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Controlling Co-Precipitation in Hydrometallurgy: From Physicochemical Parameters to Process Design and Technology Readiness

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ABSTRACT **Original Research Article**

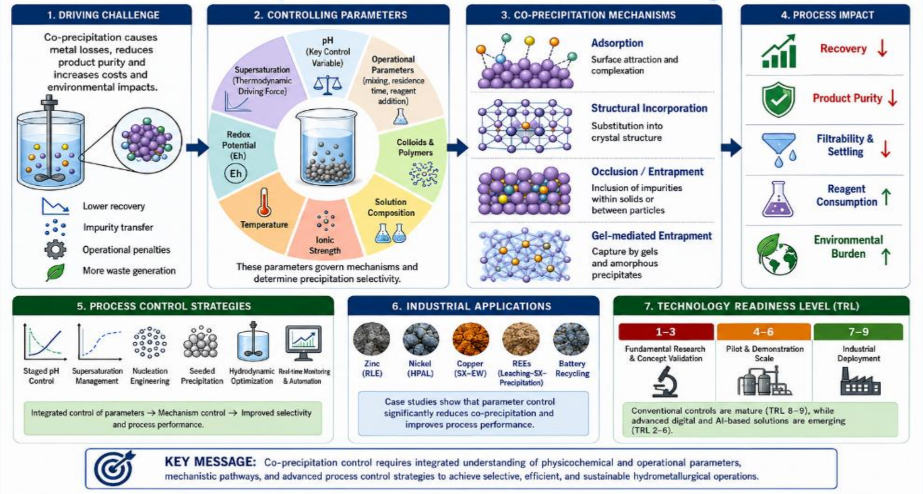
Co-precipitation is a major challenge in hydrometallurgical processing because it directly affects metal recovery, product purity, reagent consumption, solid–liquid separation, and environmental performance. Although precipitation reactions are widely used for impurity removal and selective metal recovery, co-precipitation phenomena remain insufficiently understood due to the complex interactions between thermodynamic, kinetic, hydrodynamic, and interfacial parameters. This critical review examines how physicochemical variables—including pH, supersaturation, redox potential, temperature, ionic strength, solution composition, and colloidal effects—govern the mechanisms of adsorption, structural incorporation, occlusion, and gel-mediated entrapment in multicomponent hydrometallurgical systems. The review further evaluates the influence of operational factors, including mixing intensity, residence time, reagent addition strategy, and reactor design, on precipitation selectivity and process stability. Industrial case studies of zinc, nickel, copper, rare earth, and battery recycling systems are critically analyzed alongside the technology readiness level (TRL) of conventional and emerging control strategies. The analysis demonstrates that effective co-precipitation control requires integrated process design rather than isolated parameter optimization. Current limitations in predictive modeling, real-time monitoring, and industrial multivariable control are identified as key barriers for the development of selective and sustainable hydrometallurgical processes.

Keywords: Co-Precipitation, Hydrometallurgy, Selective Precipitation, Process Control, Physicochemical Parameters, Technology Readiness Level.

Highlights

- Co-precipitation is governed by coupled thermodynamic, kinetic, and hydrodynamic parameters.
- pH and supersaturation are the dominant variables controlling impurity transfer and selectivity.
- Multicomponent industrial liquors remain poorly represented by current predictive models.
- Operational parameters strongly influence nucleation, crystal growth, and occlusion mechanisms.
- Conventional precipitation control technologies are industrially mature, whereas AI-assisted systems remain at low TRL.
- Integrated parameter control is essential for selective and sustainable hydrometallurgical processing.

Graphical Abstract



Co-precipitation causes metal losses, reduces product purity and increases costs and environmental impacts.

These parameters govern mechanisms and determine precipitation selectivity.

Integrated control of parameters → Mechanism control → Improved selectivity and process performance.

Case studies show that parameter control significantly reduces co-precipitation and improves process performance.

Conventional controls are mature (TRL 8–9), while advanced digital and AI-based solutions are emerging (TRL 2–6).

KEY MESSAGE: Co-precipitation control requires integrated understanding of physicochemical and operational parameters, mechanistic pathways, and advanced process control strategies to achieve selective, efficient, and sustainable hydrometallurgical operations.

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Introduction

Co-precipitation is a common phenomenon in hydrometallurgical systems and strongly influences metal recovery, impurity rejection, product purity, and process stability. Although precipitation is widely applied for selective separation, industrial systems rarely operate under equilibrium conditions. Instead, physicochemical and operational variables interact simultaneously, promoting impurity incorporation through adsorption, structural inclusion, occlusion, colloidal trapping, and mixed mechanisms. These effects frequently reduce selectivity and increase losses of valuable metals (Deblonde et al., 2023; Nicol, 2022).

The industrial relevance of co-precipitation spans zinc refining, nickel laterite processing, copper hydrometallurgy, rare earth element (REE) separation, and lithium-ion battery recycling. In zinc hydrometallurgy, precipitation of jarosite, goethite, and hematite may result in Zn losses of 1–5% depending on supersaturation, pH control, and washing efficiency. Similar challenges occur in HPAL systems, where scandium, cobalt, and nickel can co-precipitate with iron and aluminum hydroxides. In REE processing, selective precipitation remains difficult because lanthanides exhibit chemical similarities with thorium, uranium, iron, and aluminum. Battery-recycling liquors further increase complexity because they commonly contain Li, Ni, Co, Mn, Fe, Al, and Cu simultaneously (Akcil et al., 2021; Saleem et al., 2023; Stopic & Friedrich, 2021).

Uncontrolled co-precipitation may cause significant economic losses by reducing recovery of valuable metals and impairing downstream operations such as filtration, washing, and purification, particularly in hydroxide-rich systems (Pereira, 2025b). Environmental impacts are also important because poor precipitation control increases sludge generation, reagent consumption, and contaminant mobility. In systems containing arsenic, fluoride, or heavy metals, unstable precipitates may increase the risk of contaminant release and water pollution, especially in circular hydrometallurgy and secondary resource processing, where feed variability is high (Akcil et al., 2021; Le & Lee, 2021; Saleem et al., 2023).

Despite extensive research on precipitation chemistry, major scientific and industrial gaps remain. Most studies focus on isolated mechanisms or simplified laboratory systems operating under controlled conditions. Adsorption, structural incorporation, and occlusion are often analyzed independently, whereas industrial systems involve strongly coupled and transient interactions. In addition, many thermodynamic studies assume equilibrium conditions that are rarely achieved in industrial reactors because local supersaturation, incomplete mixing, and pH gradients strongly influence precipitation behavior. Consequently, a significant gap persists between laboratory observations and industrial performance (Deblonde et al., 2023; Nicol, 2022).

Another major limitation is the poor integration of physicochemical parameters with process engineering. Variables such as pH, redox potential, supersaturation, ionic strength, temperature, mixing, residence time, and reagent strategy are commonly investigated separately despite their strong interdependence. Co-precipitation should therefore be understood as a coupled process involving thermodynamics, kinetics, hydrodynamics, and interfacial chemistry rather than equilibrium alone.

Technology maturity also varies substantially across precipitation-control approaches. Conventional neutralization and pH-control systems are highly mature (TRL 8–9), whereas advanced approaches involving CFD, machine learning, digital twins, and AI-assisted optimization remain at intermediate maturity levels (TRL 3–6). Although these technologies show strong potential to improve selectivity and reduce metal losses, industrial validation under continuous, multicomponent conditions remains limited.

This review critically examines the principal parameters governing co-precipitation behavior in hydrometallurgical systems. The objective is to establish an integrated framework linking process variables, co-precipitation mechanisms, industrial performance, and technology readiness. Particular emphasis is placed on the influence of pH, supersaturation, redox conditions, solution chemistry, hydrodynamics, and reactor design in systems involving Zn, Ni, Cu, Co, REEs, and battery-recycling liquors, as well as on the limitations of current predictive and control strategies under industrial conditions.

Methodology

This review used a PRISMA 2020 methodology to combine broad literature coverage with assessment of industrial relevance, operational use, and technology maturity in hydrometallurgical precipitation systems. It surveyed sources like Scopus, Web of Science, ScienceDirect, and SpringerLink, chosen for their coverage of hydrometallurgy, crystallization, precipitation engineering, battery recycling, and rare-earth processing. The focus was on peer-reviewed articles, industrial studies, pilot investigations, and reviews mainly from 2020-2026, with older references included for fundamental concepts.

Search strings combined terms related to co-precipitation, selective precipitation, supersaturation, hydrometallurgy, crystallization, process control, redox chemistry, and multicomponent systems using Boolean operators. Representative combinations included (“co-precipitation” OR coprecipitation) AND hydrometallurgy, (“selective precipitation” AND rare earths), and (“battery recycling” AND precipitation). Additional searches included predictive modeling, technology readiness, and digital process optimization. Figure 1 summarizes the methodological workflow adopted in this review.

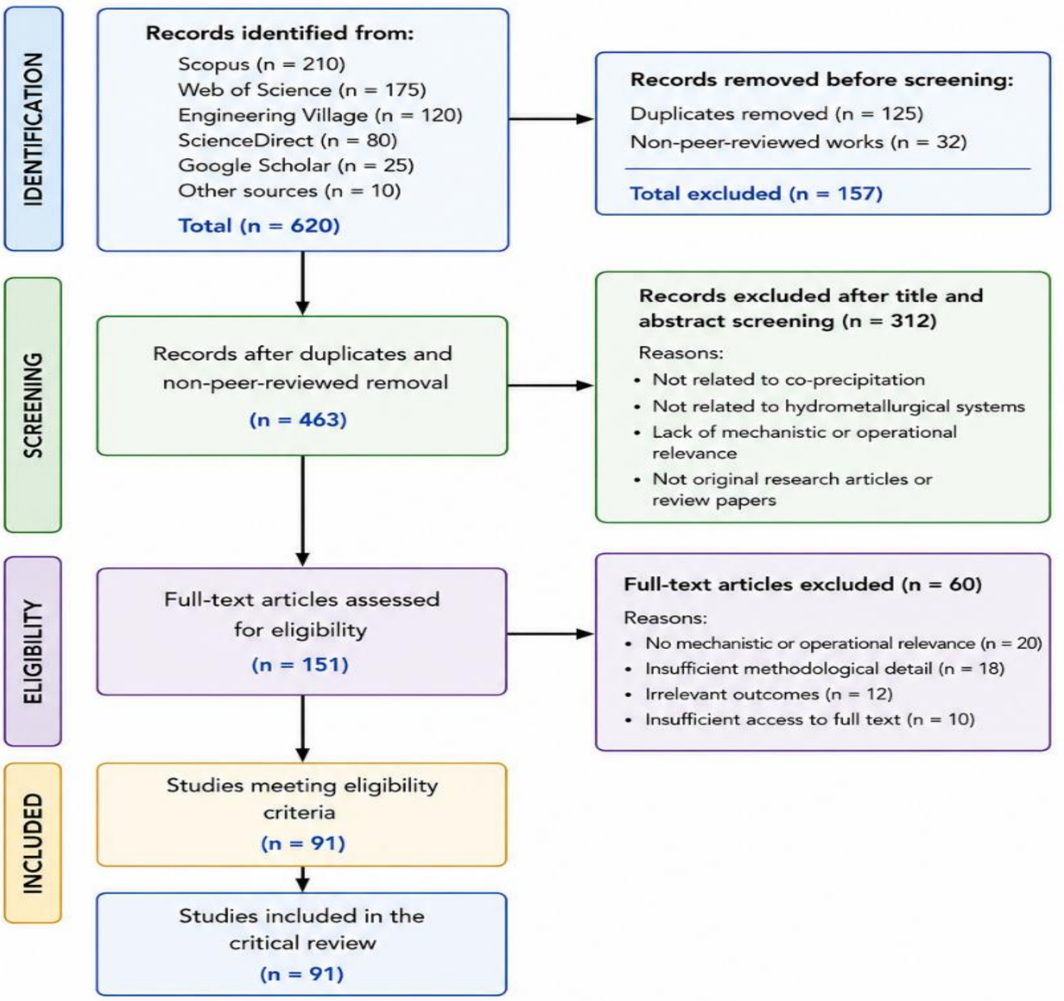


Figure 1. PRISMA-based workflow adopted for literature identification, screening, eligibility assessment, and final inclusion of studies related to co-precipitation control in hydrometallurgical systems. Adapted from Page et al. (2021).

Figure 1 outlines the filtering process used to identify studies addressing precipitation mechanisms, physicochemical interactions, process control, and technology readiness in hydrometallurgical systems. A total of 620 records were initially identified from Scopus (210), Web of Science (175), Engineering Village (120), ScienceDirect (80), Google Scholar (25), and other sources (10). Before screening, 125 duplicate records and 32 non-peer-reviewed publications were removed, resulting in 463 records for title and abstract evaluation. During screening, 312 studies were excluded because they were unrelated to co-precipitation or hydrometallurgical systems, lacked mechanistic or operational relevance, or did not correspond to original research articles or review papers. Subsequently, 151 full-text articles were assessed for eligibility, of which 60 were excluded due to insufficient methodological detail, lack of mechanistic relevance, irrelevant outcomes, or inaccessible full text. Finally, 91 studies met the eligibility criteria and were included in the critical review..

The inclusion criteria prioritized studies containing quantitative precipitation data, mechanistic interpretation of co-precipitation behavior, hydrometallurgical process data, reactor observations, process-control strategies, or industrial implications related to impurity transfer and selectivity. Studies focused exclusively on nanoparticle synthesis, pharmaceutical precipitation, or purely mineralogical characterization were excluded unless they provided transferable mechanistic insights.

The selected studies were classified by evidence quality and operational representativeness. Laboratory studies used simplified bench-scale systems under controlled conditions, while pilot-scale investigations involved semi-continuous operation with partial industrial relevance. Industrial studies included operating plants or campaigns with real feed variability and performance indicators like metal recovery, impurity transfer, filtration, residue, and reagent use.

Technology maturity was evaluated using a technology readiness level (TRL) framework adapted for hydrometallurgical systems. Emerging technologies such as AI-assisted control, digital twins, and hybrid predictive systems were generally classified between TRL 1 and 3, while pilot-validated technologies, including intensified reactors and supersaturation-control systems, were classified between TRL 4 and 6. Mature industrial technologies, such as conventional neutralization and hydroxide precipitation systems, were classified as TRL 7-9.

Data extraction focused on parameters including pH, redox potential, temperature, ionic strength, supersaturation, residence time, mixing conditions, precipitation behavior, impurity removal, filtration performance, crystal morphology, and residue stability. Comparisons were also made between laboratory and industrial systems with respect to reagent consumption, sludge generation, process selectivity, and scale-up limitations, with particular emphasis on discrepancies between equilibrium predictions and industrial performance.

Despite the large number of available studies, important limitations remain. Many investigations use simplified synthetic solutions that poorly represent industrial liquors, while operational variables such as supersaturation, micromixing, residence-time distribution, and pH gradients are often insufficiently characterized. In addition, industrial data remain limited because many precipitation systems are proprietary, increasing uncertainty in industrial extrapolation and scale-up

Fundamentals of Co-precipitation in Hydrometallurgy

Co-precipitation involves the unintended incorporation or adsorption of dissolved species during solid formation, directly affecting metal recovery, impurity rejection, and product purity. In hydrometallurgical systems, precipitation is rarely fully selective because industrial liquors contain multicomponent electrolytes operating under supersaturation, pH gradients, and competing nucleation pathways (Deblonde et al., 2023; Nicol, 2022).

The distinction between selective precipitation and co-precipitation is fundamental for process design. Selective precipitation aims to maximize target-metal recovery with minimal impurity transfer, whereas co-precipitation reduces selectivity through adsorption, structural incorporation, occlusion, and colloidal trapping. Industrial systems generally operate between these extremes. In zinc hydrometallurgy, iron precipitation may remove arsenic and germanium but also cause zinc losses, while in nickel laterite processing, scandium, cobalt, and manganese may co-precipitate with iron and aluminum hydroxides depending on pH, supersaturation, and residence time.

Scavenging precipitation captures contaminants via adsorption or surface complexation, improving purification. However, excessive scavenging can lead to metal loss and decreased selectivity. Impurity entrainment differs from co-precipitation, as dissolved species are trapped in precipitates under high supersaturation, rapid neutralization, colloidal aggregation, and poorly crystalline hydroxides formation. Gel-like precipitates with silica or ferric hydroxides retain moisture, causing filtration problems (Rodrigues &Ignatiadis, 2025).

The relationships between precipitation pathways, controlling parameters, and industrial impacts are summarized in Figure 2.

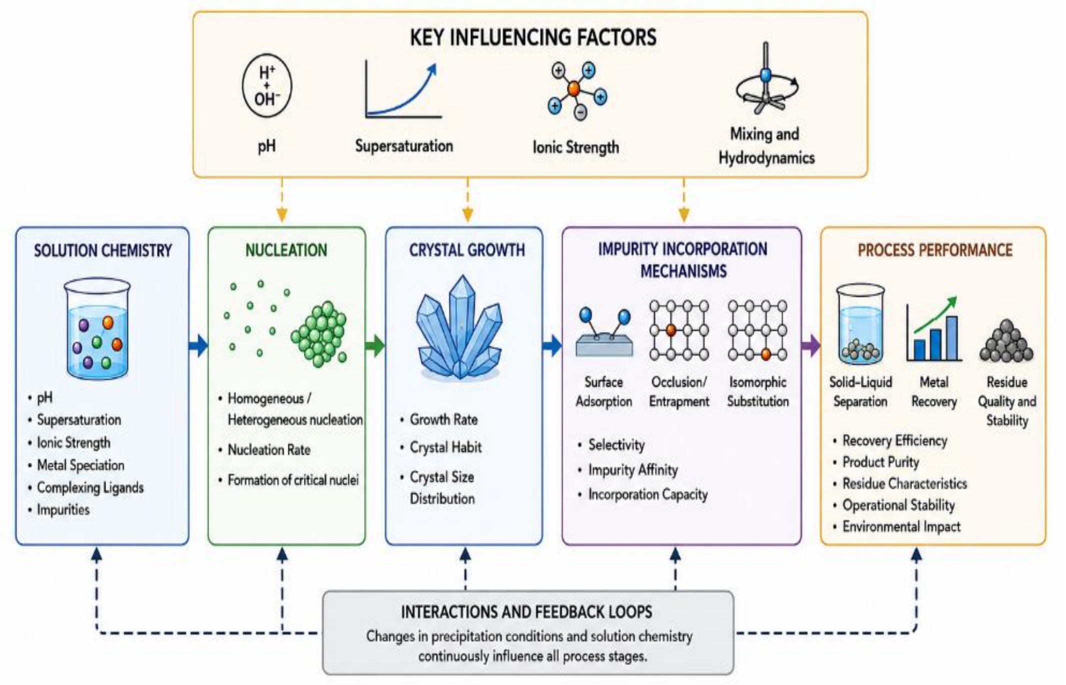


Figure 2. Simplified relationship between solution chemistry, nucleation, crystal growth, impurity incorporation mechanisms, and process performance in hydrometallurgical co-precipitation systems. Adapted from Nicol (2022), Deblonde et al. (2023), and Rodrigues and Ignatiadis (2025).

Figure 2 illustrates that co-precipitation behavior results from coupled interactions between thermodynamics, kinetics, interfacial chemistry, and hydrodynamics. Variations in pH, supersaturation, ionic strength, and mixing conditions simultaneously influence nucleation, crystal morphology, adsorption capacity, and impurity retention.

Although precipitation begins when ionic activity exceeds the solubility product, equilibrium calculations rarely capture industrial precipitation behavior accurately because hydrometallurgical systems commonly operate under transient and metastable conditions. Local supersaturation, incomplete mixing, and rapid reagent addition strongly affect precipitation pathways and solid-state evolution.

Kinetic effects are also critical. Rapid nucleation generally produces fine particles with high surface area and stronger adsorption capacity, whereas slower crystal growth promotes more ordered structures with lower impurity retention. Consequently, precipitation selectivity depends not only on equilibrium chemistry but also on reaction kinetics, hydrodynamics, and particle aging. The principal co-precipitation mechanisms are summarized in Table 1.

Table 1. Comparative overview of major co-precipitation mechanisms in hydrometallurgical systems, including dominant controlling parameters, operational conditions, industrial implications, and limitations.

Mechanism	Dominant controlling parameters	Typical operational conditions	Main industrial implications	Major limitations
Surface adsorption	pH, surface charge, ionic strength	Moderate supersaturation, fine particles	Impurity transfer, scavenging	Reversible adsorption
Structural incorporation	Crystal growth rate, ionic radius similarity	Slow precipitation, crystalline phases	Product contamination	Difficult impurity removal
Occlusion/entrapment	Supersaturation, precipitation rate	Rapid precipitation, amorphous solids	Filtration penalties, metal losses	High moisture retention
Colloidal trapping	pH, polymeric species, silica concentration	Gel formation, high colloidal stability	Poor settling and washing	Difficult solid–liquid separation

Co-precipitation becomes substantially more complex in multicomponent systems such as rare-earth processing and battery recycling, where liquors contain dissolved salts, impurities, colloids, complexing agents, and degradation products. Competitive adsorption and overlapping precipitation windows frequently produce behavior that differs significantly from simplified laboratory systems.

Overall, co-precipitation is a dynamic and process-dependent phenomenon strongly influenced by operational parameters such as mixing, residence time, and supersaturation. These factors often dominate industrial performance and explain why laboratory selectivity is not always reproduced at industrial scale (Balboni et al., 2021; Pereira, 2025c; Velasco et al., 2021).

Co-precipitation Mechanisms

Co-precipitation in hydrometallurgical systems involves coupled thermodynamic, kinetic, and interfacial phenomena rather than equilibrium alone. Impurities may interact with precipitates through adsorption, structural incorporation, entrapment, colloidal aggregation, or mixed pathways, depending on pH, supersaturation, ionic strength, crystal growth, and reactor hydrodynamics. In industrial systems, these mechanisms frequently overlap, particularly under rapid or non-homogeneous precipitation conditions (Deblonde et al., 2023; Nicol, 2022). Figure 3 summarizes the principal impurity-retention pathways.

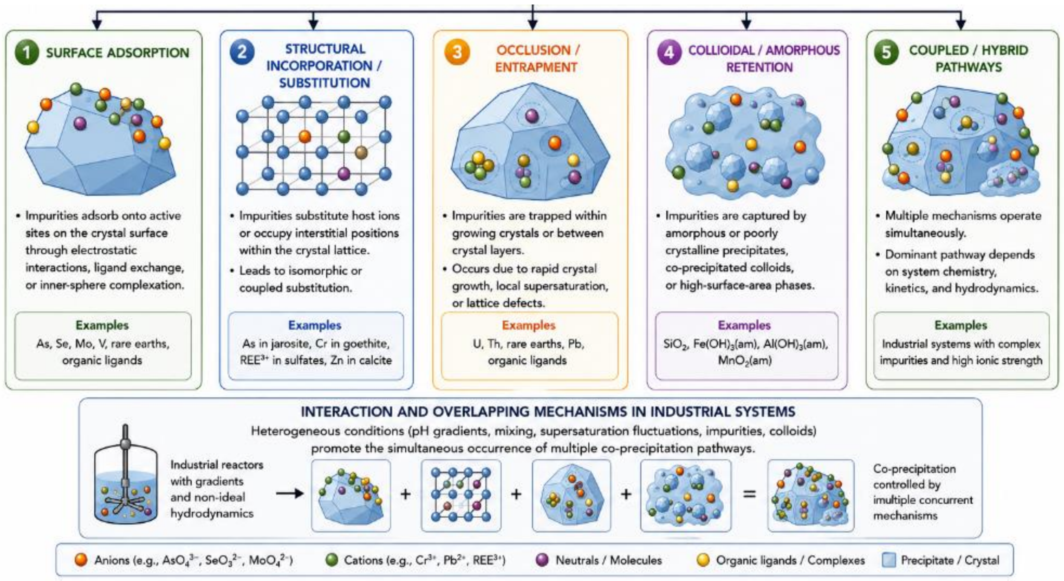


Figure 3. Main co-precipitation mechanisms in hydrometallurgical systems, including adsorption, structural incorporation, occlusion, colloidal trapping, and coupled transitional pathways. Adapted from Ahmad (2020), Deblonde et al. (2023), Rodrigues and Ignatiadis (2025), and Xu et al. (2024).

Figure 3 shows that impurity retention can occur at particle surfaces, in crystal lattices, within amorphous precipitates, or via physical trapping. In industrial reactors, these mechanisms often overlap due to non-homogeneous precipitation conditions.

Surface Adsorption

Surface adsorption is one of the main causes of impurity transfer during precipitation because freshly formed hydroxides, oxyhydroxides, carbonates, and amorphous oxides possess high surface area and strong affinity for dissolved ions. Adsorption occurs through electrostatic attraction or surface complexation depending on solution chemistry and surface charge (Ahmad, 2020; Kim et al., 2021).

Small pH variations can strongly affect zeta potential and adsorption behavior, particularly in ferric and aluminum hydroxide systems. Increased ionic strength compresses the electrical double layer, promoting adsorption and colloidal aggregation. Consequently, industrial saline liquors frequently show lower selectivity and greater impurity carryover than simplified laboratory systems (Das et al., 2020; Liu et al., 2022).

Structural Incorporation

Structural incorporation occurs when dissolved ions become incorporated into crystal lattices during growth, especially when impurity ions have similar ionic radius, valence, or coordination behavior. This mechanism is common in systems containing transition metals, rare earths, thorium, uranium, and other actinides.

Unlike adsorption, structural incorporation is generally more stable because impurities become part of the crystal structure itself, increasing product contamination and reducing purification efficiency. Crystal growth kinetics strongly influence incorporation behavior: slower growth and moderate supersaturation favor ordered lattices, whereas rapid precipitation promotes amorphous phases and surface adsorption (Balboni et al., 2021; Berk et al., 2023; Rodrigues &Ignatiadis, 2025).

Entrapment and Occlusion

Entrapment and occlusion occur when dissolved species or mother liquor become physically retained within precipitated solids, particularly under rapid nucleation and high supersaturation conditions. Rapid precipitation often generates porous or amorphous structures that trap solution species within particles and voids.

In hydroxide-rich systems, occlusion increases impurity carryover, moisture retention, and filtration resistance, especially in ferric hydroxide, aluminum hydroxide, and silica precipitates. Fine particles and colloidal aggregates further hinder washing and settling, intensifying impurity retention (Besenhard et al., 2020; Kontrec et al., 2021; Poonoosamy et al., 2020).

Gel-Mediated and Colloidal Mechanisms

Gel-mediated and colloidal mechanisms are particularly important in systems containing silica, ferric hydroxides, aluminum hydroxides, or polymeric species. These systems may generate highly hydrated structures with poor settling, strong water retention, and significant impurity trapping.

Colloidal aggregation complicates selectivity because particle interactions depend on electrostatic stabilization, ionic strength, and polymeric bridging rather than crystal growth alone. As a result, equilibrium models often fail to predict industrial precipitation behavior accurately (Ahmad, 2020; Masindi et al., 2023). Impurity retention in these systems commonly involves overlapping mechanisms of adsorption, colloidal trapping, and occlusion (Rodrigues &Ignatiadis, 2025).

Before discussing coupled and transitional behavior, Table 2 summarizes the principal co-precipitation mechanisms and their industrial implications.

Table 2. Comparative analysis of co-precipitation mechanisms in hydrometallurgical systems.

Mechanism	Dominant parameters	Typical conditions	Main industrial impacts	Major limitations	TRL
Surface adsorption	pH, ionic strength, surface charge	Fine particles, high surface area	Impurity scavenging, metal losses	Reversible adsorption	8–9
Structural incorporation	Crystal growth rate, ionic similarity	Moderate supersaturation	Product contamination	Difficult impurity removal	7–9
Occlusion/entrapment	Supersaturation, precipitation rate	Rapid precipitation	Filtration penalties, high moisture	Poor washing efficiency	8–9
Gel-mediated trapping	Silica, hydroxides, polymers	Gel formation	Settling and filtration problems	Difficult solid-liquid separation	6–8
Coupled mechanisms	Multivariable interactions	Industrial multicomponent systems	Reduced selectivity	Difficult mechanistic isolation	3–6

Table 2 shows that industrial precipitation is governed by overlapping pathways, not isolated mechanisms. Therefore, equilibrium chemistry alone often can't replicate industrial selectivity and impurity transfer.

Coupled and Transitional Mechanisms

In industrial systems, co-precipitation mechanisms are dynamic and transitional. Adsorption may evolve into structural incorporation during crystal aging, while amorphous precipitates may recrystallize into more ordered phases with different impurity-retention behavior. Colloidal aggregation and occlusion also frequently occur simultaneously under high supersaturation conditions.

These transitions are strongly influenced by mixing intensity, reagent-injection strategy, residence-time distribution, and temperature gradients. Industrial multicomponent systems further increase complexity because adsorption, structural incorporation, colloidal trapping, and occlusion may occur simultaneously within the same precipitated phase. This helps explain why industrial circuits commonly exhibit lower selectivity and higher metal losses than predicted by simplified laboratory or equilibrium-based models (Berk et al., 2023; Xu et al., 2024; Kontrec et al., 2021; Poonoosamy et al., 2020).

Classification of Controlling Parameters

Co-precipitation in hydrometallurgy relies on interconnected thermodynamic, kinetic, hydrodynamic, chemical, and interfacial factors. Industrial systems show how changes in one parameter, like pH,affecting solubility, surface charge, nucleation, colloidal stability, and adsorption, influence others. Mixing conditions impact supersaturation, particle growth, and impurity incorporation.

This interdependence explains why laboratory precipitation selectivity often isn't observed industrially, where reactors face transient, heterogeneous conditions such as fluctuating supersaturation, incomplete mixing, variable feed, and changing hydrodynamics. Thus, precipitation depends more on coupled interactions than on isolated variables. Figure 4 summarizes these hierarchical interactions in hydrometallurgical co-precipitation.

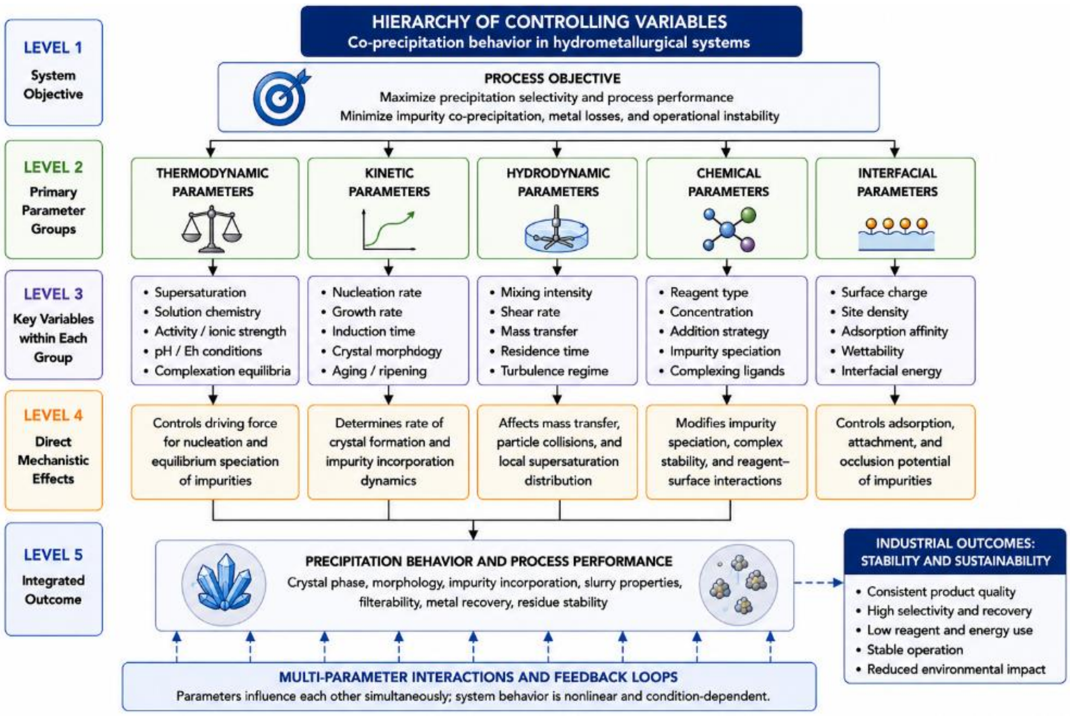


Figure 4. Hierarchical interaction between thermodynamic, kinetic, hydrodynamic, chemical, and interfacial parameters controlling co-precipitation behavior in hydrometallurgical systems. Adapted from Deblonde et al. (2023), Nicol (2022), and Xu et al. (2024).

Figure 4 shows that precipitation selectivity arises from coupled parameters, not isolated equilibrium. Industrial stability depends on controlling multiple variables simultaneously.

Thermodynamic Parameters

Thermodynamic parameters such as solubility, speciation, and activity coefficients determine phase stability and precipitation windows under specific conditions (Deblonde et al., 2023; Nicol, 2022). In multicomponent systems, small changes in pH, temperature, or ionic composition may substantially alter selective precipitation behavior.

Activity coefficients are especially important in concentrated industrial liquors with high ionic strength, whereas dissolved metals often exist as hydroxo, sulfate, chloride, carbonate, or organic complexes rather than free ions. Consequently, selective precipitation often depends more on solution speciation than on intrinsic solubility differences (Gontijo et al., 2022).

Kinetic parameters

Kinetic parameters control nucleation, crystal growth, diffusion, and impurity incorporation during precipitation. Rapid nucleation generally produces fine particles with high surface area and stronger adsorption behavior, whereas slower growth favors more ordered structures with lower impurity retention (Berk et al., 2023).

Diffusion limitations are particularly important in concentrated or viscous liquors where local concentration gradients develop near particles or reagent-injection zones. Industrial systems commonly operate under conditions where nucleation and growth occur simultaneously, making kinetic effects dominant even under relatively stable thermodynamic conditions (Abiev et al., 2023; Xu et al., 2024).

Hydrodynamic Parameters

Hydrodynamic conditions strongly influence supersaturation, reagent dispersion, particle aggregation, and residence-time distribution (RTD). Poor micromixing may generate localized supersaturation zones that promote rapid nucleation, amorphous precipitation, and colloidal aggregation, while excessive shear can destabilize aggregates and modify particle growth.

Non-ideal RTD behavior also increases heterogeneity because newly formed and aged crystals coexist within the same reactor. Industrial observations frequently show that hydrodynamics may dominate precipitation selectivity under high-throughput conditions (Abiev et al., 2023; Xue et al., 2023).

Chemical Parameters

Chemical parameters affect interactions between dissolved species and strongly influence selectivity. Ligands, ionic competition, and complexation may alter solubility, adsorption, nucleation, and crystal growth behavior. Sulfate, chloride, carbonate, ammonia, fluoride, and organic ligands commonly shift precipitation windows or modify redox stability in hydrometallurgical systems.

Ionic competition is particularly important in multicomponent liquors such as rare-earth and battery-recycling systems, where several metals compete simultaneously for adsorption, incorporation, and complexation pathways (Hassas et al., 2021; Huang et al., 2024; Wang et al., 2023).

Interfacial Parameters

Interfacial parameters govern particle–solution interactions during precipitation and therefore influence adsorption, colloidal stability, aggregation, filtration, and washing behavior. Surface charge and zeta potential are particularly important in fine-particle and amorphous systems because small pH changes near the point of zero charge can significantly alter aggregation and impurity retention.

Although zeta potential is commonly used as an indicator of colloidal stability, its predictive power is limited in industrial liquors due to high ionic strength and complex multicomponent chemistry. Colloidal stabilization often causes poor settling, high cake moisture, and impurity carryover, especially in silica- and hydroxide-rich systems (Ahmad, 2020; Kim et al., 2021; Velasco et al., 2021).

Before discussing specific physicochemical variables, Table 3 summarizes the principal parameter groups controlling co-precipitation behavior in hydrometallurgical systems.

Table 3. Classification of controlling parameters governing co-precipitation behavior in hydrometallurgical systems. Adaptedfrom Ahmad (2020), Kim et al. (2021), Velasco et al. (2021), Deblonde et al. (2023), Saleem et al. (2023), and Crespo et al. (2025).

Parameter group	Main variables	Principal effects	Industrial sensitivity	Typical controllability
Thermodynamic	Solubility, speciation, activity	Phase stability, precipitation window	Very high	Moderate
Kinetic	Nucleation, growth, diffusion	Particle morphology, impurity incorporation	Very high	Moderate to low
Hydrodynamic	Mixing, turbulence, RTD	Local supersaturation, aggregation	High	Moderate
Chemical	Ligands, ionic competition	Selectivity, complexation	Very high	Moderate
Interfacial	Surface charge, zetapotential	Adsorption, colloidal stability	High	Moderate to high

Table 3 shows that precipitation selectivity depends on parameters with varying industrial sensitivity and controllability. While thermodynamic conditions set theoretical limits, kinetic and hydrodynamic factors often dominate industrial behavior. Effective control requires managing coupled parameters, not just optimizing individual ones.

Physicochemical Parameters Governing Co-precipitation

Physicochemical parameters strongly influence precipitation behavior, impurity incorporation, particle morphology, and separation efficiency in hydrometallurgical systems. Although thermodynamic equilibrium defines potential phase stability, industrial performance depends on coupled effects involving pH, supersaturation, redox potential, temperature, ionic strength, solution composition, and colloidal behavior. Small variations in these parameters may simultaneously alter speciation, nucleation, adsorption, and impurity retention. Figure 5 summarizes the interactions among the principal physicochemical variables controlling co-precipitation behavior.

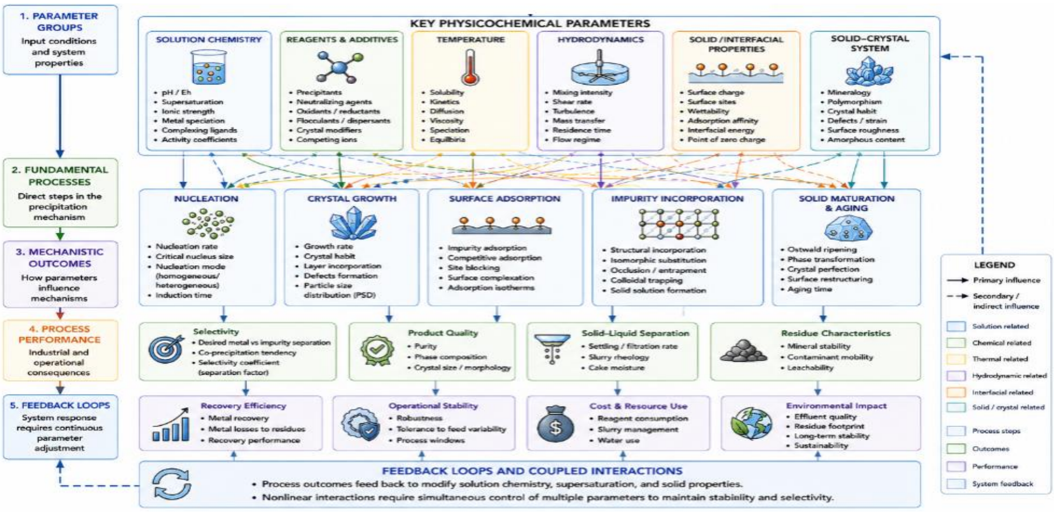


Figure 5. Interactions among physicochemical parameters that control co-precipitation behavior in hydrometallurgical systems, including their influence on nucleation, crystal growth, adsorption, impurity incorporation, and process performance. Adapted from Nicol (2022), Deblonde et al. (2023), and Xu et al. (2024).

Figure 5 shows that precipitation selectivity depends on interactions among coupled parameters, not just on individual variables. Maintaining process stability requires controlling multiple physicochemical conditions simultaneously.

pH as the Master Variable

pH is the most influential parameter in co-precipitation because it controls hydrolysis, metal speciation, solubility, surface charge, nucleation, and colloidal stability (Chao et al., 2026; Nicol, 2022). In hydrometallurgy, selective precipitation largely depends on pH-controlled differences in solubility.

Hydrolysis equilibria strongly affect precipitation windows. Ferric species commonly precipitate near pH 2–3, whereas aluminum hydroxides typically precipitate between pH 4 and 6 depending on ionic strength and sulfate concentration. In rare-earth systems, even small pH variations may substantially affect selectivity.

pH also influences surface charge and adsorption behavior, particularly in ferric and aluminum hydroxide systems, where minor changes near the point of zero charge may significantly affect impurity retention (Kim et al., 2021; Velasco et al., 2021). Although conventional pH-controlled precipitation is fully mature (TRL 9), predictive AI-assisted optimization remains at intermediate maturity levels (TRL 4–7).

Supersaturation as the Driving Force

Supersaturation is the main driving force for nucleation and crystal growth, strongly affecting particle size, morphology, impurity incorporation, and colloidal behavior. High supersaturation promotes rapid nucleation, fine-particle formation, adsorption, and occlusion, whereas lower supersaturation favors slower crystal growth and more ordered crystalline phases with reduced impurity retention (Ali et al., 2025; Berk et al., 2023).

Hydroxide-rich systems commonly exhibit transient amorphous intermediates under rapid neutralization conditions. Industrial supersaturation control is considerably more difficult than laboratory control because reagent addition, mixing, and residence time generate heterogeneous supersaturation fields inside reactors (Poonoosamy et al., 2020; Quintero et al., 2020). Conventional supersaturation management is industrially mature (TRL 8–9), while predictive dynamic control remains less developed (TRL 3–5) (Xu et al., 2024).

Redox Potential (Eh)

Redox potential influences the precipitation behavior of species such as Fe, Mn, Co, Cu, Cr, and As because oxidation state directly affects solubility, hydrolysis, and phase stability. In iron systems, the Fe^{2+}/Fe^{3+} transition strongly affects precipitation because ferric hydroxides are much less soluble than ferrous phases. Similar effects occur in manganese systems, where oxidation state controls the formation of hydroxides, oxides, or mixed phases (Dong et al., 2023; Pereira, 2025a).

Eh and pH are strongly coupled variables, as demonstrated by Pourbaix stability regions. Industrial ORP monitoring is fully mature (TRL 9), whereas predictive redox optimization remains at intermediate maturity levels (TRL 5–6) (Ichlas et al., 2020; Mang et al., 2023).

Temperature

Temperature affects precipitation through its influence on solubility, reaction kinetics, diffusion, crystal growth, and phase stability. Higher temperatures generally improve crystallinity, diffusion, and recrystallization, producing denser particles with lower moisture content and improved filtration behavior (He et al., 2022).

However, temperature may also modify precipitation selectivity and reagent consumption depending on supersaturation and hydrodynamic conditions. Conventional thermal-control systems are fully industrialized (TRL 9), whereas predictive thermal optimization remains at intermediate maturity levels (TRL 4–6) (Takano et al., 2022; Zhao et al., 2025).

Ionic Strength

Ionic strength influences precipitation by modifying activity coefficients, electrostatic interactions, adsorption, and colloidal stability. In concentrated industrial liquors, deviations from ideal behavior become significant, especially in sulfate- and chloride-rich systems.

Increasing ionic strength compresses the electrical double layer, promoting aggregation and adsorption while simultaneously destabilizing selective precipitation windows (Kontrec et al., 2021). Although industrial awareness of ionic-strength effects is high, predictive integration of ionic-strength-dependent precipitation remains limited, as most industrial systems still rely primarily on empirical adjustments (Poonoosamy et al., 2020; Stec et al., 2020).

Solution Composition and Multicomponent Interactions

Industrial hydrometallurgical liquors are highly multicomponent systems containing dissolved metals, salts, ligands, colloids, and degradation products. In many cases, precipitation behavior depends more on interactions among species than on individual equilibrium constants.

Complexation with sulfate, chloride, carbonate, fluoride, ammonia, or organic ligands may stabilize dissolved metals or shift precipitation windows. Competitive precipitation is particularly important in rare-earth processing and battery recycling, where chemically similar metals exhibit overlapping hydrolysis behavior (Han et al., 2023; Huang et al., 2024). Predictive modeling of multicomponent systems remains limited because industrial liquors are highly variable and complex (Li et al., 2020; Wang et al., 2023; Yun et al., 2025).

Colloids, Silica, and Polymers

Colloidal species and polymeric phases strongly affect precipitation stability, filtration, and impurity carryover. Silica gels, hydroxide colloids, and polymeric flocs commonly dominate solid–liquid separation behavior in industrial systems.

Silica-rich systems often exhibit poor settling, strong water retention, and high impurity carryover. Flocculation improves settling and filtration performance, although flocculant efficiency depends strongly on pH, ionic strength, particle size, and shear conditions. Polymer engineering and advanced colloidal control remain at intermediate maturity levels (TRL 4–6) because predictive industrial control is still limited (Ahmad, 2020; Masindi et al., 2023).

Before discussing operational variables, Table 4 summarizes the principal physicochemical parameters governing co-precipitation behavior in hydrometallurgical systems.

Table 4. Comparative overview of physicochemical parameters governing co-precipitation behavior in hydrometallurgical systems, including dominant operational effects, industrial limitations, and technology readiness levels (TRLs). Adapted from Deblonde et al. (2023), Nicol (2022), and Xu et al. (2024).

Parameter	Main effects	Typical industrial implications	Main limitations	Typical TRL
pH	Speciation, hydrolysis, adsorption	Selective precipitation control	Local gradients, instability	9
Supersaturation	Nucleation, morphology, occlusion	Fine-particle generation	Difficult real-time control	8–9
Redox potential (Eh)	Oxidation-statestability	Fe, Mn, Co, Cu control	Coupled Eh–pH complexity	9
Temperature	Crystallinity, kinetics	Filtration and morphology	Energy consumption	9
Ionic strength	Activity correction, aggregation	Adsorption variability	Limited predictive integration	3–5
Multicomponent chemistry	Competitive precipitation	Reduced selectivity	Modeling complexity	2–4
Colloids and polymers	Gel formation, flocculation	Filtration penalties	Poor predictability	4–6

Table 4 shows that conventional precipitation control techniques are mature for pH and temperature, but predictive control of multicomponent and colloidal systems is less developed. The main challenge now is not the lack of equilibrium data but the integration of coupled physicochemical interactions under real industrial conditions.

Process and Operational Parameters

Operational conditions strongly influence co-precipitation because industrial hydrometallurgical systems rarely operate under homogeneous equilibrium conditions. Even when pH and supersaturation appear controlled at the bulk scale, local operational effects may substantially alter nucleation, crystal growth, adsorption, and impurity incorporation. Variables such as mixing intensity, residence time, reagent-addition strategy, reactor configuration, and precipitation mode are therefore critical for industrial selectivity and stability.

Many discrepancies between laboratory and industrial precipitation behavior arise primarily from operational rather than thermodynamic limitations. Bench-scale systems often assume ideal mixing, whereas industrial reactors exhibit concentration gradients, micromixing limitations, dead zones, and broad residence-time distributions. As a result, precipitation selectivity frequently depends more on reactor hydrodynamics and operational design than on equilibrium chemistry alone. Figure 6 summarizes the influence of operational parameters on industrial precipitation behavior.

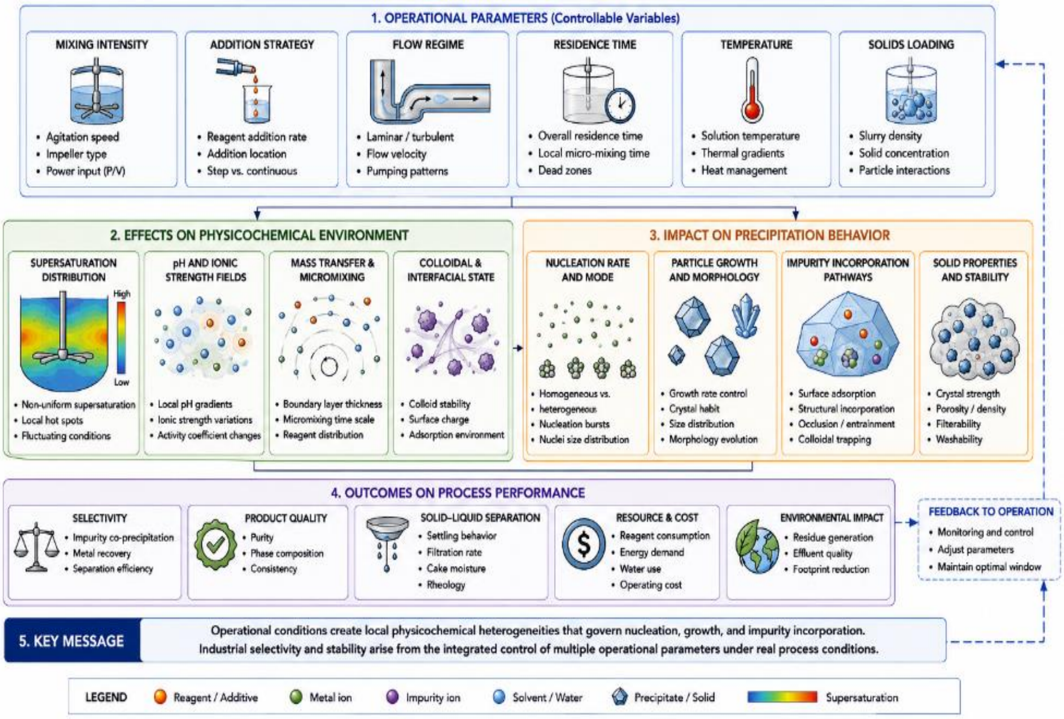


Figure 6. Influence of operational parameters on precipitation behavior in hydrometallurgical systems, including mixing effects, supersaturation distribution, particle growth, and impurity incorporation pathways. Adapted from Abiev et al. (2023), Xu et al. (2024), and Xue et al. (2023).

Figure 6 shows that operational conditions influence precipitation through local physicochemical heterogeneities, often controlling industrial selectivity.

Mixing Intensity

Mixing intensity affects supersaturation distribution, nucleation, particle aggregation, and impurity incorporation. In precipitation systems, micromixing is often more important than bulk mixing because precipitation reactions begin immediately after reagent contact.

Insufficient mixing generates localized supersaturation zones near reagent-injection points, promoting rapid nucleation, adsorption, occlusion, and colloidal trapping. Conversely, excessive turbulence may destabilize aggregates and hinder crystal growth (Abiev et al., 2023). Because industrial mixing does not scale linearly from laboratory systems, large reactors commonly exhibit lower selectivity and higher impurity carryover under otherwise similar conditions (Xue et al., 2023; Xu et al., 2024).

Residence Time

Residence time influences crystal growth, recrystallization, particle aging, and impurity redistribution. Short residence times favor nucleation and fine-particle formation, whereas longer aging periods promote crystal maturation and improved crystallinity.

Industrial reactors typically exhibit non-ideal residence-time distribution (RTD) behavior caused by recirculation zones, dead volumes, and bypassing, resulting in particles with different crystallization histories within the same system (Polierer et al., 2020). Crystal aging may also alter impurity incorporation during recrystallization, while insufficient aging often produces poorly crystalline precipitates with high moisture retention and reduced filtration performance (Berk et al., 2023; Guse et al., 2022).

Reagent Addition Strategy

Reagent-addition strategy strongly affects local supersaturation, pH gradients, and precipitation pathways. Rapid reagent injection may generate over-neutralization, amorphous precipitation, and colloidal formation, whereas staged addition generally reduces supersaturation peaks and promotes more controlled crystal growth.

Industrial systems commonly use lime, limestone, sodium hydroxide, ammonia, or carbonate reagents, and precipitation behavior depends strongly on injection location, dilution, and mixing efficiency. Staged neutralization generally improves selectivity and reduces impurity carryover compared with single-stage operation (Chang et al., 2025; Quintero et al., 2020).

Reactor Configuration and Design

Reactor geometry and flow configuration influence hydrodynamics, supersaturation distribution, particle collision frequency, and precipitation stability. Stirred-tank reactors remain the dominant industrial technology because of their operational flexibility and scalability (TRL 9).

Large industrial reactors often face hydrodynamic issues like dead zones, broad RTD, and poor mixing, which lower selectivity and increase impurities. Advanced designs such as tubular, oscillatory-flow, static mixers, intensified, and multistage reactors aim to improve micromixing and supersaturation, but scale-up and operational robustness limit industrial use (Li et al., 2024; Besenhard et al., 2020; Polierer et al., 2020).

Seeded and Staged Precipitation

Seeded precipitation reduces uncontrolled nucleation and stabilizes crystal growth by promoting heterogeneous growth over spontaneous nucleation. Several industrial studies report improvements in filtration, moisture reduction, and impurity control using seeded systems (Gerold et al., 2020).

Staged precipitation also improves selectivity by distributing precipitation across multiple pH or reagent stages, particularly in nickel laterite processing and rare-earth separation systems. Nevertheless, long-term industrial performance remains partly contradictory, as adsorption and colloidal trapping may persist even under staged operation (Hassas & Rezaee, 2023; Mousavi et al., 2025).

Continuous Versus Batch Precipitation

Continuous and batch precipitation systems differ in hydrodynamics and kinetics. Batch systems are more flexible and controllable locally, while industrial hydrometallurgy prefers continuous operation for higher throughput and easier integration.

Continuous reactors commonly exhibit stronger hydrodynamic gradients, broader RTD behavior, and more pronounced local supersaturation effects than batch systems, which partly explains why industrial selectivity is often lower than laboratory selectivity.

Before discussing coupled operational interactions, Table 5 summarizes the principal operational parameters affecting co-precipitation behavior in hydrometallurgical systems.

Table 5. Comparative overview of operational parameters affecting co-precipitation behavior in hydrometallurgical systems. Adapted from Ahmad (2020), Kim et al. (2021), Velasco et al. (2021), Deblonde et al. (2023), Lou et al. (2025), Saleem et al. (2023), and Nicol (2022).

Operational parameter	Main effects	Industrial implications	Major limitations	Typical TRL
Mixing intensity	Local supersaturation, nucleation	Selectivity instability	Scale-up heterogeneity	9
Residence time	Crystal maturation, aging	Filtration and impurity redistribution	Non-ideal RTD	8–9
Reagent addition	Local pH and supersaturation gradients	Amorphous precipitation	Injection heterogeneity	8–9
Reactor configuration	Hydrodynamics, particle growth	Process scalability	Fouling and mixing limitations	5–9
Seeded precipitation	Crystal growth stabilization	Improved filtration	Seed aging variability	7–9
Continuous operation	High throughput	Industrial integration	Hydrodynamic complexity	9
Intensified reactors	Micromixing optimization	Narrow PSD and selectivity improvement	Limited industrial validation	3–6

Table 5 shows operational parameters often dominate industrial processes, requiring equilibrium optimization, reactor engineering, hydrodynamics, and operational integration, even with favorable thermodynamics.

Coupled Effects and Parameter Interactions

Co-precipitation in hydrometallurgical systems involves coupled interactions of pH, supersaturation, redox potential, temperature, hydrodynamics, ionic strength, and residence time. These parameters interact nonlinearly under transient industrial conditions, so precipitation selectivity is often governed more by feedback mechanisms than by equilibrium constraints.

This complexity explains why lab optimization often fails during industrial scale-up. Lab studies typically examine isolated variables under controlled conditions, while industrial reactors face fluctuating feeds, concentration gradients, uneven mixing, and changing solid phases. As a result, precipitation pathways can change even when bulk variables seem stable. Figure 7 summarizes the main interactions affecting industrial precipitation.

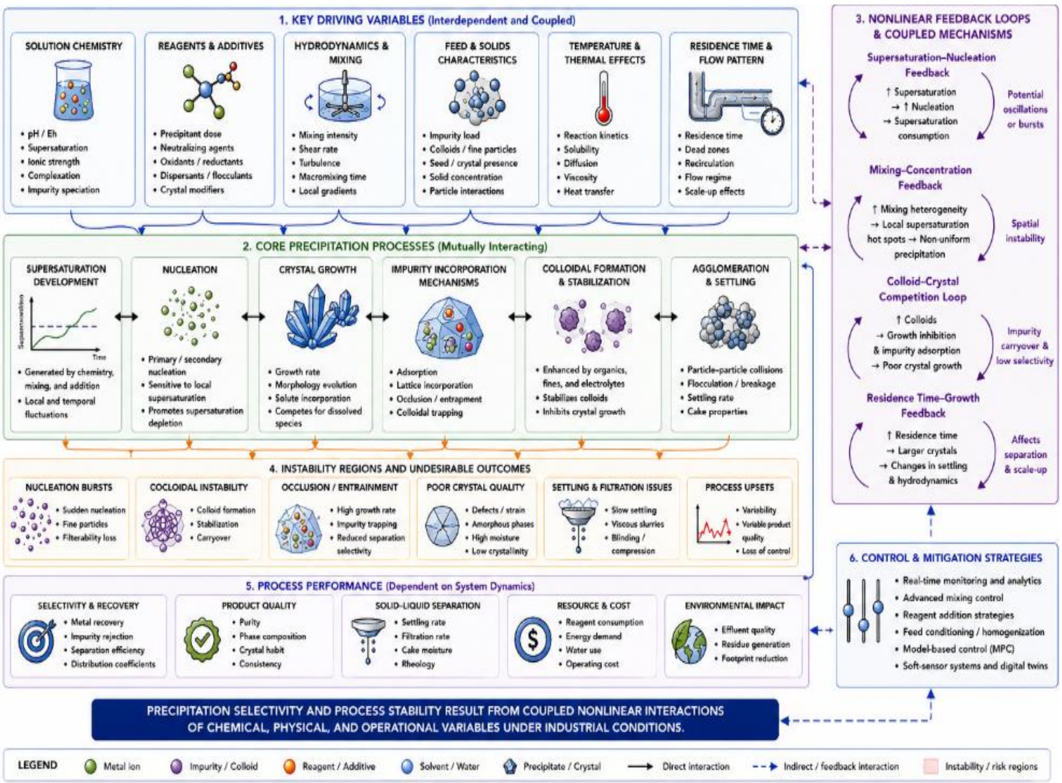


Figure 7. Precipitation behavior in hydrometallurgical systems, including nonlinear feedback mechanisms and instability regions. Adapted from Abiev et al. (2023), Kontrec et al. (2021), Poonoosamy et al. (2020), and Xu et al. (2024).

Figure 7 shows that precipitation selectivity depends on coupled dynamical interactions rather than isolated variables. Many industrial instabilities stem from feedback loops involving supersaturation, nucleation, mixing heterogeneity, and colloidal formation.

pH × Supersaturation

The interaction between pH and supersaturation is one of the most important factors controlling precipitation selectivity. Increasing pH generally reduces metal solubility and increases supersaturation, although the relationship remains strongly nonlinear because hydrolysis, nucleation, and crystal growth respond differently under changing conditions.

Low supersaturation favors slower crystal growth and larger particles, whereas rapid pH increases generate supersaturation spikes that promote amorphous precipitation, colloidal formation, adsorption, and occlusion (Kontrec et al., 2021). In industrial neutralization systems, reagent addition often occurs faster than micromixing, producing local supersaturation substantially higher than predicted from bulk conditions (Poonoosamy et al., 2020).

Eh × pH

Eh–pH interactions strongly influence precipitation stability in redox-sensitive systems involving Fe, Mn, Co, Cu, As, and Cr. Pourbaix stability regions demonstrate that precipitation depends simultaneously on oxidation state and acid–base equilibria rather than on pH alone.

In iron systems, oxidation state determines whether dissolved Fe remains soluble as Fe^{2+} or precipitates as ferric hydroxides. Similar effects occur in manganese systems, where oxidation kinetics affect morphology and impurity incorporation (Dong et al., 2023). Although industrial ORP control is mature, integrated Eh–pH optimization remains limited in practice (Mang et al., 2023).

Temperature × Kinetics

Temperature and precipitation kinetics are closely coupled because temperature affects diffusion, hydrolysis, nucleation, crystal growth, and phase transformation. Higher temperatures generally improve crystallinity and recrystallization, although highly supersaturated systems may also experience accelerated nucleation and formation of fine particles with stronger adsorption behavior.

This interaction is particularly important in rare-earth oxalate and transition-metal hydroxide systems, where filtration behavior may vary significantly under similar temperature conditions depending on hydrodynamics and precipitation rate (Berk et al., 2023). Industrial temperature optimization, therefore, remains largely empirical because predictive thermodynamic–kinetic models are still insufficiently validated (Xu et al., 2024)

Mixing × Nucleation

Mixing and nucleation are strongly interconnected because local supersaturation depends directly on reagent dispersion and micromixing efficiency. Since nucleation occurs immediately upon contact with the reagent, precipitation behavior is often governed by local hydrodynamics rather than by bulk chemistry.

Poor mixing promotes localized supersaturation peaks and rapid amorphous precipitation, while improved micromixing favors more stable crystal growth. Excessive turbulence may also destabilize aggregates and reduce settling performance. Industrial reactors generally exhibit lower selectivity than laboratory systems because hydrodynamic heterogeneity at the reactor scale dominates (Abiev et al., 2023; Xue et al., 2023).

Ionic Strength × Adsorption

Ionic strength affects adsorption through changes in electrostatic interactions, activity coefficients, and colloidal stability. Increasing ionic strength compresses the electrical double layer, reducing particle repulsion and promoting aggregation and adsorption. However, excessively high ionic strength may destabilize selective precipitation through competitive adsorption and activity effects, particularly in sulfate- and chloride-rich liquors.

Because industrial salt concentrations are much higher than those typically used in laboratory systems, industrial adsorption behavior is often substantially more complex than predicted from simplified experimental conditions.

Residence Time × Crystallinity

Residence time and crystallinity strongly influence precipitation stability and impurity incorporation. Short residence times generally favor poorly crystalline or amorphous precipitates, whereas longer aging promotes denser and more ordered solids (Rodrigues &Ignatiadis, 2025; Xu et al., 2024; Nicol, 2022; Kontrec et al., 2021). Improved crystallinity usually decreases adsorption and occlusion by reducing surface reactivity and porosity, although prolonged aging may increase structural incorporation of chemically similar ions.

Industrial reactors commonly exhibit broad residence-time distributions (RTD) and nonuniform hydrodynamics, generating particles with different crystallization histories within the same circuit (Abiev et al., 2023; Xue et al., 2023; Poonoosamy et al., 2020; Stec et al., 2020). Consequently, industrial precipitation systems are governed by coupled nonlinear interactions involving supersaturation, nucleation, adsorption, and hydrodynamic heterogeneity.

Before discussing industrial implications, Table 6 summarizes the principal coupled parameter interactions governing co-precipitation behavior in hydrometallurgical systems

Table 6. Principal coupled parameter interactions affecting co-precipitation behavior in hydrometallurgical systems. Adapted from: Abiev et al. (2023), Charbonneau et al. (2025), Kontrec et al. (2021), Nicol (2022), Poonoosamy et al. (2020), Rodrigues and Ignatiadis (2025), Stec et al. (2020), Xue et al. (2023), andXu et al. (2024).

Coupled interaction	Dominant effects	Main instability mechanisms	Industrial implications	Predictive control maturity
pH × supersaturation	Nucleation and selectivity	Local supersaturation spikes	Amorphou sprecipitation	Moderate
Eh × pH	Oxidation-state stability	Redox instability	Variable impurity scavenging	Moderate
Temperature × kinetics	Crystal maturation	Rapid nucleation transitions	Filtration variability	Moderate
Mixing × nucleation	Particle-sizedistribution	Micromixing heterogeneity	Selectivity loss	Low to moderate
Ionic strength × adsorption	Surface interaction changes	Double-layer compression	Increased impurity carryover	Low
Residence time × crystallinity	Crystal aging and ordering	Broad RTD behavior	Variable impurity incorporation	Moderate

Table 6 demonstrates that industrial precipitation systems are governed by coupled nonlinear interactions rather than independent variables. Instability regions commonly arise from feedback among supersaturation, nucleation, adsorption, and hydrodynamic heterogeneity, rendering single-variable optimization insufficient for reliable industrial control.

Most industrial operations still rely mainly on simplified control based on bulk pH or reagent dosage. Integrated multivariable control involving supersaturation, hydrodynamics, crystallization kinetics, and colloidal behavior remains limited. However, digital monitoring, AI-assisted optimization, and predictive control systems show increasing potential despite still operating mostly at intermediate maturity levels (TRL 3–6).

Industrial Case Studies and Technology Readiness

Industrial precipitation systems demonstrate that co-precipitation behavior is highly process-dependent and considerably more complex than laboratory predictions. Although the fundamental mechanisms are similar across hydrometallurgy, variations in solution chemistry, impurities, operating conditions, and economic constraints strongly affect the relative importance of adsorption, structural incorporation, occlusion, and colloidal trapping. Conventional precipitation methods based on pH adjustment and oxidation control are fully industrialized, whereas advanced predictive and multivariable control strategies remain less mature despite promising laboratory results. Before discussing individual sectors, Figure 8 summarizes the relationship between precipitation complexity and technology readiness across major hydrometallurgical applications. .

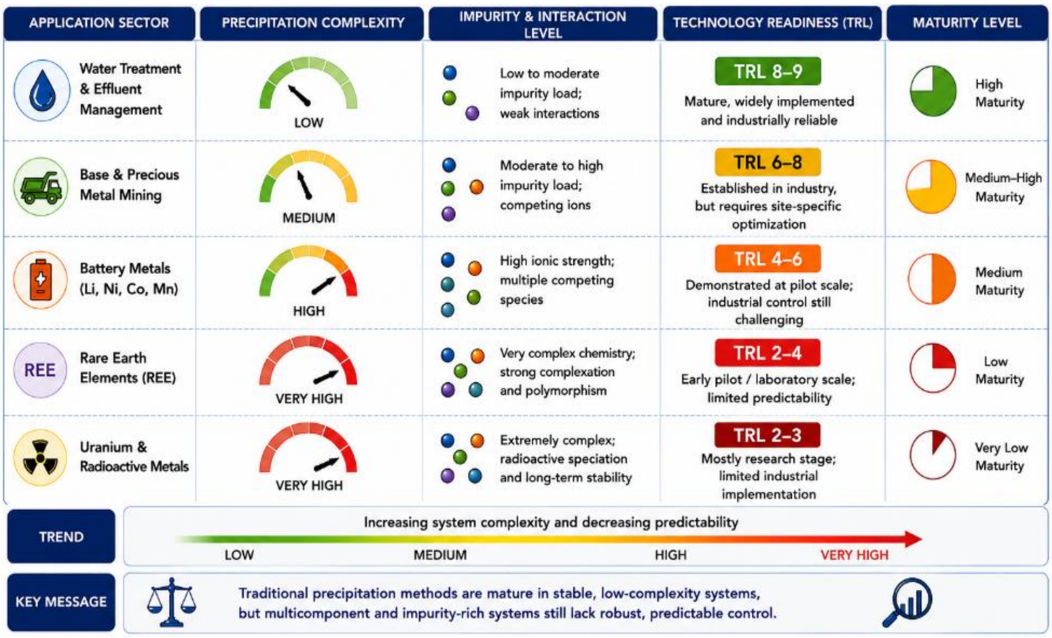


Figure 8. Relationship between precipitation complexity, impurity interactions, and technology readiness levels (TRLs) in major hydrometallurgical systems. Adapted from Deblonde et al. (2023), Saleem et al. (2023), and Stopic and Friedrich (2021).

Figure 8 shows that traditional precipitation methods are mature in stable systems, but in multicomponent and impurity-rich systems, control remains unpredictable.

Zinc Hydrometallurgy (RLE Systems)

Zinc hydrometallurgy is a mature process in which iron is removed through jarosite, goethite, or hematite precipitation under acidic sulfate conditions. Iron removal commonly exceeds 90–95%, although zinc, germanium, indium, gallium, and arsenic may co-precipitate with ferric residues (Shao et al., 2022). Industrial zinc losses in jarosite and goethite systems are typically 1–5%, depending on supersaturation, washing efficiency, and crystallinity. Rapid precipitation and poor crystal growth increase zinc retention within ferric precipitates (Wu et al., 2022).

Recent studies indicate that conversion of ferric hydroxides into crystalline hematite improves filtration and moisture removal, although valuable metals may remain associated with recrystallized phases (Pereira, 2025a). Conventional precipitation technologies are fully industrialized (TRL 9), while predictive AI-based control strategies remain limited by insufficient industrial validation under continuous operation (Li et al., 2024; Xiong et al., 2026).

Nickel Hydrometallurgy (HPAL Systems)

High-pressure acid leaching (HPAL) systems are characterized by complex precipitation behavior due to leach liquors containing Fe, Al, Cr, Mn, Co, Sc, Mg, and silica. Neutralization is essential for impurity removal, but scandium, cobalt, and nickel may be lost through adsorption, structural incorporation, and colloidal trapping in ferric and aluminum precipitates. Scandium losses exceeding 20–40% have been reported under unfavorable conditions (Mang et al., 2023).

Cr-bearing systems are highly sensitive to Eh–pH interactions, while manganese precipitation behavior depends strongly on oxidation kinetics and filtration characteristics (Ichlas et al., 2020). Advanced strategies such as staged neutralization, seeded precipitation, and reagent optimization show promising pilot-scale results, but industrial implementation remains challenging because of multicomponent instability and colloidal behavior under fluctuating conditions (Mousavi et al., 2025). Conventional neutralization systems are industrially mature (TRL 9), whereas advanced predictive precipitation technologies generally remain between TRL 5 and 7 (Zhao et al., 2025).

Copper Hydrometallurgy (SX–EW Systems)

Copper SX–EW circuits rely less on bulk precipitation than zinc or nickel systems, but precipitation still strongly affects purification and crud formation. Crud commonly contains colloidal silica, ferric precipitates, gypsum, suspended solids, organics, and entrained electrolyte, reducing separation efficiency and operational stability (Passos et al., 2021).

Impurity precipitation caused by pH or redox fluctuations may destabilize electrolyte quality and increase cathode contamination (Shen et al., 2021). Conventional control methods are fully mature (TRL 9), whereas AI-assisted predictive systems remain in early development stages (TRL 4–5) due to limited integration among chemistry, hydrodynamics, and phase behavior.

Rare Earth Element Systems

Rare earth precipitation systems are particularly challenging because lanthanides exhibit similar ionic radii and hydrolysis behavior, making selectivity highly sensitive to pH, supersaturation, and complexation. Co-precipitation of thorium and uranium remains a major issue because radioactive contamination affects REE purity and residue handling. Oxalate precipitation is widely used due to the low solubility and favorable filtration characteristics of REE oxalates, although impurity incorporation by Fe, Al, Ca, Mg, Th, and U remains significant (Stopic & Friedrich, 2021).

Small pH variations can strongly affect selectivity, and fractional precipitation only partially improves separation under industrial conditions (Masmoudi-Soussi et al., 2020; Han, 2020). Advanced approaches, including hydrothermal processing, selective ligands, and staged precipitation, remain largely at laboratory or pilot scale (TRL 3–5) because of limited industrial validation (Anawati& Azimi, 2022; Kuzmin et al., 2023). Conventional oxalate precipitation is industrially mature (TRL 8–9), whereas selective multicomponent precipitation remains less developed (Constantine et al., 2022; Gontijo et al., 2022; Gupta et al., 2023).

Battery Recycling and Secondary Resources

Battery recycling liquors are highly complex because they contain Li, Ni, Co, Mn, Fe, Al, Cu, fluorides, organics, graphite products, and secondary contaminants. Compared with primary hydrometallurgical systems, recycling streams exhibit greater impurity variability and stronger multicomponent interactions, complicating selective precipitation during cobalt–nickel–manganese separation. Oxalate, carbonate, hydroxide, and phosphate precipitation routes have all been investigated, although impurity carryover remains a persistent limitation (Djoudi et al., 2021; Korkmaz et al., 2020).

Circular hydrometallurgy places strong emphasis on impurity management because recycled streams frequently contain contaminants absent from primary ores, including fluoride species and organic compounds that affect nucleation and colloidal behavior (Saleem et al., 2023). Advanced strategies involving selective ligands, staged neutralization, AI optimization, and multivariable control show promising pilot-scale results, but most systems remain between TRL 5 and 7 because of limited long-term robustness under industrial multicomponent conditions (Ai et al., 2025; Chang et al., 2025; Jha et al., 2021; Kordloo et al., 2025; Li et al., 2020; Schmitz et al., 2024; Takano et al., 2022; Yun et al., 2025). Before discussing process performance impacts, Table 7 summarizes the dominant precipitation challenges, co-precipitation mechanisms, operational limitations, and technology maturity levels observed across major hydrometallurgical sectors.

Table 7. Comparative overview of precipitation behavior, dominant co-precipitation mechanisms, operational limitations, and technology readiness levels (TRLs) in major hydrometallurgical systems. Adapted from: Ai et al. (2025), Chang et al. (2025), Jha et al. (2021), Kordloo et al. (2025), Li et al. (2020), Schmitz et al. (2024), Takano et al. (2022), Yun et al. (2025), and Pereira (2025b).

Industrial system	Main precipitation challenges	Dominant co-precipitation mechanisms	Typical operational limitations	Typical TRL
Zinc RLE	Zn losses during Fe removal	Adsorption, occlusion	Residue washing and crystallinity	9
Nickel HPAL	Fe–Al–Cr impurity precipitation	Adsorption, colloidal trapping	Multicomponent instability	9
Copper SX–EW	Crud and electrolyte contamination	Colloidal aggregation	Organic–solid interactions	9
Rare earth systems	Th/U co-precipitation	Structural incorporation	Narrow selectivity windows	8–9
Battery recycling	Complex multimetal liquors	Mixed coupled mechanisms	High impurity variability	5–7

Table 7 shows that the maturity of precipitation engineering varies across hydrometallurgical sectors. Conventional systems are well established, but advanced selective and predictive technologies are less mature, especially in multicomponent and recycling applications.

Impact on Process Performance

Co-precipitation affects much more than impurity concentration in hydrometallurgical systems. In industrial operation, it directly influences metal recovery, selectivity, product purity, filtration, moisture retention, reagent consumption, waste generation, and overall operating costs. Consequently, co-precipitation control is both an operational and economic challenge.

Industrial precipitation circuits commonly operate under conflicting objectives. Maximizing impurity removal may increase valuable-metal losses, whereas maximizing selectivity may reduce overall recovery efficiency. As a result, industrial systems generally operate under compromise conditions. Figure 9 summarizes the relationship between precipitation behavior and downstream process performance.

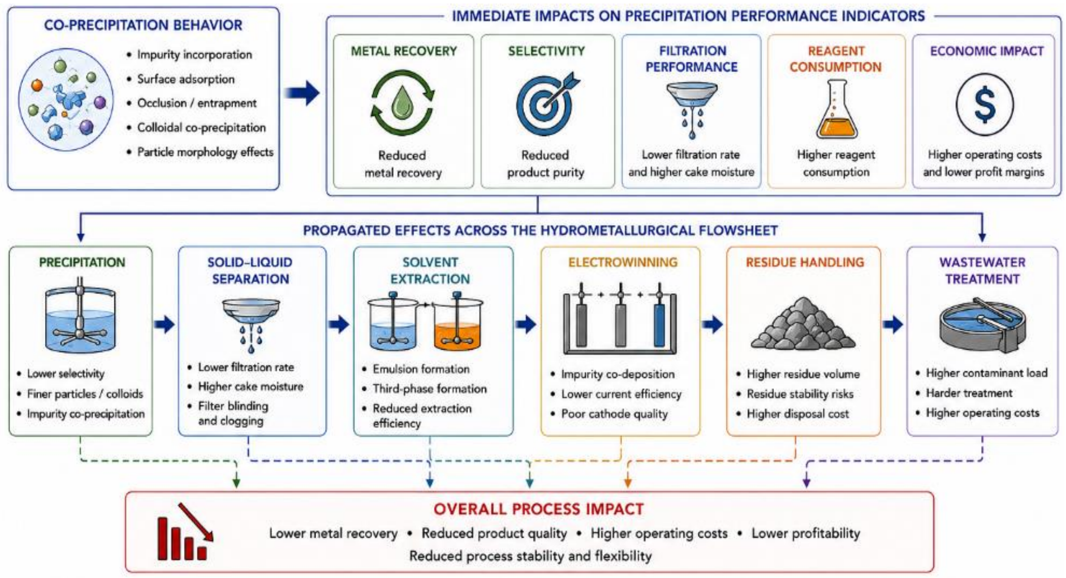


Figure 9. Relationship between co-precipitation behavior and industrial process performance indicators, including recovery, selectivity, filtration, reagent consumption, and economic impacts. Adapted from Pereira (2025b), Wu et al. (2022), and Crespo et al. (2025).

Figure 9 illustrates that precipitation performance affects the entire hydrometallurgical flowsheet, not just the precipitation stage. Operational penalties frequently propagate to filtration, solvent extraction, electrowinning, residue handling, and wastewater treatment systems.

Selectivity and Recovery

Selectivity and metal recovery are primary indicators of precipitation performance because co-precipitation may simultaneously remove impurities and valuable metals through adsorption, structural incorporation, and occlusion. In zinc hydrometallurgy, Zn losses associated with ferric precipitates are typically 1–5% under optimized conditions, although unstable systems may produce substantially higher losses (Wu et al., 2022).

In nickel laterite processing, scandium losses during Fe and Al neutralization may exceed 20–40% depending on pH control and precipitation kinetics (Pereira, 2025b). Selectivity becomes particularly difficult in systems containing chemically similar ions, such as rare-earth and battery-recycling liquors, where overlapping precipitation windows increase sensitivity to pH and supersaturation fluctuations (Chang et al., 2025). Although laboratory systems frequently show higher selectivity, industrial reactors operate under transient gradients, mixing limitations, and feed variability that reduce separation efficiency (Caulfield et al., 2023). Consequently, co-precipitation losses often generate economic penalties because valuable metals must be reprocessed or are permanently discarded in residues (Lou et al., 2025).

Product Purity

Co-precipitation reduces product purity by retaining impurities within precipitates, particularly in battery materials, rare-earth products, and electrowinning electrolytes with strict impurity limits. Structural incorporation causes the most persistent contamination because impurities become part of the crystal lattice, whereas adsorbed species may be partially removed by washing or recrystallization.

Amorphous and porous precipitates generally retain impurities more strongly than dense crystalline phases. In copper SX–EW systems, impurity precipitation and crud formation may degrade electrolyte quality and contaminate cathodes (Shen et al., 2021). Product purity generally improves with controlled crystal growth and higher crystallinity because dense crystalline particles retain fewer impurities than amorphous solids (Huang et al., 2024).

Filtration and Settling Behavior

Filtration and settling are strongly affected by co-precipitation because fine particles, colloids, silica gels, and amorphous hydroxides hinder solid–liquid separation and promote impurity carryover. Crystalline precipitates with narrow particle-size distributions generally improve permeability, settling, and moisture removal compared with colloidal or aggregated solids.

Rapid precipitation under high supersaturation commonly generates fine particles with poor settling characteristics (Rodrigues &Ignatiadis, 2025). Hydroxide-rich systems are especially problematic because ferric and aluminum precipitates have high surface area and strong water retention. Incomplete crystal growth increases filtration area requirements, flocculant demand, washing intensity, and overall operational costs (Pereira, 2025b). High moisture retention also increases residue mass, handling costs, and environmental risks.

Reagent Consumption and Waste Generation

Poor precipitation selectivity increases reagent consumption because valuable metals retained in precipitates frequently require re-leaching, re-neutralization, or additional purification stages. Operational instability and excessive supersaturation also increase acid or alkali demand through repeated pH adjustments.

Inefficient precipitation control may generate large volumes of residues including ferric sludges, gypsum, hydroxides, jarosite, and silica precipitates, increasing disposal costs and environmental liabilities (Vecino et al., 2021). These effects are particularly critical in systems containing arsenic, chromium, thorium, uranium, or fluoride, where long-term residue stability is essential. Poorly crystalline precipitates generally show lower chemical stability and greater contaminant mobility than ordered phases.

Precipitation inefficiencies also increase energy consumption because pumping, washing, filtration, and drying requirements become more severe in systems containing fine or highly hydrated solids. Studies indicate that poor precipitation performance increases overall OPEX beyond the precipitation stage itself (Crespo et al., 2025).

Before discussing broader industrial implications, Table 8 summarizes the principal impacts of co-precipitation on process performance and operational costs.

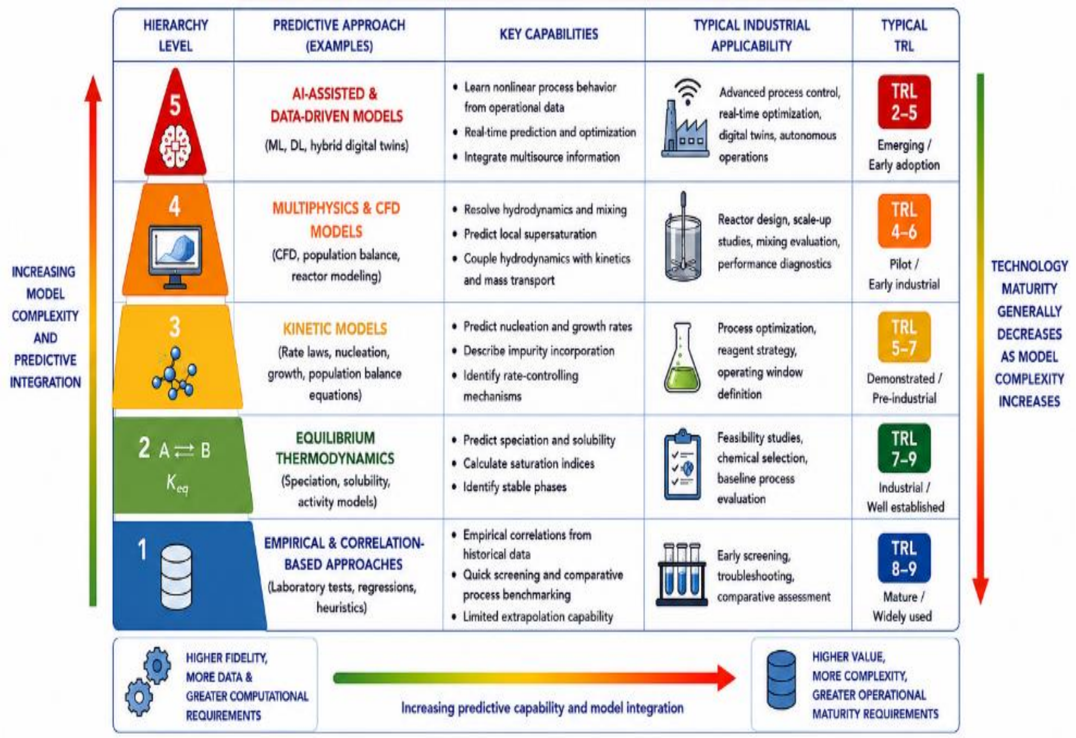
Table 8. outlines co-precipitation impacts on performance and costs. Adapted from: Crespo et al. (2025), Vecino et al. (2021), Wu et al. (2022), Chang et al. (2025), Lou et al. (2025), Rodrigues and Ignatiadis (2025), Huang et al. (2024), and Pereira (2025b).

Performance parameter	Main precipitation-related effects	Industrial consequences	Typical economic impacts
Recovery	Valuable-metal co-precipitation	Yield losses	Reduced revenue
Selectivity	Impurity incorporation	Additional purification stages	Increased OPEX
Productpurity	Structural incorporation and adsorption	Product contamination	Reduced product value
Filtration	Fine particles and gels	Low filtration rates	Larger equipment and energy demand
Settling	Colloidal stabilization	Thickener instability	Increased flocculant consumption
Moisture retention	Porouspre cipitates	High residue mass	Increased disposal and transport cost
Reagent consumption	Process instability	Excess neutralization demand	Increased chemical cost
Waste generation	Poor selectivity	Large residue volumes	Environmental liabilities

Table 8 shows that precipitation behavior impacts both technical and economic performance. Poor control can increase costs related to filtration, residue management, energy, and environmental compliance, beyond metal recovery losses. Co-precipitation control should be viewed as a process-wide optimization, not just a separation step.

Modeling and Predictive Approaches

Modeling and predictive methods are crucial for understanding co-precipitation in hydrometallurgy. Industrial circuits involve complex thermodynamics, kinetics, hydrodynamics, and interfaces that are difficult to optimize empirically. As a result, computational models predict stability, impurity distribution, supersaturation, crystal growth, and reactor performance. Despite progress, predictive methods have limitations with multicomponent systems. Many rely on equilibrium assumptions, simplified chemistry, or ideal flow, which reduces accuracy during scale-up. Figure 10 summarizes the hierarchy of predictive tools in hydrometallurgical precipitation systems.



HIERARCHY LEVEL	PREDICTIVE APPROACH (EXAMPLES)	KEY CAPABILITIES	TYPICAL INDUSTRIAL APPLICABILITY	TYPICAL TRL
5	AI-ASSISTED & DATA-DRIVEN MODELS (ML, DL, hybrid digital twins)	• Learn nonlinear process behavior from operational data • Real-time prediction and optimization • Integrate multisource information	Advanced process control, real-time optimization, digital twins, autonomous operations	TRL 2–5 Emerging / Early adoption
4	MULTIPHYSICS & CFD MODELS (CFD, population balance, reactor modeling)	• Resolve hydrodynamics and mixing • Predict local supersaturation • Couple hydrodynamics with kinetics and mass transport	Reactor design, scale-up studies, mixing evaluation, performance diagnostics	TRL 4–6 Pilot / Early industrial
3	KINETIC MODELS (Rate laws, nucleation, growth, population balance equations)	• Predict nucleation and growth rates • Describe impurity incorporation • Identify rate-controlling mechanisms	Process optimization, reagent strategy, operating window definition	TRL 5–7 Demonstrated / Pre-industrial
2 $A \rightleftarrows B$ K_{eq}	EQUILIBRIUM THERMODYNAMICS (Speciation, solubility, activity models)	• Predict speciation and solubility • Calculate saturation indices • Identify stable phases	Feasibility studies, chemical selection, baseline process evaluation	TRL 7–9 Industrial / Well established
1	EMPIRICAL & CORRELATION-BASED APPROACHES (Laboratory tests, regressions, heuristics)	• Empirical correlations from historical data • Quick screening and comparative process benchmarking • Limited extrapolation capability	Early screening, troubleshooting, comparative assessment	TRL 8–9 Mature / Widely used

Figure 10. Hierarchy of predictive approaches applied to hydrometallurgical precipitation systems, including thermodynamic, kinetic, CFD, and AI-assisted models, together with their typical industrial applicability and technology readiness levels (TRLs). Adapted from Deblonde et al. (2023), Xu et al. (2024), and Lou et al. (2025).

Figure 10 shows predictive complexity increases from equilibrium thermodynamics to AI-assisted systems, while technology maturity decreases as model integration and operational complexity grow.

Thermodynamic Modeling

Thermodynamic modeling is the most established predictive approach for precipitation systems. Software such as PHREEQC, HSC Chemistry, and FactSage is widely used to estimate speciation, saturation indices, phase stability, and precipitation equilibria. These models are particularly useful for evaluating pH-dependent precipitation, redox stability, and multicomponent interactions, especially in rare-earth systems involving oxalate precipitation and thorium co-precipitation (Gontijo et al., 2022).

Activity-correction methods improve predictions under high ionic-strength conditions typical of industrial liquors (Nigri et al., 2022). However, thermodynamic models assume equilibrium-controlled behavior and therefore cannot fully represent rapid nucleation, supersaturation gradients, incomplete mixing, or hydrodynamic effects. As a result, equilibrium approaches often overestimate selectivity and underestimate amorphous precipitation, despite their high industrial maturity (TRL 8–9).

Kinetic and Crystallization Models

Kinetic models describe precipitation behavior beyond equilibrium conditions using population balance models (PBMs), nucleation kinetics, and crystal growth models to predict particle-size evolution, aggregation, crystal maturation, and filtration behavior. PBMs are especially valuable because they integrate nucleation, growth, aggregation, and breakage processes, often outperforming equilibrium-only approaches in hydroxide and oxalate systems (Berk et al., 2023).

Crystal growth models also help describe transitions between amorphous and crystalline structures during aging and recrystallization. However, kinetic approaches are highly sensitive to calibration because reliable nucleation and growth parameters are rarely available for industrial multicomponent liquors. Consequently, predictive reliability often decreases during industrial scale-up (Xu et al., 2024).

CFD and Hydrodynamic Modeling

Computational fluid dynamics (CFD) is important for evaluating reactor-scale precipitation because hydrodynamics strongly affect supersaturation, mixing, nucleation, and impurity incorporation. CFD models predict residence-time distribution, turbulence, and reagent dispersion, helping identify supersaturation hotspots and dead zones not detected by bulk measurements.

Several studies show that local hydrodynamic gradients may significantly influence precipitation behavior even when global operating conditions appear stable (Abiev et al., 2023). Nevertheless, most CFD approaches simplify precipitation chemistry because full coupling between hydrodynamics, thermodynamics, nucleation, and colloidal behavior remains computationally demanding (Xue et al., 2023). Current industrial applications are therefore mainly semi-empirical and remain at intermediate maturity levels (TRL 4–6).

AI and Predictive Systems

Artificial intelligence (AI) and machine learning are increasingly explored for predictive precipitation control by integrating operational data, thermodynamics, kinetics, and hydrodynamics into adaptive frameworks. Machine-learning approaches have been applied to predict selectivity, filtration performance, particle size, and reagent demand, while hybrid models combining mechanistic and data-driven approaches show promising results (Li et al., 2024). Digital twins have also been proposed for real-time optimization of pH control, supersaturation management, and impurity transfer minimization.

Despite strong potential, AI-assisted systems remain limited by the scarcity of high-quality industrial datasets and the lack of real-time monitoring of supersaturation, particle size, and crystallization behavior. As a result, most AI-assisted systems remain between TRL 2 and 5, while autonomous digital twins are still largely conceptual (TRL 2–4) (Lou et al., 2025).

Limitations of Current Predictive Approaches

The main limitation of current predictive methods is the difficulty of integrating multicomponent chemistry, transient hydrodynamics, crystallization kinetics, and interfacial phenomena simultaneously under industrial conditions. Industrial precipitation systems involve coupled reactions, ionic competition, colloidal behavior, adsorption, and structural incorporation occurring simultaneously, while most plants monitor only bulk variables such as pH and temperature (Deblonde et al., 2023).

Scale-up uncertainty remains another major limitation. Laboratory systems operate under controlled conditions, whereas industrial reactors exhibit broad residence-time distributions, nonuniform mixing, variable feed chemistry, and operational disturbances. Consequently, predictive models calibrated under laboratory conditions often fail to reproduce industrial precipitation behavior reliably (Nicol, 2022). Table 9 summarizes the principal predictive approaches applied to hydrometallurgical precipitation systems, including their capabilities, limitations, and maturity levels.

Table 8. Comparative overview of predictive approaches applied to hydrometallurgical precipitation systems, including modeling scope, major strengths, industrial limitations, and technology readiness levels (TRLs). Adapted from Deblonde et al. (2023), Lou et al. (2025), and Xu et al. (2024).

Modeling approach	Main capabilities	Major limitations	Typical industrial applicability	Typical TRL
Thermodynamic modeling	Speciation and equilibrium prediction	Limited kinetic realism	Process design and optimization	8–9
Kinetic/PBM models	Particle-size and growth prediction	Extensive calibration required	Pilot and laboratory systems	5–7
CFD modeling	Reactor hydrodynamics and mixing	Simplified chemistry integration	Reactor optimization	4–6
AI-assisted systems	Predictive optimization	Sparse industrial datasets	Emerging digital control	2–5
Digital twins	Real-time integrated control	Limited industrial validation	Conceptual and pilot systems	2–4

Table 9 shows that predictive maturity decreases with increasing model integration complexity. While thermodynamic approaches are already mature, fully integrated multivariable predictive control remains in an early stage of development.

Strategies for Process Control and Optimization

The increasing complexity of hydrometallurgical precipitation systems has shifted process optimization from simple pH adjustment toward integrated multivariable control strategies. Industrial circuits must simultaneously balance selectivity, recovery, filtration behavior, reagent consumption, and operational stability under continuously changing conditions. Consequently, modern precipitation control increasingly combines physicochemical optimization, reactor engineering, real-time monitoring, and predictive automation (Li et al., 2024; Xu et al., 2024; Chernyshova et al., 2023). Despite these advances, most industrial systems still rely primarily on conventional controls based on pH, ORP, and reagent dosage.

Staged pH Control

Staged pH control is widely used in industrial hydrometallurgy to distribute precipitation across multiple operational windows, reducing supersaturation and improving impurity separation. In zinc and nickel systems, staged neutralization minimizes valuable-metal losses and promotes larger, denser particles with improved filtration behavior (Hassas & Rezaee, 2023).

Although highly mature (TRL 9), staged systems increase operational complexity because they require multiple reactors, sensors, and reagent-injection points, particularly under fluctuating feed conditions (Stec et al., 2020).

Supersaturation Management

Supersaturation control is essential for minimizing amorphous precipitation, fine-particle formation, and impurity occlusion. Strategies such as controlled reagent addition, dilution, staged neutralization, and optimized hydrodynamics favor crystal growth over excessive nucleation, improving particle size, selectivity, and filtration performance (Ali et al., 2025).

However, supersaturation is difficult to monitor directly because local gradients may persist even under stable bulk pH conditions. Conventional supersaturation-control strategies are relatively mature (TRL 8–9), whereas predictive adaptive systems remain at lower maturity levels (TRL 3–5).

Nucleation Engineering

Nucleation engineering aims to control particle formation in order to improve selectivity, crystal size, and separation efficiency. Techniques such as controlled reagent dispersion, optimized mixing, thermal regulation, and seed-assisted crystallization reduce excessive nucleation and limit impurity adsorption by decreasing total particle surface area.

Population balance and crystallization studies show that nucleation behavior strongly affects filtration and washing performance (Berk et al., 2023). Nevertheless, industrial nucleation remains difficult to control because precipitation reactions often occur faster than mixing, leading to local supersaturation spikes and uncontrolled nucleation (Xu et al., 2024).

Seeded Precipitation

Seeded precipitation improves crystal growth stability and reduces fine-particle formation by promoting heterogeneous nucleation on existing particles. In rare-earth oxalate systems, seeding improves particle-size distribution, settling, and filtration behavior (Gerold et al., 2020).

Seeded systems may also reduce supersaturation sensitivity, although seed aging, attrition, and fouling can alter long-term industrial performance. Excessive seed loading may additionally increase slurry viscosity and affect reactor hydrodynamics (Mousavi et al., 2025). Industrial maturitygenerally ranges from TRL 7 to 9.

Hydrodynamic Optimization

Hydrodynamic optimization improves micromixing, reagent dispersion, and residence-time distribution, reducing local supersaturation heterogeneity. Reactor hydrodynamics strongly influence nucleation, aggregation, and impurity incorporation. Common strategies include optimized impellers, multistage reactors, static mixers, oscillatory flow, and intensified reactor designs (Abiev et al., 2023).

Scale-up remains a major challenge because turbulence, slurry rheology, and mixing behavior often change significantly between laboratory and industrial systems. Although CFD-assisted optimization shows strong potential, most fully coupled hydrodynamic–precipitation systems remain at intermediate maturity levels (TRL 5–7) (Xue et al., 2023).

Real-Time Monitoring and Automation

Real-time monitoring is increasingly important for stabilizing industrial precipitation systems operating under rapidly changing conditions. Conventional monitoring typically includes pH, ORP, temperature, conductivity, slurry density, and reagent consumption. Advanced systems may also incorporate inline particle-size analysis, turbidity monitoring, and process analytical technologies (PAT).

Automated control improves process reproducibility and can reduce reagent consumption while improving selectivity (Chernyshova et al., 2023). However, current systems still provide limited information about local supersaturation, nucleation behavior, and crystal morphology, making most industrial automation systems predominantly reactive rather than predictive. Conventional monitoring systems are mature (TRL 8–9), while predictive automation remains less developed (TRL 6–8).

Emerging Selective Precipitation Strategies

Emerging strategies seek to improve selectivity through targeted chemical control, advanced ligands, electrochemically assisted precipitation, polymer engineering, and hybrid process integration. Selective ligands have shown promising results in rare-earth, cobalt, and battery-recycling systems by modifying precipitation windows and reducing impurity incorporation (Comel et al., 2021).

Electrochemically assisted precipitation enables local control of pH and redox conditions, whereas polymer engineering may influence colloidal stability and crystal morphology. However, most advanced selective precipitation technologies remain at TRL 3-6 due to limited industrial validation under continuous, multicomponent operation (Dong et al., 2021; Huang et al., 2024). Before discussing sustainability aspects, Table 10 summarizes the principal process-control and optimization strategies applied to hydrometallurgical precipitation systems.

Table 9. Comparative overview of process-control and optimization strategies for hydrometallurgical precipitation systems, including operational objectives, principal benefits, limitations, and technology readiness levels (TRLs). Adapted from Li et al. (2024), Xu et al. (2024), and Chernyshova et al. (2023).

Control strategy	Main operational objective	Principal benefits	Major limitations	Typical TRL
Staged pH control	Selective impurity removal	Reduced metal losses	Operational complexity	9
Supersaturation management	Control of nucleation and growth	Improved filtration and selectivity	Difficult real-time monitoring	8–9
Nucleation engineering	PSD and crystal-growth control	Reduced amorphou sprecipitation	Sensitive to mixing conditions	5–7
Seeded precipitation	Crystal-growth stabilization	Improved settling and filtration	Seed aging and fouling	7–9
Hydrodynamic optimization	Micromixing improvement	Reduced local supersaturation	Scale-upuncertainty	5–7
Real-time monitoring	Operational stabilization	Faster process response	Limited local parameter sensing	8–9
AI-assisted automation	Predictive process optimization	Adaptive control potential	Sparse industrial datasets	3–5
Digital integrated control	Multivariable optimization	Potential autonomous operation	Limited industrial validation	2–4

Table 10 shows that conventional precipitation-control technologies are already mature, whereas integrated predictive optimization remains under development. The main challenge in future precipitation engineering is the reliable integration of physicochemical and operational variables into robust decision-making frameworks..

Environmental and Sustainability Aspects

The environmental impact of hydrometallurgical precipitation systems extends beyond impurity removal and directly affects residue management, water use, reagent consumption, resource efficiency, and ESG performance. Industrial precipitation circuits generate large quantities of residues, including jarosite, goethite sludges, gypsum, ferric hydroxides, silica wastes, and mixed-metal precipitates. Their environmental behavior depends strongly on precipitation conditions, crystallinity, impurity incorporation, and moisture retention. Poorly controlled systems often produce unstable and highly hydrated residues with greater contaminant mobility and more difficult handling characteristics (Vecino et al., 2021). Improved precipitation selectivity can reduce metal losses, enhance recycling efficiency, and minimize environmental impacts. Figure 11 summarizes the relationship between co-precipitation control, process efficiency, residue generation, and environmental sustainability in hydrometallurgical systems.

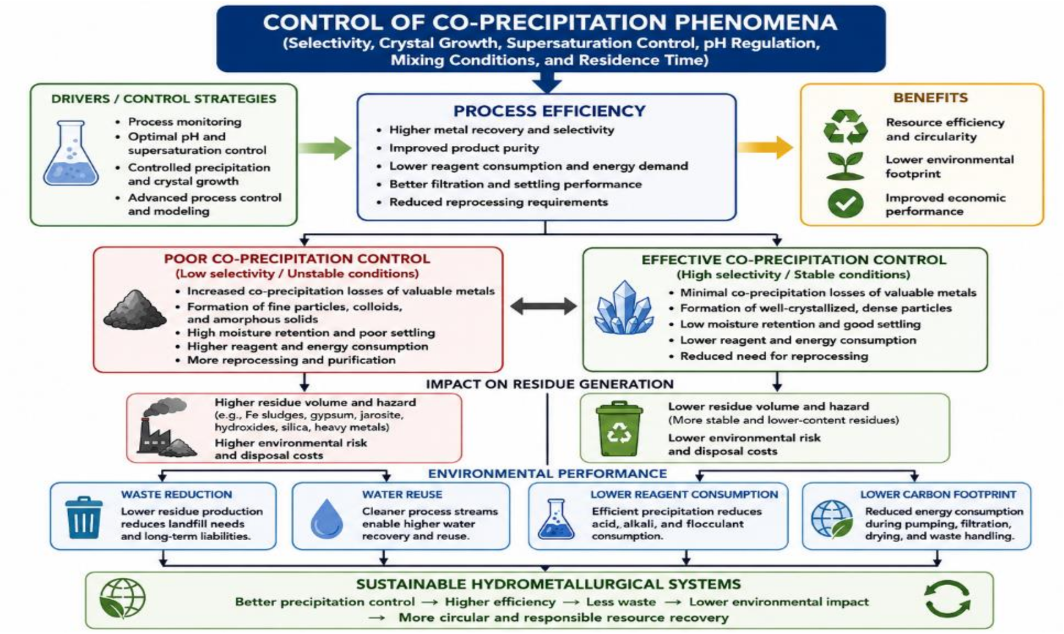


Figure 11. Relationship between co-precipitation control, process efficiency, residue generation, and environmental sustainability in hydrometallurgical systems. Adapted from Akcil et al. (2021), Saleem et al. (2023), and Crespo et al. (2025).

Figure 11 shows how precipitation impacts environmental performance via waste, water reuse, reagent use, and process efficiency.

Waste Minimization and Sludge Stabilization

Waste minimization is one of the main sustainability objectives in precipitation engineering because poor selectivity and co-precipitation increase residue generation and losses of valuable metals. Iron-removal residues, such as jarosite, goethite, and ferric hydroxides, constitute major waste streams in hydrometallurgical operations (Akcil et al., 2021).

Sludge stabilization is equally important because residue mineralogy controls long-term environmental stability. Poorly crystalline precipitates generally exhibit higher moisture retention, lower stability, and greater contaminant mobility than more ordered crystalline phases. Residues containing arsenic, chromium, fluoride, thorium, or uranium are particularly sensitive to precipitation conditions. Controlled precipitation and crystal aging may improve residue stability and reduce contaminant leachability (Masindi et al., 2023)

Reduced Impurity Discharge and Water Reuse

Improved precipitation selectivity can substantially reduce dissolved impurities in effluents and recycled water systems, particularly for arsenic, fluoride, selenium, chromium, manganese, and radioactive elements. Water reuse is increasingly important because many hydrometallurgical plants operate under freshwater restrictions.

However, extensive water recirculation also increases ionic strength and promotes the accumulation of sulfate, chloride, calcium, magnesium, and silica, which may alter precipitation selectivity and increase colloidal stabilization. Consequently, water reuse improves sustainability but can simultaneously increase process instability and impurity carryover (Passos &Ignatiadis, 2025).

Resource Efficiency and Circular Hydrometallurgy

Resource efficiency depends strongly on co-precipitation control because losses of valuable metals reduce overall material recovery. Circular hydrometallurgy relies heavily on selective precipitation due to the complexity of secondary resource liquors derived from battery recycling, e-waste, slags, and industrial residues.

Several studies indicate that improved precipitation control can enhance critical-metal recovery, reduce residue generation, and lower reagent consumption in recycling systems (Saleem et al., 2023). Nevertheless, selective precipitation remains difficult under highly variable multicomponent conditions, particularly in impurity-rich rare-earth streams.

Energy Efficiency and Carbon Implications

Precipitation performance also affects energy consumption and carbon intensity indirectly through downstream operations. Poor filtration and high-moisture residues increase the requirements for pumping, washing, drying, and sludge handling. In addition, excessive reagent consumption increases indirect carbon emissions because neutralizing agents such as lime, sodium hydroxide, and ammonia have significant upstream environmental footprints.

Improved precipitation selectivity has been associated with lower energy demand, reduced sludge generation, and improved operational efficiency (Crespo et al., 2025). However, isolated optimization of impurity removal may not reduce the total environmental footprint if reagent use or downstream energy demand increases.

ESG Implications and Life-Cycle Considerations

Environmental, social, and governance (ESG) requirements are increasingly influencing hydrometallurgical process design. Residue stability, water consumption, carbon emissions, and metal recovery are now considered strategic performance indicators. Life-cycle assessments show that co-precipitation losses reduce resource efficiency and increase environmental burdens associated with extraction, reprocessing, and waste disposal.

Current industrial strategies increasingly emphasize integrated sustainability metrics involving recovery efficiency, residue management, water reuse, reagent consumption, and carbon footprint. Nevertheless, predictive integration between precipitation engineering and life-cycle assessment remains limited because most industrial systems are still optimized mainly for short-term operational performance rather than comprehensive sustainability criteria (Gupta et al., 2023). Before discussing future perspectives, Table 11 summarizes the main environmental and sustainability implications associated with co-precipitation behavior in hydrometallurgical systems.

Table 10. Environmental and sustainability implications of co-precipitation behavior in hydrometallurgical systems, including operational impacts, ESG relevance, and major industrial challenges. Adapted from Akcil et al. (2021), Saleem et al. (2023), and Crespo et al. (2025).

Sustainability aspect	Main precipitation-related effects	Industrial implications	Major environmental concerns
Waste minimization	Reduced co-precipitation losses	Lower residue generation	Reduced disposal demand
Sludge stabilization	Improved crystallinity	Enhanced residue stability	Reduced contaminant mobility
Water reuse	Increased recirculation efficiency	Reduced freshwater demand	Salt accumulation and instability
Resource efficiency	Higher metal recovery	Improved circularity	Reduced primary extraction demand
Energy efficiency	Improved filtration and settling	Lower operational energy demand	Reduced indirect emissions
Reagent optimization	Lower chemical consumption	Reduced OPEX	Lower carbon footprint
ESG performance	Integrated sustainability metrics	Improved regulatory compliance	Long-term environmental liability reduction

Table 11 demonstrates that precipitation control is directly connected to environmental performance, operational efficiency, and long-term sustainability. In modern hydrometallurgy, precipitation engineering is therefore essential not only for impurity removal, but also for sustainable resource management and circular processing.

Knowledge Gaps and Future Directions

Despite major advances in hydrometallurgical precipitation science, important scientific and industrial limitations remain. Although understanding of adsorption, nucleation, crystallization, and multicomponent interactions has improved considerably, industrial predictability is still limited because most operations rely on simplified control strategies and empirical optimization. A major contradiction is that mechanistic understanding has advanced faster than industrial predictive capability. Laboratory studies commonly investigate isolated phenomena, whereas industrial systems continue to experience instability, limited selectivity, and scale-up uncertainty. Future progress will therefore depend on integrated multiscale process understanding rather than isolated equilibrium analysis. Figure 12 summarizes the principal scientific and technological barriers limiting predictive precipitation control in industrial hydrometallurgy.

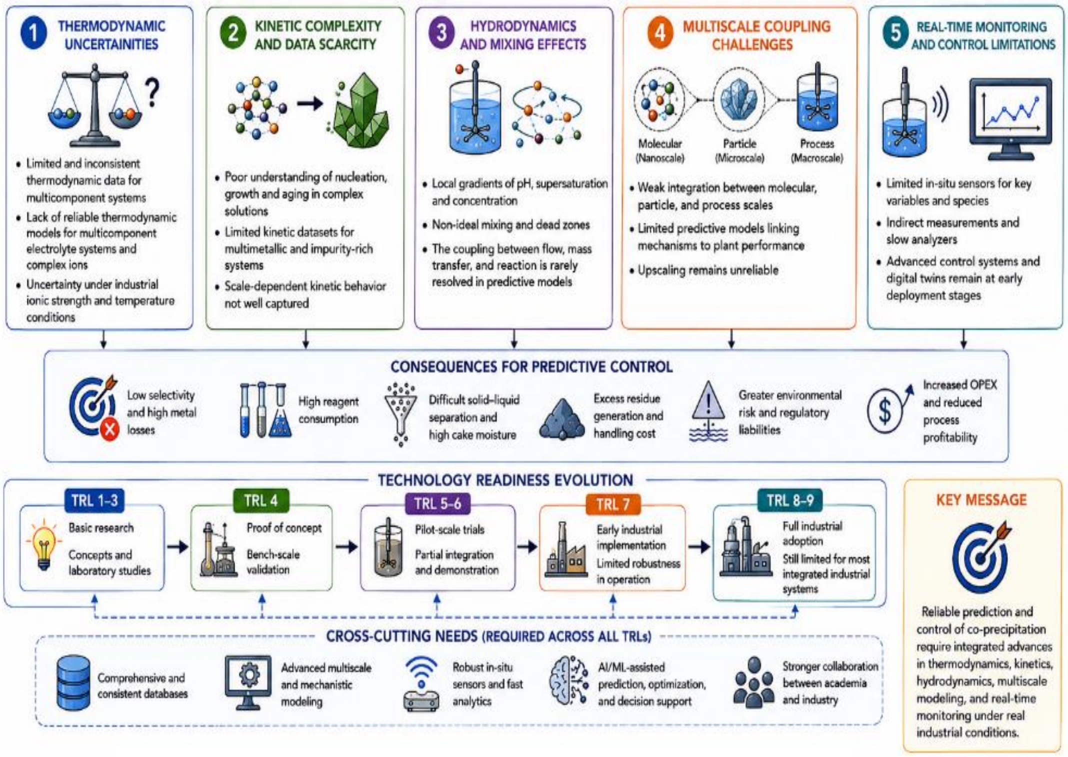


Figure 12. Principal scientific and technological gaps evolution that limit predictive control of co-precipitation in industrial hydrometallurgical systems, including multiscale coupling challenges and the evolution of technology readiness. Adapted from Deblonde et al. (2023), Lou et al. (2025), and Nicol (2022).

Figure 12 shows that current limitations stem from poor integration of thermodynamics, kinetics, hydrodynamics, and real-time process monitoring in industrial conditions.

Integrated Predictive Modeling

One of the main limitations in precipitation science is the absence of integrated predictive frameworks. Thermodynamic, kinetic, and hydrodynamic models are usually developed separately, even though industrial systems involve strongly coupled multiscale phenomena. Equilibrium approaches frequently neglect transient nucleation, local supersaturation, and hydrodynamic effects, while CFD and kinetic models often oversimplify thermodynamics and multicomponent interactions (Nicol, 2022).

These limitations are especially severe in concentrated industrial liquors containing transition metals, rare earths, sulfate complexes, silica, and organic species. Future research should prioritize integrated frameworks coupling speciation, supersaturation, crystal growth, and reactor-scale hydrodynamics (Deblonde et al., 2023).

Real-Time Monitoring and Digitalization

Limited operando monitoring remains a major obstacle to predictive precipitation control. Most industrial plants monitor only bulk variables such as pH, ORP, temperature, and reagent dosage, while local phenomena including supersaturation, nucleation, crystal morphology, and colloidal aggregation are rarely measured in real time.

Emerging technologies such as inline spectroscopy, turbidity sensors, Raman analysis, and particle imaging may significantly improve precipitation monitoring, although industrial implementation remains limited by fouling, calibration, robustness, and slurry-handling challenges (Chernyshova et al., 2023). Digitalization also varies substantially across hydrometallurgical sectors, with smaller and recycling plants still relying heavily on manual operation (Li et al., 2024).

AI-Assisted Process Optimization

Artificial intelligence and machine learning are increasingly explored for precipitation optimization because industrial systems generate large volumes of operational data with highly nonlinear interactions. Machine-learning models may help identify hidden operational relationships involving reagent consumption, selectivity, filtration performance, and process instability. Hybrid digital twins combining mechanistic models with real-time operational data also show strong potential for adaptive pH control, supersaturation management, and predictive nucleation control. However, industrial datasets remain sparse, poorly standardized, and strongly system-dependent, limiting model generalization and long-term calibration (Dong et al., 2021). Consequently, AI-assisted optimization technologies remain mostly between TRL 2 and 5, while autonomous systems are still largely conceptual (Lou et al., 2025).

Multicomponent Industrial Systems

Multicomponent precipitation systems remain among the least understood areas of industrial hydrometallurgy. Most experimental studies still focus on simplified binary or ternary systems, despite industrial liquors commonly containing dozens of dissolved species. Competitive adsorption, coupled hydrolysis, colloidal stabilization, organic interactions, and transient supersaturation effects become substantially more complex under real industrial conditions.

This complexity is particularly important in battery recycling and secondary-resource processing, where feed compositions vary significantly and contain transition metals, alkali metals, fluorides, sulfate complexes, graphite degradation products, and organic contaminants (Saleem et al., 2023). Future research should therefore emphasize realistic multicomponent systems and long-term precipitation studies under industrially relevant conditions (Hassas et al., 2021).

Emerging Selective Precipitation Technologies

Emerging selective precipitation technologies, including advanced ligands, electrochemical methods, engineered polymers, selective crystallization, and hybrid separation systems, have shown promising laboratory-scale results, especially for rare earths and critical metals. However, industrial implementation remains limited because many of these technologies involve high reagent costs, operational sensitivity, or poor robustness under fluctuating industrial conditions.

Autonomous precipitation control also remains at an early stage of development. Fully integrated systems capable of adjusting pH, supersaturation, mixing, and nucleation dynamically in real time are still uncommon in industrial practice. Future progress will depend on integrating mechanistic understanding with adaptive digital systems capable of handling multicomponent industrial environments (Pereira, 2026; Stopic & Friedrich, 2021). Table 12 summarizes the principal knowledge gaps, industrial barriers, emerging technologies, and future research priorities associated with predictive co-precipitation control.

Table 11. Principal knowledge gaps, emerging technologies, industrial barriers, and future research directions for predictive co-precipitation control in hydrometallurgical systems. Adapted from Deblonde et al. (2023), Lou et al. (2025), and Nicol (2022).

Research area	Main current limitations	Future development priorities	Typical TRL
Integrated predictive modeling	Poor multiscale coupling	Thermodynamic–kinetic–hydrodynamic integration	3–5
Real-time monitoring	Limited operando sensing	Inline spectroscopy and advanced PAT	4–6
AI-assisted optimization	Sparse industrial datasets	Hybrid digital twins	2–5
Multicomponent systems	Simplified laboratory studies	Industrially representative liquor studies	3–5
Autonomous precipitation control	Limited adaptive control	Self-optimizing precipitation systems	2–4
Emerging selective technologies	Limited industrial validation	Scale-up and robustness assessment	3–6

Table 12 shows that future precipitation engineering relies on integration over isolated optimization. The main challenge is now developing predictive, adaptive, and robust systems to handle complex multicomponent precipitation environments in real time.

Conclusions

Co-precipitation is a complex and crucial aspect of hydrometallurgy, impacting recovery, selectivity, purity, filtration, reagent use, residue, and sustainability. It should be understood as a result of interconnected physicochemical, kinetic, hydrodynamic, and operational interactions under dynamic conditions, not just an isolated equilibrium phenomenon.

pH and supersaturation are key variables influencing precipitation, impurity incorporation, nucleation, and crystal growth, but their effects are intertwined with redox, ionic strength, mixing, residence time, hydrodynamics, and multicomponent chemistry. As a result, industrial precipitation often differs from simple lab predictions and equilibrium expectations.

The analysis shows industrial performance relies on integrated process control, not isolated parameter optimization. Conventional precipitation methods, such as staged neutralization and reactor engineering, are mature and widely used. Conversely, advanced systems such as predictive multivariable control, AI optimization, digital twins, and autonomous management still have low technology readiness levels despite recent progress.

Multicomponent industrial liquors remain the largest unresolved challenge in precipitation engineering. Competitive adsorption, colloidal stabilization, coupled hydrolysis, transient supersaturation, and impurity interactions remain insufficiently understood under realistic industrial conditions, particularly in battery recycling, rare earth processing, and secondary-resource hydrometallurgy.

Future advances in precipitation engineering will rely more on integration than isolated mechanistic refinement. Next-generation systems will need combined thermodynamic–kinetic–hydrodynamic modeling, operando monitoring, real-time analytics, and adaptive digital optimization to respond to changing conditions.

Precipitation engineering is shifting from empirical practice to an integrated, predictive process-science discipline. Advanced process control will be key to enhancing selectivity and recovery, and to enabling sustainable, low-waste hydrometallurgical systems aligned with future circular-economy needs.

Declarations

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Conflicts of Interest

The author declares no conflict of interest.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

Antonio Clareti Pereira: Conceptualization, methodology, literature review, data analysis, visualization, writing—original draft preparation, writing—review and editing.

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