (2023). The twelve principles of circular hydrometallurgy. *Journal of Sustainable Metallurgy, 9*, 1–25. https://doi.org/10.1007/s40831-022-00636-3

Cao, Y., Cui, K., Chen, Y., Cui, M., Li, G., Li, D., & Yang, X. (2021). Efficient degradation of tetracycline by H_2O_2 catalyzed by FeOCl: A wide range of pH values from 3 to 7. *Solid State Sciences, 113*, Article 106548. https://doi.org/10.1016/j.solidstatesciences.2021.106548

Chen, C., Yu, T., Yang, M., Zhao, X., & Shen, X. (2019). An all-solid-state rechargeable chloride ion battery. *Advanced Science, 6*, Article 1802130. https://doi.org/10.1002/advs.201802130

Chen, J., Macfarlane, S., Zhang, C., Yu, K., & Zhou, W. (2017). Chemistry of hydrolysis of $FeCl_3$ in the presence of phosphate to form hematite nanotubes and nanorings. *Crystal Growth & Design, 17*, 5975–5983. https://doi.org/10.1021/acs.cgd.7b01083

Chen, Y., Miller, C. J., Collins, R. N., & Waite, T. D. (2021). Key considerations when assessing novel Fenton catalysts: Iron oxychloride (FeOCl) as a case study. *Environmental Science & Technology, 55*(19), 13317–13325. https://doi.org/10.1021/acs.est.1c04370

Chepushtanova, T., Altmyshbayeva, A., Merkibayev, Y., Mamyrbayeva, K., Yespenova, Z., & Mishra, B. (2025). Development of technology for processing pyrite–cobalt concentrates to obtain pigments of the composition Fe_2O_3 and Fe_3O_4. *Metals, 15*(8), Article 886. https://doi.org/10.3390/met15080886

Dou, D., Tian, H., Hu, T., Zhou, B., Lin, G., Zhang, L., Song, J., Shi, J., & Yang, Y. (2026). A comprehensive review on the mechanism, applicability and selection of chlorinating agents. Journal of Environmental Chemical Engineering, 14(2), Article 122065. https://doi.org/10.1016/j.jece.2026.122065

Dumbre, D., Amin, M. H., Loh, Q., Choudhary, V. R., Selvakannan, P. R., & Bhargava, S. K. (2016). Nanocrystalline $FeOCl_x$-grafted MCM-41 as an active mesoporous catalyst for

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/08/2026 - **Accepted:** 21/09/2026
Vol: 01.05
DOI: 10.66104/a1p8y062
Pages: 1-57

the solvent-free multi-condensation reaction. *RSC Advances, 6*, 69334–69342. https://doi.org/10.1039/C6RA14736D

Fan, Z.-Y., Wang, L., Zhang, R.-Y., Wang, Y.-Y., Zhang, T.-A., Wang, X.-J., Li, J.-D., Zhao, X.-X., & Li, W.-J. (2025). Research and application mechanism of chlorination roasting for polymetallic minerals and waste. *Minerals Engineering, 232*, Article 109493. https://doi.org/10.1016/j.mineng.2025.109493

Feng, Z., Zhou, B., Li, H., Gai, N., Chen, Y., Yuan, R., Chen, Z., Luo, S., & Chen, H. (2024). Influence of different stalks on the metallization degree of $FeCl_3$-derived magnetic biochar through pyrolysis behavior and compositional differences. *Environmental Research, 259*, Article 119513. https://doi.org/10.1016/j.envres.2024.119513

Gao, Y., Yue, T., Sun, W., He, D., Lu, C., & Fu, X. (2021). Acid recovering and iron recycling from pickling waste acid by extraction and spray pyrolysis techniques. *Journal of Cleaner Production, 312*, Article 127747. https://doi.org/10.1016/j.jclepro.2021.127747

Gesualdi, J., Schneiderlochner, E. S., Lichtenstein, T., & Hawthorne, K. L. (2025). Thermochemical measurements of $FeCl_2$ in LiCl via electromotive force, coulometric titration, and cyclic voltammetry. *Electrochimica Acta, 536*, Article 146694. https://doi.org/10.1016/j.electacta.2025.146694

Gomez-Martin, A., Schnepp, Z., & Ramirez-Rico, J. (2021). Structural evolution in iron-catalyzed graphitization of hard carbons. *Chemistry of Materials, 33*(9), 3087–3097. https://doi.org/10.1021/acs.chemmater.0c04385

Gonzalez-Aguirre, J. A., Islam, M. N., Dutta, A., Sagues, W. J., Rowland, S., & Park, S. (2026). Techno-economic analysis of recycling strategies for catalyst and acid during catalytic graphitization. *Energy Storage Materials, 90*, Article 105414. https://doi.org/10.1016/j.ensm.2026.105414

Gueccia, R., Bogle, D., Randazzo, S., Tamburini, A., Cipollina, A., Winter, D., Koschikowski, J., & Micale, G. (2022). Economic benefits of waste pickling solution valorization. *Membranes, 12*(2), Article 114. https://doi.org/10.3390/membranes12020114

Gueccia, R., Winter, D., Randazzo, S., Cipollina, A., Koschikowski, J., & Micale, G. (2021). An integrated approach for the HCl and metals recovery from waste pickling solutions: Pilot plant and design operations. *Chemical Engineering Research and Design, 168*, 383–396. https://doi.org/10.1016/j.cherd.2021.02.016

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/08/2026 - **Accepted:** 21/09/2026
Vol: 01.05
DOI: 10.66104/a1p8y062
Pages: 1-57

He, Y., Xu, J., Ma, Z., Pang, Z., Zhu, F., Zou, X., & Lu, X. (2024). Study on the influences of melt components on the physical properties of molten salt chlorination system. *Iron Steel Vanadium Titanium, 45*(4), 8–15, 28.

Höber, L., Witt, K., & Steinlechner, S. (2022). Selective chlorination and extraction of valuable metals from iron precipitation residues. *Applied Sciences, 12*(7), Article 3590. https://doi.org/10.3390/app12073590

Kaczmarczyk, R., & Gurgul, S. (2024). Thermodynamic analysis of chloride corrosion in steel for energy system applications in Fe-O-Cl-Na environments. *Energies, 17*(13), Article 3223. https://doi.org/10.3390/en17133223

Kaczmarczyk, R., & Mlonka-Mędrala, A. (2016). Chloride corrosion in biomass-fired boilers—Fe-O-Cl system thermodynamic analysis. *E3S Web of Conferences, 10*, Article 00060. https://doi.org/10.1051/e3sconf/20161000060

Kargin, J., Sanchez Cornejo, H., Konyukhov, Y. V., Lileev, A. S., Kozlovskiy, A., Albino Aguiar, J., Silva, V. A. J., Celis Rojas, S. R., Barnes, C. H. W., & De Los Santos Valladares, L. (2025). Thermal-reduction and -oxidation of iron oxide slags generated from rolling mill steel industry. *Heat Treatment and Surface Engineering, 7*(1), Article 2494356. https://doi.org/10.1080/25787616.2025.2494356

Kim, K.-J., Huynh, N. T., Lee, Y., Nguyen, T., Pham, V. H., Gao, Y., Li, Y., Bhandari, G., Wang, C., & Matranga, C. (2026). Highly crystalline, low-ash, graphite from coal using an Fe_2O_3-based catalytic process with recovery and reuse of catalyst and process acid. *Carbon, 246*, Article 120920. https://doi.org/10.1016/j.carbon.2025.120920

Li, X., Meng, B., Pan, T. J., Lu, P., & Tang, Z. (2025). Effects of $FeCl_3$ concentration on corrosion of 316 stainless steel in NaCl–$MgCl_2$ molten salt vapor at 600 °C. *Solar Energy Materials and Solar Cells, 292*, Article 113751. https://doi.org/10.1016/j.solmat.2025.113751

Li, Y., Zhu, M., & Ding, T. (2026). Iron oxychloride (FeOCl)-based materials as high-performance heterogeneous Fenton-like catalysts: Crystal structure, reaction mechanisms, material engineering, and environmental applications. *Catalysts, 16*(8), Article 703. https://doi.org/10.3390/catal16080703

Liu, C., Zhou, S., Yu, D., Etschmann, B., & Zhang, L. (2023). Flowsheet modelling and techno-economic analysis of CO_2 capture coupled pyro-hydrolysis of $CaCl_2$ waste for HCl acid regeneration. *Journal of Cleaner Production, 419*, Article 138195. https://doi.org/10.1016/j.jclepro.2023.138195

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/08/2026 - **Accepted:** 21/09/2026
Vol: 01.05
DOI: 10.66104/a1p8y062
Pages: 1-57

Liu, J., Tao, L., Guan, H., Chen, Z., Evrendilek, F., Jia, D., Chen, J., Yao, C., He, Y., Cai, B., Huang, J., Li, W., & Huang, W. (2026). Influence of $FeCl_3$ addition on sulfur and chlorine retention and transformation during pyrolysis of textile-dyeing sludge under N_2 and CO_2 atmospheres. *Fuel, 410*, Article 137868. https://doi.org/10.1016/j.fuel.2025.137868

Lorenz, M., Seitfudem, G., Randazzo, S., Gueccia, R., Gehring, F., & Prenzel, T. M. (2023). Combining membrane and zero brine technologies in waste acid treatment for a circular economy in the hot-dip galvanizing industry: A life cycle perspective. *Journal of Sustainable Metallurgy, 9*, 537–549. https://doi.org/10.1007/s40831-023-00668-3

Lu, P., Liu, Q., Bao, H., Pan, T. J., & Tang, Z. (2023). Effect of $FeCl_3$ in NaCl–$MgCl_2$ molten salts on the corrosion behavior of 316 stainless steel at 600 °C. *Corrosion Science, 212*, Article 110961. https://doi.org/10.1016/j.corsci.2023.110961

Lv, C., Sun, M.-H., & Yin, H.-X. (2021). The effect of pyrolysis conditions on the preparation of Fe_2O_3 particles using simulated pickling liquor in a Venturi reactor. *Frontiers in Materials, 8*, Article 733257. https://doi.org/10.3389/fmats.2021.733257

Motovilov, I. Y., & Luganov, V. A. (2016). High-temperature hydrolysis of iron (II) chloride. *Gornyi Zhurnal Kazakhstana*, (1), 41–46.

Motovilov, I. Y., Luganov, V. A., Mishra, B., & Chepushtanova, T. A. (2018). Oxide powders production from iron chloride. *CIS Iron and Steel Review, 15*, 28–32. https://doi.org/10.17580/cisisr.2018.01.06

Mu, W., Cheng, H., Xu, J., Luo, S., Zhai, Y., & Xu, Q. (2021). Extraction of valuable metals from low-grade nickel matte by $FeCl_3 \cdot 6H_2O$ roasting and water leaching process with studies on phase evolution and kinetics analysis of chlorination process. *Hydrometallurgy, 202*, Article 105614. https://doi.org/10.1016/j.hydromet.2021.105614

Niazi, S., Olsen, E., & Nygård, H. S. (2022). Electrochemical removal of Cu, Fe and Mn from molten $ZnCl_2$:KCl:NaCl. *Separation and Purification Technology, 299*, Article 121705. https://doi.org/10.1016/j.seppur.2022.121705

Oarga-Mulec, A., Luin, U., & Valant, M. (2024). Back to the future with emerging iron technologies. *RSC Advances, 14*, 20765–20779. https://doi.org/10.1039/D4RA03565H

Özkaya, M., Acır, A., & Yalçın, Ş. (2023). Investigation of the hydrogen production of the PACER fusion blanket integrated with Fe–Cl thermochemical water splitting cycle. *Nuclear Engineering and Technology, 55*(11), 4287–4294. https://doi.org/10.1016/j.net.2023.08.007

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/08/2026 - **Accepted:** 21/09/2026
Vol: 01.05
DOI: 10.66104/a1p8y062
Pages: 1-57

Pereira, A. C. (2026). Avoiding PCDD/F formation in metal chloride–based chlorination–calcination processes: Mechanisms, risk factors and best available practices. *Revista Multidisciplinar do Nordeste Mineiro, 2*(2), 1–47. https://doi.org/10.66104/72db6485

Peterson, K. M., Heaney, P. J., & Post, J. E. (2016). A kinetic analysis of the transformation from akaganeite to hematite: An in situ time-resolved X-ray diffraction study. *Chemical Geology, 444*, 27–36. https://doi.org/10.1016/j.chemgeo.2016.09.017

Riabik, P., & Amosov, A. (2025). Analytical review of obtaining oxide compounds from chloride pickling solutions. *Collection of Scholarly Papers of Dniprovsk State Technical University (Technical Sciences), 1*(46), 170–177. https://doi.org/10.31319/2519-2884.46.2025.20

Robić, M., Ristić, M., Krehula, S., & Musić, S. (2022). Forced hydrolysis of $FeCl_3$ solutions in the presence of guanylurea phosphate. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 634*, Article 128047. https://doi.org/10.1016/j.colsurfa.2021.128047

Robić, M., Ristić, M., Kuzmann, E., Homonnay, Z., Krehula, S., & Musić, S. (2021). Forced hydrolysis of $FeCl_3$ solutions in the presence of Cr^{3+} ions. *Journal of Physics and Chemistry of Solids, 156*, Article 110166. https://doi.org/10.1016/j.jpcs.2021.110166

Safari, F., & Dincer, I. (2020). A study on the Fe–Cl thermochemical water splitting cycle for hydrogen production. *International Journal of Hydrogen Energy, 45*(38), 18867–18875. https://doi.org/10.1016/j.ijhydene.2020.04.208

Stefenon, F. L., Jaerger, S., Schneider, R., Anaissi, F. J., & González-Borrero, P. P. (2026). Synthesis and characterisation of iron oxides: Effect of calcination temperature and their application as inorganic pigment. Coloration Technology, 142(2), 222–235. https://doi.org/10.1111/cote.12826

Steinlechner, S., & Witt, K. (2023). Simultaneous extraction of valuable metals from iron-containing residues by selective chlorination and evaporation. *Mining, Metallurgy & Exploration, 40*, 2023–2036. https://doi.org/10.1007/s42461-023-00872-5

Sun, Z., Wang, X., Jia, S., Liang, J., Ning, X., & Li, C. (2024). Fabrication of pollution-free coal gangue-based catalytic material utilizing ferrous chloride as an activator for efficient peroxymonosulfate activation. *International Journal of Coal Science & Technology, 11*, Article 5. https://doi.org/10.1007/s40789-023-00659-5

Taninouchi, Y.-K., & Okabe, T. H. (2018). Effective alloying treatment for platinum using iron chloride vapor. *Materials Transactions, 59*(1), 88–97. https://doi.org/10.2320/matertrans.M-M2017844

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/08/2026 - **Accepted:** 21/09/2026
Vol: 01.05
DOI: 10.66104/a1p8y062
Pages: 1-57

Taninouchi, Y.-K., Sunagawa, K., Okabe, T. H., & Nakano, H. (2024). Iron chloride vapor treatment for leaching platinum group metals from spent catalysts. *Journal of Sustainable Metallurgy, 10*, 2227–2240. https://doi.org/10.1007/s40831-024-00910-6

Tao, L., Guan, H., He, Y., Chen, Z., Evrendilek, F., Chen, T., Zhong, S., Li, L., Huang, W., Li, W., & Liu, J. (2026). Dual role of $FeCl_3$ in metal stabilization and volatilization during multi-atmosphere pyrolysis of high-sulfur textile dyeing sludge. *Fuel, 407*, Article 137233. https://doi.org/10.1016/j.fuel.2025.137233

Valant, M., & Luin, U. (2024). Chemistry of the iron-chlorine thermochemical cycle for hydrogen production utilizing industrial waste heat. *Journal of Cleaner Production, 438*, Article 140681. https://doi.org/10.1016/j.jclepro.2024.140681

Wei, A., Mu, W., Han, M., Shi, G., Lei, X., & Luo, S. (2025). Recycling of valuable metals from low-grade nickel sulfide ores by preroasting followed by chlorination with $FeCl_3 \cdot 6H_2O$: Thermodynamics, kinetics, and process intensification. *Inorganic Chemistry, 64*(39), 19842–19854. https://doi.org/10.1021/acs.inorgchem.5c03528

Xing, Z., Cheng, G., Yang, H., Xue, X., & Jiang, P. (2020). Mechanism and application of the ore with chlorination treatment: A review. *Minerals Engineering, 154*, Article 106404. https://doi.org/10.1016/j.mineng.2020.106404

Xu, J., Tian, F., Zhu, F., Pang, Z., Ma, Z., Miao, H., Zhang, X., Han, C., Xu, Q., Zou, X., & Lu, X. (2025). Molecular dynamics simulations of ionic transport, local structures, and physicochemical properties of multi-component $NaCl–MgCl_2–CaCl_2–FeCl_2/FeCl_3$ molten salt systems. *Materials Today Communications, 45*, Article 112271. https://doi.org/10.1016/j.mtcomm.2025.112271

Yamamoto, M., Takamura, Y., Kokubo, Y., Urushihara, M., Horiuchi, N., Dai, W., Hayasaka, Y., Kita, E., & Takao, K. (2023). Solid-state Schikorr reaction from ferrous chloride to magnetite with hydrogen evolution as the kinetic bottleneck. *Inorganic Chemistry, 62*(36), 14580–14589. https://doi.org/10.1021/acs.inorgchem.3c01676

Yan, Q., Li, J., Zhang, X., Zhang, J., & Cai, Z. (2018). Synthetic bio-graphene-based nanomaterials through different iron catalysts. *Nanomaterials, 8*(10), Article 840. https://doi.org/10.3390/nano8100840

Yang, F., Wu, Y., Fang, X., & Ma, L. (2020). Experimental and theoretical study on the behavior of a pickling solution: The role of ferrous ions. *Journal of Cleaner Production, 243*, Article 118631. https://doi.org/10.1016/j.jclepro.2019.118631

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Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/08/2026 - **Accepted:** 21/09/2026
Vol: 01.05
DOI: 10.66104/a1p8y062
Pages: 1-57

Yang, Z., Yin, H., Guo, F., Chen, L., Lai, X., Chen, S., Wang, Y., & Tang, Z. (2023). Design optimization and key thermophysical properties of the NaCl–KCl–$FeCl_3$ molten salts for low-temperature thermal energy storage. *Journal of Energy Storage, 72*, Article 108255. https://doi.org/10.1016/j.est.2023.108255

Yang, Z., Yin, H., Guo, F., Chen, L., Lai, X., & Tang, Z. (2024). Corrosion behavior and mechanism of 316 stainless steel in NaCl–KCl–$FeCl_3$ molten salt and vapor at 300 °C. *Materials and Corrosion, 75*(2), 266–274. https://doi.org/10.1002/maco.202313895

Yin, S., Yi, H., Liu, M., Yang, J., Yang, S., Zhang, B.-W., Chen, L., Cheng, X., Huang, H., Huang, R., Jiang, Y., Liao, H., & Sun, S. (2024). An in situ exploration of how Fe/N/C oxygen reduction catalysts evolve during synthesis under pyrolytic conditions. *Nature Communications, 15*, Article 6229. https://doi.org/10.1038/s41467-024-50629-x

Yoshimura, A., Mizoguchi, M., Maeda, Y., Sano, M., Okuda, K., & Matsuno, Y. (2026). Recovery of neodymium from spent neodymium magnets using “dry aqua regia”. *Journal of Sustainable Metallurgy, 12*, 3948–3961. https://doi.org/10.1007/s40831-026-01525-9

Yu, T., Li, Q., Zhao, X., Xia, H., Ma, L., Wang, J., Meng, Y. S., & Shen, X. (2017). Nanoconfined iron oxychloride material as a high-performance cathode for rechargeable chloride ion batteries. *ACS Energy Letters, 2*, 2341–2348. https://doi.org/10.1021/acsenergylett.7b00699

Yu, T., Xing, A., Wang, S., Zhao, D., & Liang, S. (2023). Growth of FeOCl nanoparticles via thermal decomposition under reduced pressure and rotation. *Journal of Crystal Growth, 609*, Article 127147. https://doi.org/10.1016/j.jcrysgro.2023.127147

Zhang, J., Liu, G., Wang, P., & Liu, S. (2017). Facile synthesis of FeOCl/iron hydroxide hybrid nanosheets: Enhanced catalytic activity as a Fenton-like catalyst. *New Journal of Chemistry, 41*, 10339–10346. https://doi.org/10.1039/C7NJ01993A

Zhong, P., Mu, W., Li, L., Gu, M., Xin, H., Lei, X., & Luo, S. (2022). Extraction of metals from nickel concentrate via $FeCl_3 \cdot 6H_2O$ chlorination followed by water leaching and the preparation of (Ni,Cu)Fe_2O_4 catalyst. *Minerals Engineering, 188*, Article 107826. https://doi.org/10.1016/j.mineng.2022.107826

Zhou, S., Etschmann, B., Qian, B., Liu, C., & Zhang, L. (2021). Synchrotron X-ray absorption spectroscopy study of the evolution of chlorine during the pyro-hydrolysis of calcium and magnesium chloride waste. *Waste Management, 120*, 608–615. https://doi.org/10.1016/j.wasman.2020.10.026

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