IKR Publishers

IKR Journal of Multidisciplinary Studies (IKRJMS)
Journal homepage: https://ikrpublishers.com/ikrjms/
Volume-2, Issue-5 (September-October) 2026

OPEN ACCESS
ISSN: 3107-3999 (Online)

In Situ Recovery and In Situ Leaching of Selected Critical and Strategic Metals: A Critical Review of Geological Preconditions, Reactive Transport, Process Engineering, Environmental Risk, and Scale-Up (2015–2026)

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DOI: *10.5281/zenodo.22904358*

ARTICLE INFO

Article history:
Received : 11-09-2026
Accepted : 18-09-2026
Available online : 22-09-2026

Citation: Pereira, A. C. (2026). In Situ Recovery and In Situ Leaching of Selected Critical and Strategic Metals: A Critical Review of Geological Preconditions, Reactive Transport, Process Engineering, Environmental Risk, and Scale-Up (2015–2026). *IKR Journal of Multidisciplinary Studies (IKRJMS)*, *2*(5), 43-62.

ABSTRACT **Original Research Article**

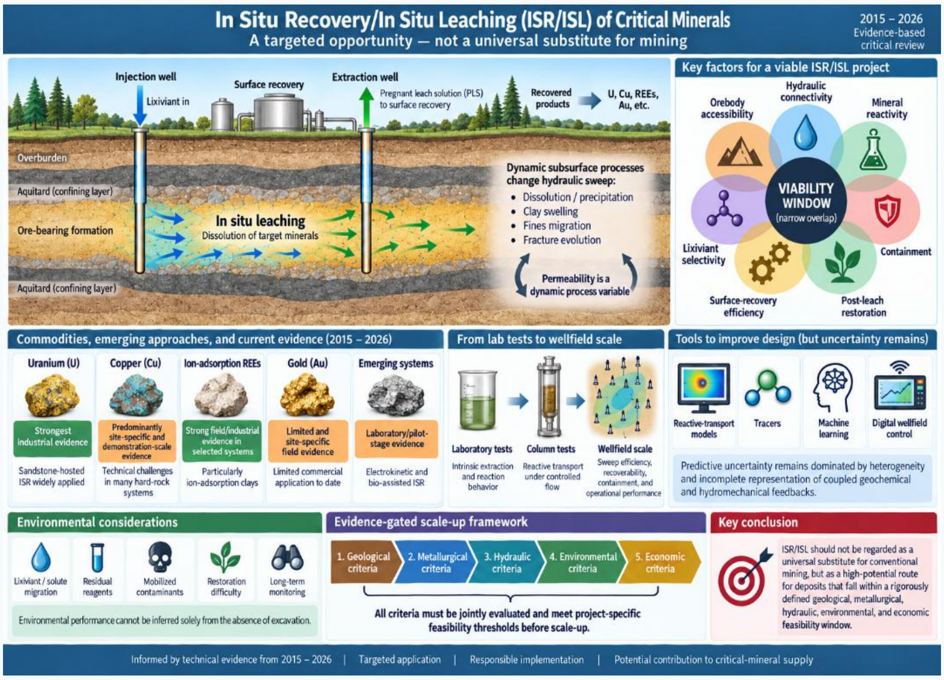
In situ recovery (ISR), also termed in situ leaching (ISL), is increasingly considered a low-disturbance alternative to conventional mining. This critical review synthesizes an author-curated corpus of 80 records published from 2015 through 2026 and evaluates ISR/ISL for uranium, copper, ion-adsorption rare earth elements (REEs), gold, and emerging electrokinetic and bio-assisted systems. The central distinction is between extraction measured in laboratory or column tests and recoverability at wellfield scale. Viability requires a narrow overlap among orebody accessibility, hydraulic connectivity, mineral reactivity, lixiviant selectivity, hydraulic containment, surface-recovery efficiency, and post-leach restoration. Permeability is treated as a dynamic process variable because dissolution, precipitation, clay swelling, fines migration, and fracture evolution can continuously modify hydraulic sweep. The strongest industrial evidence remains associated with sandstone-hosted uranium and selected ion-adsorption REE systems, whereas hard-rock copper, gold, and several electrokinetic concepts remain more site-specific or demonstration-oriented. Reactive-transport models, tracers, machine learning, and digital wellfield control are improving design capability, but predictive uncertainty remains dominated by heterogeneity and incomplete representation of coupled geochemical and hydromechanical feedbacks. Environmental performance cannot be inferred from the absence of excavation alone; groundwater migration, residual reagents, mobilized contaminants, restoration difficulty, and long-term monitoring remain decisive. An evidence-gated scale-up framework is therefore proposed in which geological, metallurgical, hydraulic, environmental, and economic criteria must be satisfied together. ISR is best regarded not as a universal substitute for conventional mining but as a high-potential route for deposits that fall within a rigorously defined feasibility window.

Keywords: In Situ Recovery, In Situ Leaching, Reactive Transport, Hydrogeology, Critical Metals, Sustainable Mining.

Highlights

- ISR feasibility is governed by the overlap of geological, chemical, hydraulic, environmental, and economic constraints.
- Permeability evolves during leaching through dissolution, precipitation, clay response, fines migration, and fracture modification.
- Reactive-transport modeling and digital wellfield control improve design but do not remove uncertainty caused by orebody heterogeneity.
- Scale-up should be evidence-gated, with restoration and closure performance treated as design criteria rather than end-of-life corrections.

Graphical Abstract



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Introduction

Declining ore grades, deeper resources, increasingly complex mineralogy, water constraints, and stricter limits on land disturbance are pushing mineral processing beyond conventional combinations of excavation, comminution, concentration, and surface hydrometallurgy. ISR/ISL is attractive because it mobilizes target elements within the orebody and recovers them through a controlled fluid circuit, thereby reducing material movement and comminution. Yet the apparently simple “inject, dissolve, and recover” concept conceals a coupled subsurface reactor in which geology, hydrology, chemistry, and process control are inseparable. Project economics and environmental outcomes therefore depend strongly on deposit architecture and hydraulic behavior, rather than on leach chemistry alone (Seredkin et al., 2016; Sinclair & Thompson, 2015). Recent reviews likewise indicate that ISR is most viable where orebody geometry, permeability, confinement, and reaction chemistry can be characterized with sufficient confidence (Li & Yao, 2024).

A recurrent weakness in the literature is using laboratory extraction as a proxy for field recoverability. High dissolution in crushed samples or short columns can coexist with poor sweep efficiency, excessive reagent consumption, precipitation, channeling, or incomplete hydraulic containment at scale. This distinction matters especially for deep or hard-rock concepts, where the economics of gold and copper recovery depend on creating sufficient connectivity without generating uncontrolled flow paths (Kuhar, Breuer, et al., 2018; H. Wang et al., 2022). Electrokinetic methods can extend the accessible domain by adding an electrical driving force to hydraulic transport, but they introduce additional electrochemical and geochemical constraints (Dushyantha et al., 2024; Martens et al., 2021).

This review therefore treats ISR as a systems-engineering problem rather than as an isolated leaching operation. The central question is whether a heterogeneous orebody can be contacted, reacted, swept, recovered, monitored, and restored cost-effectively over the full project life cycle. This paper compares the 2015–2026 evidence base across uranium, copper, REEs, and gold. Here, “critical” and “strategic” are used in a broad resource-security and supply-chain sense rather than as a single jurisdiction-independent legal classification. Figure 1 locates ISR feasibility within the overlap of three coupled domains rather than along a single extraction axis.

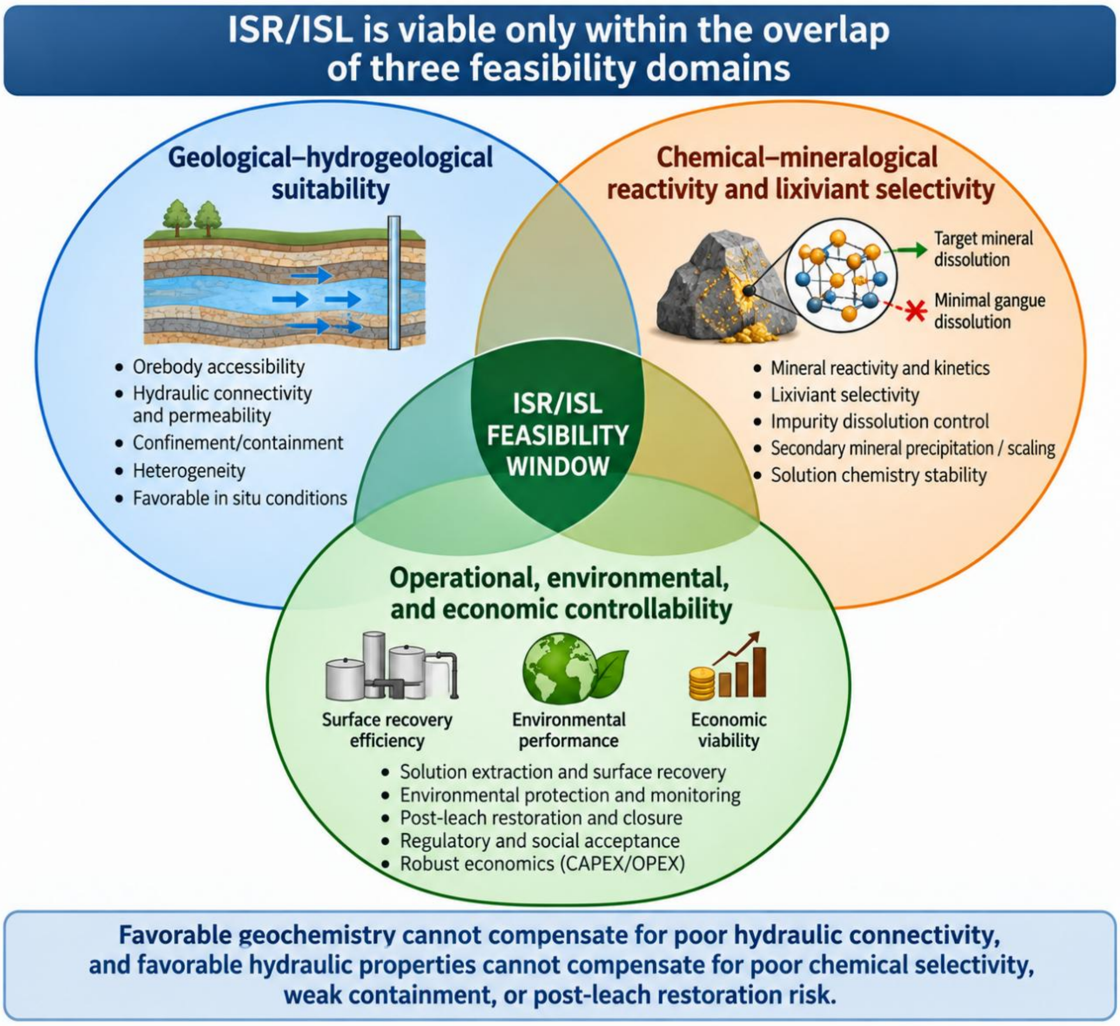

Figure 1. *Conceptual ISR Feasibility Envelope Based on Overlapping Geological–Hydrogeological, Chemical–Mineralogical, and Process–Environmental–Economic Constraints*

Note. Author's conceptual synthesis based on the feasibility logic discussed by Kuhar, Bunney, et al. (2018), Li and Yao (2024), Pereira (2026b), Seredkin et al. (2016), and Sinclair and Thompson (2015).

Figure 1 reframes ISR project selection as a problem of simultaneous feasibility. A deposit that falls outside any one of the three domains should be treated as conditionally unsuitable until the limiting mechanism has been resolved with evidence. Thus, a favorable lixiviant cannot compensate for poor hydraulic connectivity, high permeability cannot compensate for uncontrolled contaminant mobility, and low projected CAPEX cannot compensate for uncertain restoration liability. This systems view is used throughout the review to distinguish configurations supported by integrated evidence from concepts that remain mechanistically attractive but insufficiently demonstrated.

Review Scope, Evidence Base, and Critical Assessment Framework

This article is a critical narrative review based on an author-curated corpus of 80 records published from 2015 through 2026. The evidence base includes field and pilot studies, laboratory and column investigations, reactive-transport models, environmental and restoration assessments, process-integration studies, and selected review articles. Records were used when they provided direct evidence on at least one decision domain relevant to ISR amenability: geological access, hydrogeological control, reaction chemistry, solution recovery and surface processing, environmental containment and restoration, or industrial/economic maturity. The review does not claim to be a systematic or exhaustive bibliometric survey; instead, it emphasizes mechanistic triangulation and explicit interpretation of evidence at the scale at which it was generated. The cross-commodity comparison is intentional because important ISR lessons are transferable at the mechanism level even when ore minerals and lixiviants differ. For example, precipitation-induced plugging in carbonate uranium systems, clay response in ion-adsorption REE ores, and secondary-phase formation during electrokinetic copper treatment are distinct expressions of the same feedback: reaction changes transport, and altered transport changes subsequent reaction (T. Chen et al., 2024; Ortega-Tong, Jamieson, Bostick, et al., 2023; L. Zhang et al., 2024).

The critical assessment is organized around five questions: (1) Can the mineralized domain be contacted without excavation? (2) Can the target reaction proceed in situ with useful kinetics and selectivity? (3) Can the pregnant solution be recovered and processed at the surface? (4) Can the groundwater–rock system be contained, monitored, and restored? and (5) Does the integrated flowsheet remain economically viable after accounting for monitoring, reagent recycle, restoration, uncertainty, and scale-up? Table 1 translates these questions into an evidence hierarchy for ISR projects.

Table 1. Critical Evidence Hierarchy for Assessing ISR/ISL Amenability

Decision domain	Minimum evidence	Failure signal	Scale-up implication
Geology and mineralogy	Continuous ore geometry; host-mineral association; gangue reactivity; confinement	Encapsulation, discontinuous mineralization, reactive gangue, or uncertain barriers	Laboratory extraction alone does not establish field recoverability
Hydrogeology	Effective permeability; connectivity; anisotropy; hydraulic capture; tracer response	Short-circuiting, stagnant zones, leakage, or strongly variable injectivity	Well spacing and recovery estimates remain unstable
Reaction chemistry	Speciation; kinetics; reagent demand; impurity dissolution; secondary phases	Rapid reagent loss, precipitation, scaling, or low selectivity	Surface plant and wellfield become chemically coupled
Process control	Injection/production balance; monitoring; recovery circuit; recycle strategy	Unstable pressure, low PLS grade, excessive bleed, or poor control	Operational complexity can offset nominal CAPEX advantage
Environment and closure	Baseline hydrochemistry; mobilized species; restoration tests; long-term monitoring	Persistent solutes, residual lixiviant, off-pattern migration, or incomplete restoration	Closure liability must be included in project selection
Economics and maturity	Recovery variance; reagent/energy demand; monitoring/restoration cost; demonstrated scale	Economics depend on optimistic recovery or omitted closure costs	Pilot and demonstration gates are required before commercial extrapolation

Note. Author's synthesis of recurring constraints reported across uranium, copper, REE, gold, and electrokinetic ISR studies, including Kuhar, Bunney, et al. (2018), Lagneau et al. (2019), Li and Yao (2024), Martens et al. (2021), and Seredkin et al. (2016).

The framework deliberately separates evidence of dissolution from evidence of controlled recovery. A mechanistic study can be scientifically valuable without demonstrating economic viability, and a numerical model can improve design without proving that its permeability field or reaction network represents field conditions. Accordingly, claims are interpreted by both evidence type and scale: solution/mineral mechanism, intact-core or column behavior, pilot/wellfield behavior, industrial operation, and post-leach restoration. Later sections distinguish mineralogical/hydrogeological, chemical, transport/modeling, field-operational, environmental, and techno-economic evidence. For the qualitative maturity–uncertainty synthesis used later in Figure 4, maturity is interpreted from demonstrated scale, duration, hydraulic control, surface-process integration, and restoration evidence, whereas uncertainty is interpreted from heterogeneity, transport predictability, site dependence, and confidence in environmental control. These are interpretive criteria rather than numerical scores. Because the corpus is author-curated, the conclusions should be read as a mechanism-focused critical synthesis rather than as a quantitative meta-analysis of the complete ISR literature.

Geological, Mineralogical, and Hydrogeological Preconditions

Deposit Architecture and Hydraulic Accessibility

The orebody is the reactor vessel in ISR, but unlike an engineered reactor, its geometry and internal transport properties are only partially known. Sandstone-hosted uranium deposits remain the canonical application because permeable mineralized horizons may be bounded by lower-permeability strata and accessed with patterned injection and production wells. Amenability studies show that ore-zone continuity, permeability distribution, redox mineralogy, and aquifer architecture are decisive before lixiviant optimization begins (Kuhar, Bunney, et al., 2018; L. Meng et al., 2024). Aquifer vulnerability downgradient from ISR sites further demonstrates that confinement cannot be assumed from nominal stratigraphy alone; hydraulic gradients and preferential pathways must be characterized directly (Saunders et al., 2016).

Hydraulic accessibility is more difficult in fractured or low-permeability deposits. In such systems, permeability is not a single scalar property but a spatially connected network of pores, fractures, and barriers. High-energy gas fracturing has been investigated to improve access in low-permeability uranium strata, while electrokinetic transport has been proposed to supplement weak hydraulic gradients (C. Li et al., 2025; Y. Zhang et al., 2024). These approaches may expand the ISR domain, but they also create additional questions regarding flow-path stability, containment, and the representativeness of small-scale tests.

Mineralogical Controls on Leachability and Selectivity

Mineralogy controls both the desired reaction and the parasitic reactions that determine reagent efficiency. In copper systems, multistage solution–mineral contact experiments show that extraction, acid consumption, gangue alteration, and precipitation evolve together rather than independently (Hidalgo et al., 2020). Model-based analysis of copper ISR likewise identifies mineralogical composition as a primary control on reaction fronts and recovery performance (Ortega-Tong, Jamieson, Kuhar, et al., 2023). For uranium, thermodynamic and reactive-transport studies demonstrate that ore composition controls oxidation, complexation, and precipitation pathways and therefore the amount of uranium that can be mobilized under a given solution chemistry (Kurmanseiit et al., 2022; Panfilov et al., 2016; Shen et al., 2020).

Weathered-crust elution-deposited REE ores illustrate a different mineralogical regime because target REEs are commonly ion-exchangeable on clay-rich materials rather than locked within a primary mineral lattice. This enhances chemical accessibility but makes geotechnical and hydrological behavior highly sensitive to ion exchange, particle migration, and clay response. Column studies have quantified coupled REE and Al leaching kinetics, while later work has shown that pore structures evolve under seepage and chemical interaction (X. Chen et al., 2021; Z. He et al., 2016). Micro-CT characterization confirms the strong heterogeneity of undisturbed ore fabrics, emphasizing the need to preserve natural structure when extrapolating test results (Yin et al., 2021).

Permeability Is a Dynamic Process Variable

One of the most important advances since 2015 is the recognition that permeability can evolve during leaching. Hydrochemical-coupling measurements in REE ores show that permeability responds to solution chemistry, while subsequent studies document pore evolution, fines migration, and newly formed clay particles that can either open or obstruct flow paths (Deng et al., 2023; X. Wang et al., 2018; L. Zhang et al., 2024; X. Zhang et al., 2023). Mechanical weakening of basement or host rock under leach-solution exposure adds a geomechanical dimension to this feedback (Zhong et al., 2022).

Uranium systems exhibit a comparable response. Acid ISR can modify ore-zone permeability through mineral dissolution and secondary precipitation, while CO_2 + O_2 systems can alter fracture morphology and pore networks during operation (T. He et al., 2024; Niu et al., 2025). Smectite-bearing roll-front deposits add a further complication because clay transformations can affect both sorption and transport (Robin et al., 2020). These observations invalidate design approaches that treat pre-leach permeability as constant over the project life cycle.

Figure 3 later summarizes the practical implication: dissolution, solute transport, secondary precipitation, fines migration, porosity, permeability, and hydraulic sweep form a coupled feedback loop. Project characterization should therefore address not only initial permeability but also the direction and magnitude of permeability evolution under representative solution chemistry, stress, residence time, and recycle conditions.

Chemistry of In Situ Leaching Systems

Lixiviant Families and Reaction Windows

Robust ISR chemistries balance dissolution kinetics with selectivity, transport stability, and downstream recovery. Uranium ISR commonly uses acidic systems or carbonate/bicarbonate media with an oxidant, depending on mineralogy and groundwater chemistry. Thermodynamic modeling shows that uranium speciation and mineral saturation are sensitive to pH, redox potential, carbonate activity, and competing ions (Shen et al., 2020). In carbonate systems, $CaCO_3$ precipitation can reduce injectivity; recent work indicates that P(V) salts can inhibit such precipitation, illustrating how solution conditioning may protect hydraulic performance (Yang et al., 2025).

Copper ISR faces a broader gangue-acid-consumption problem. Alternative bioleaching schemes seek to generate or sustain oxidizing conditions in situ, whereas conventional acid systems must manage gangue dissolution and secondary mineral formation (Hidalgo et al., 2020; Vargas et al., 2020). Even in spent heaps, which are more accessible than undisturbed orebodies, in situ-style solution recovery remains sensitive to residual permeability and mineralogical reactivity (Lizama, 2023). For gold, alkaline glycine has been investigated because it can dissolve gold under milder conditions than cyanide in selected mineral systems. Microfluidic and paleochannel studies support the chemical plausibility of glycine-based approaches, but scale-up to intact heterogeneous rock remains a separate challenge (Azadi et al., 2019; Oraby et al., 2019).

Ion-adsorption REE systems rely primarily on ion exchange rather than aggressive mineral dissolution. Ammonium salts have historically been effective, but environmental concerns regarding ammonia-nitrogen residues have encouraged alternatives such as $MgSO_4$ and compound lixiviants (Xiao et al., 2015, 2017; Yan et al., 2018). Ion characteristics strongly influence desorption and mass transfer, and $MgSO_4$ has been proposed as a lower-ammonium option with distinct selectivity and environmental trade-offs (Pereira, 2026a; Z. Zhang et al., 2020). Table 2 compares the principal lixiviant families from a process-integration perspective.

Table 2. Lixiviant Families, Principal Advantages, and ISR-Specific Trade-Offs

System/lixiviant	Primary application	Main advantage	Critical ISR trade-off
Acidic solutions	Uranium; copper; selected hard-rock targets	Fast dissolution and broad mineral reactivity	High gangue consumption, mobilization of impurities, secondary phases, and restoration burden
Carbonate / bicarbonate + oxidant	Sandstone uranium	More selective uranium complexation under suitable conditions	Carbonate scaling, oxidant management, and site-specific mineral saturation
Ammonium salts	Ion-adsorption REE	Effective ion exchange and established practice	Residual ammonium, water-quality impacts, and reagent recovery requirements
$MgSO_4$ / compound salts	Ion-adsorption REE	Lower ammonia-nitrogen burden and tunable ion exchange	Potential sulfate loading, competing-ion effects, and variable desorption efficiency
Glycine / mild complexants	Gold; exploratory polymetallic concepts	Potential selectivity under alkaline, lower-toxicity conditions	Kinetics and field contact remain less demonstrated than chemistry
Bio-assisted systems	Copper; REE; emerging systems	In situ generation of reactive species and potentially lower chemical intensity	Microbial control, kinetics, heterogeneity, and ecological uncertainty
Electrokinetic-assisted leaching	Low-permeability U, Cu, and REE concepts	Adds electric migration/electroosmosis where hydraulic flow is weak	Energy, electrode reactions, pH fronts, secondary phases, and scale-up complexity

Note. Synthesis based on Dushyantha et al. (2024), Martens et al. (2021), Pereira (2026a), Vargas et al. (2020), Xiao et al. (2015), Yang et al. (2025), and Z. Zhang et al. (2020).

Precipitation, Plugging, and Reagent Loss

Precipitation is often treated as an operational nuisance, but in ISR it can become a first-order recovery constraint because solids form inside the flow network rather than in an accessible reactor. Field-oriented work on CO_2 + O_2 uranium ISR has documented precipitation and plugging mechanisms that directly reduce permeability (T. Chen et al., 2024). Electrokinetic copper experiments likewise show that secondary phases can form during treatment of intact sulfide ore, altering both electrical and hydraulic transport (Ortega-Tong, Jamieson, Bostick, et al., 2023). At the pore-to-core scale, coupled electrokinetic–geochemical studies further demonstrate that dissolution and precipitation fronts depend on transport regime and local solution composition (Tang et al., 2025).

The process consequence is nonlinear: a small quantity of precipitate deposited at a critical pore throat can cause a disproportionate loss of injectivity. Saturation indices, local mixing zones, oxidant consumption, ion exchange, and fines mobility should therefore be treated as design variables. A high extraction percentage measured after a destructive test can conceal precipitation or clogging behavior that would terminate a field operation.

Solution Selectivity and Surface-Recovery Compatibility

ISR chemistry must be evaluated together with the surface plant because low-grade pregnant leach solutions (PLS), high impurity loads, and large recycle volumes can erode the nominal benefit of avoiding excavation. Bubble-supported organic liquid membranes have been explored for yttrium-rich heavy-REE solutions, illustrating the need for selective downstream separations tailored to dilute ISR liquors (J. Wang et al., 2022). Reuse of REE carbonate-precipitation mother liquor and recovery of residual ammonium from tailings illustrate a complementary strategy: close the reagent loop rather than treat surface processing as a once-through step (Feng et al., 2024; Wu et al., 2024). In situ solvent extraction from lignite has also been proposed as an unconventional means of combining leaching and separation, although the evidence remains at an emerging stage (Feole & Folkedahl, 2025).

Process Engineering: Wellfields, Hydraulic Control, and Surface Integration

Wellfield Architecture and Contact Efficiency

Wellfield design converts subsurface heterogeneity into a partially controllable process. Pattern geometry, well spacing, injection and production rates, pressure limits, and flow reversal determine the fraction of the orebody contacted and the residence-time distribution of the lixiviant. Hydrodynamic simulations show that injection-rate regulation changes the extent of the leaching zone, while stagnation-point methods provide a quantitative basis for delineating the hydraulically influenced area (C. Zhang et al., 2022, 2025). Well-location optimization using fast-marching methods and related algorithms seeks to improve coverage without excessive drilling density (Jia et al., 2024).

Hydraulic control is not equivalent to maximizing injection. Production must maintain inward hydraulic capture and prevent solution migration beyond the intended pattern. Field-oriented studies show that injection/production management can materially alter uranium wellfield performance (Y. Li et al., 2024). Periodic injection and extraction have been shown, through reactive-transport modeling and field testing, to improve efficiency under selected conditions by altering concentration gradients and contact patterns (M. Chen et al., 2024). Well reversal can also modify sweep and cost, although the benefit depends on reversal timing and spatial heterogeneity (Shayakhmetov et al., 2023).

Novel solution-injection approaches for ion-adsorption REE ores similarly seek to improve distribution while limiting preferential flow (Z. Zhang et al., 2016). These studies reinforce a general principle: ISR performance is governed by the distribution of residence time, not merely the average flow rate. A successful pattern must contact slow domains without creating excessive reagent loss in fast channels.

Surface Processing, Recycle, and Water Balance

The surface circuit receives a fluid whose composition changes as reaction fronts advance. This variability affects ion exchange, solvent extraction, membrane processes, precipitation, reagent make-up, and bleed requirements; consequently, the surface plant requires operating flexibility rather than a single design-point composition. Closed-loop behavior is particularly important in REE systems, where ammonium or sulfate can accumulate over repeated cycles and become environmental or selectivity constraints (Feng et al., 2024; Huang et al., 2021; Wu et al., 2024).

Figure 2 presents the ISR flowsheet as a coupled subsurface–surface loop. The wellfield and surface plant exchange not only target metals but also acidity/alkalinity, oxidants, major ions, suspended fines, and evolving redox history. Monitoring therefore spans the entire loop because hydraulic and chemical measurements are needed to determine whether declining production reflects depletion, poor sweep, plugging, or off-pattern loss.

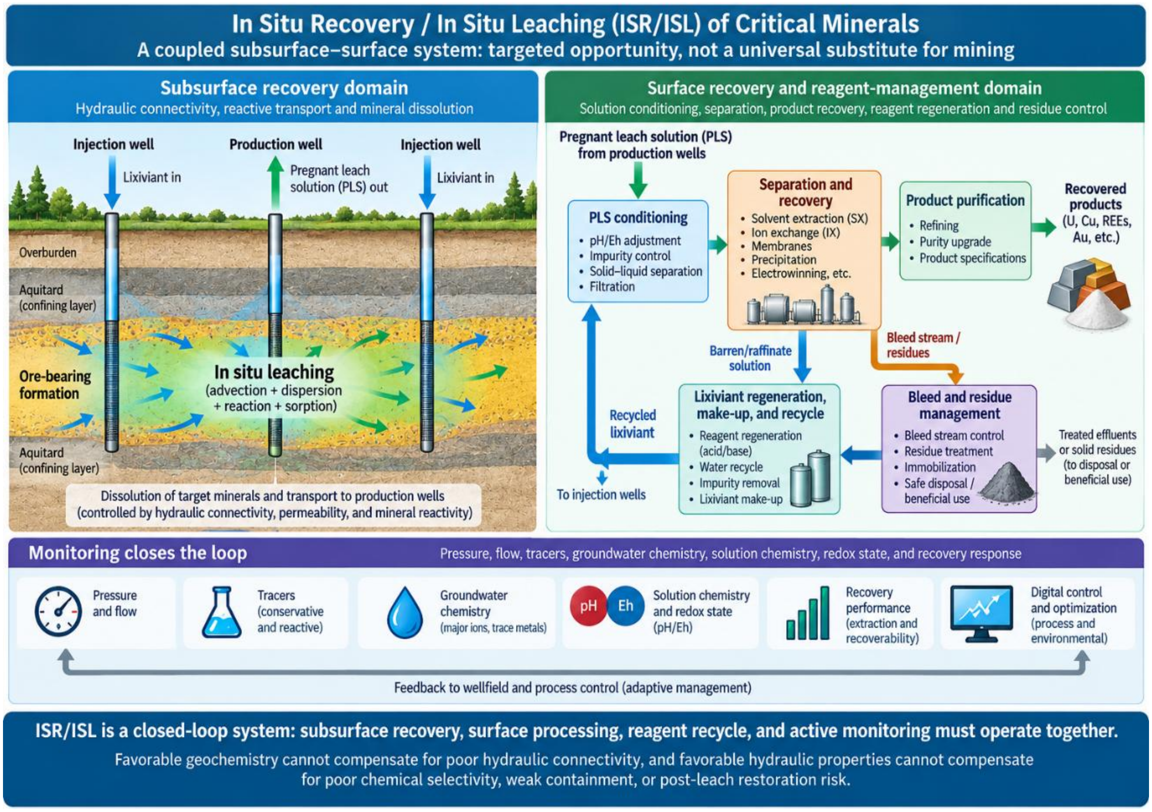

Figure 2. *Integrated ISR Process Architecture Linking the Subsurface Recovery Domain to Surface Separation, Lixiviant Regeneration, Recycle, and Monitoring*

Note. Author's conceptual synthesis based on wellfield and process-control concepts reported by M. Chen et al. (2024), Lagneau et al. (2019), Li and Yao (2024), Y. Li et al. (2024), and C. Zhang et al. (2022).

The integrated architecture in Figure 2 is essential for techno-economic analysis. Large solution inventories, bleed streams, reagent regeneration, and water treatment can become dominant costs even when the ore is never excavated. Conversely, effective recycle and selective surface recovery can improve both environmental performance and operating economics. The appropriate design objective is therefore to minimize total process burden per unit of recovered product rather than to minimize subsurface reagent concentration or maximize instantaneous extraction in isolation.

Reactive-Transport Modeling, Monitoring, and Digital Optimization

From Flow Models to Reactive Digital Twins

At advanced project stages, reactive-transport modeling becomes essential because reaction fronts and flow paths evolve simultaneously. Uranium ISR studies have progressively incorporated multispecies reactions, ore-composition effects, three-dimensional flow, stochastic variability, and full wellfield geometry (Aizhulov et al., 2022; Collet et al., 2022; Kurmanseiit et al., 2022; Lagneau et al., 2019; Panfilov et al., 2016). Large-scale applications show that such models can support production forecasting and resource estimation, but their predictive value depends on calibration data and on whether the reaction network captures the controlling mineralogy.

Recent work increasingly emphasizes surrogate modeling and data-assisted optimization. Machine-learning approaches have been applied to acid-ISR process optimization, while generative surrogate frameworks aim to reduce the computational burden of reactive-transport simulation (Ji et al., 2024; B. Wang et al., 2023). Deep-learning multiobjective optimization extends this approach to design under uncertainty, and hybrid CNN–LSTM–LightGBM models have been used to predict injection volume and leaching rate (Qiu et al., 2025; Z. Liu et al., 2025). Digital-intelligent mining concepts further propose continuous integration of sensor data, process models, and operational decisions (Liu & Zhang, 2025).

Monitoring Variables and Model Validation

A digital model is only as useful as the field information used to constrain and validate it. Pressure, flow, recovery, groundwater composition, tracer breakthrough, isotopic indicators, and mineralogical change provide complementary views of the evolving system. Isotopic ratios in uranium leach liquors have been proposed as indicators of residual uranium, illustrating how geochemical monitoring can complement hydraulic measurements (Semenishchev & Titova, 2025). Reactive-transport characterization of uranium-bearing sandstone likewise provides a basis for linking core-scale reaction behavior to field response (Su et al., 2025).

Table 3 summarizes monitoring and modeling tools according to the decisions they can support. The critical distinction is between observability and controllability: a model may explain a process retrospectively without identifying a variable that operators can manipulate. The highest-value digital tools are therefore those linked to practical decisions such as flow redistribution, reagent concentration, well reversal, bleed rate, or remediation sequencing.

Table 3. Monitoring and Modeling Tools for ISR Decision Support

Tool/data stream	Primary information	Operational use	Key limitation
Pressure and flow monitoring	Injectivity, productivity, hydraulic imbalance	Detect plugging, loss of capture, and well deterioration	May not distinguish geochemical from mechanical causes
Tracer tests	Connectivity and residence-time distribution	Refine well spacing and identify short circuits/stagnant zones	Tracer behavior may not reproduce reactive solute behavior
Groundwater geochemistry	pH, Eh, major ions, mobilized contaminants, lixiviant residuals	Control chemistry and detect migration	Sparse sampling can miss preferential pathways
Reactive-transport simulation	Coupled flow and geochemical reactions	Forecast fronts, recovery, and remediation	Sensitive to mineralogy, permeability fields, and kinetic parameters
Surrogate/machine-learning models	Fast approximation of nonlinear process response	Optimization and near-real-time control	Can extrapolate poorly beyond training domain
Isotopic and mineralogical indicators	Residual target element and reaction pathways	Diagnose incomplete recovery and post-leach state	Site-specific calibration is required
Digital twin/integrated control	Synchronized field data and predictive model	Adaptive injection, production, and reagent management	Requires robust sensors, governance, uncertainty treatment, and fail-safe logic

Note. Conceptual synthesis based on Aizhulov et al. (2022), Collet et al. (2022), Ji et al. (2024), Qiu et al. (2025), Semenishchev and Titova (2025), B. Wang et al. (2023), and Z. Liu et al. (2025).

Coupled Feedbacks and Model Uncertainty

Model uncertainty is strongly influenced by the fact that reactions modify the pore network that controls subsequent reactions. Figure 3 formalizes this feedback. Lixiviant delivery drives dissolution; dissolution changes solute composition; solutes may precipitate or mobilize fines; these changes alter porosity and permeability; and the modified permeability field changes residence time and chemical access. This loop has been observed across uranium, REE, and electrokinetic systems rather than being confined to one commodity (T. He et al., 2024; Tang et al., 2025; L. Zhang et al., 2024).

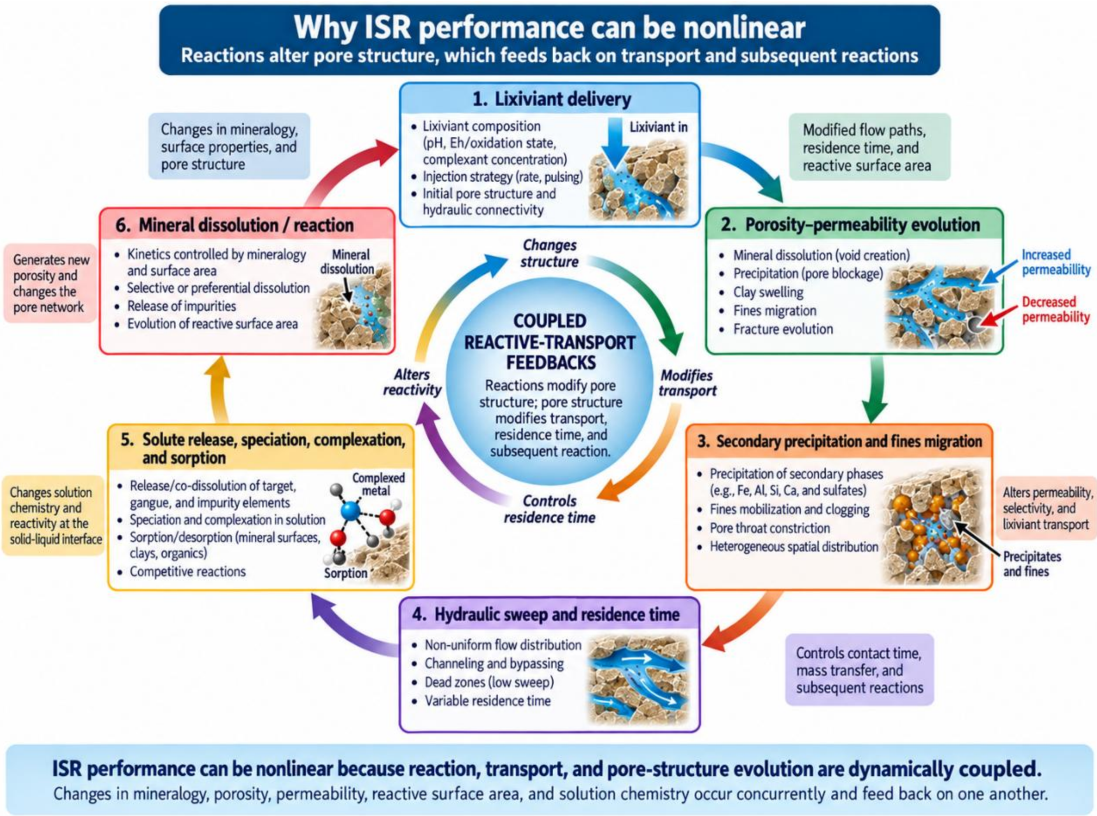

Figure 3. *Coupled Reactive-Transport Feedbacks That Cause Nonlinear ISR Performance*

Note. Author's conceptual synthesis based on T. Chen et al. (2024), T. He et al. (2024), Niu et al. (2025), Tang et al. (2025), and L. Zhang et al. (2024).

Figure 3 implies that calibration against early-time production data may be misleading if permeability evolves differently at later times. A model that reproduces solute breakthrough but not mineral alteration may therefore overstate predictive confidence. For critical decisions, uncertainty should be propagated from geological architecture, permeability, kinetic parameters, and secondary-phase behavior through recovery, reagent demand, and off-pattern migration rather than being reduced to a single model-fit statistic.

Environmental Risks, Restoration, and Closure

Groundwater Contamination and Persistent Geochemical Change

The environmental advantage of ISR is often framed in terms of reduced surface disturbance, but groundwater is the dominant environmental receptor. Uranium ISR studies have shown that redox-sensitive uranium species may persist after operations and that both uranium and radium mobility can continue to evolve after acidic leaching (de Boissezon et al., 2020; Gallegos et al., 2015). Variability in sorption parameters adds uncertainty to predictions of contaminant retardation and restoration performance (Dangelmayr et al., 2018). Reviews of North China sandstone-hosted uranium systems similarly emphasize the need to integrate geological and hydrochemical models rather than relying on generic plume assumptions (Zheng et al., 2023).

Field and modeling studies also show that leaching can modify microbial and mineralogical systems. Microbial communities associated with uranium ISR may resemble acid-mine-drainage assemblages under acidic conditions, while biostimulation has been investigated to neutralize acidity and immobilize uranium after mining (Coral et al., 2018, 2022). These findings matter because restoration is not merely dilution; it is the controlled transition toward a stable geochemical state after the orebody has been intentionally perturbed.

Residual Reagents and REE-Specific Environmental Concerns

Ion-adsorption REE mining presents a different environmental profile. Residual ammonium sulfate can remain vertically distributed within weathered-crust ore after leaching, creating a long-term water-quality concern if it is not recovered or immobilized (Huang et al., 2021). REE patterns and Ce/Eu anomalies in aqueous systems have been used to evaluate migration pathways and changes caused by in situ leaching (X.-R. Liu et al., 2022). Ammonium recovery through combined elution, struvite precipitation, and adsorption illustrates the type of closed-loop remediation that should be designed alongside extraction rather than after production (Wu et al., 2024).

At industrial scale, ecological-impact assessment becomes a core performance metric rather than a supporting exercise. Recent industrial-scale bioleaching work on ion-adsorption REE ores explicitly evaluates ecological effects, while large-scale electrokinetic REE mining demonstrates that process intensification must be assessed against environmental disturbance and reagent transport as well as recovery (X. Meng et al., 2026; G. Wang et al., 2025). These studies broaden the definition of process performance from metal recovery alone to ecosystem-compatible resource recovery.

Restoration as a Design Criterion

Groundwater restoration has historically been one of the hardest ISR stages to predict. Field evidence from uranium operations indicates that restoration effectiveness depends on the geochemical state created during mining and on the ability to reverse or stabilize mobilized species (Ruiz et al., 2019). Field deployment of dithionite and acetate has provided practical insight into reductive restoration strategies, while reactive-transport modeling is increasingly used to compare remediation options before implementation (Reimus et al., 2022; Seigneur et al., 2024).

Recent groundwater studies at active or representative uranium sites document changes in groundwater and mineral composition and model contaminant transport under acid-leach scenarios (Li, Muhammad, & Tang, 2024; Li, Tang, & Xiang, 2024). Restoration should therefore be incorporated into the initial geochemical model, pilot design, and cost estimate. If a project cannot define a credible pathway from leaching conditions to an acceptable post-mining state, the absence of an open pit does not make the project environmentally low risk.

Table 4 summarizes recurrent environmental failure modes and the monitoring signals that should trigger intervention. The table is intentionally operational: environmental control is strongest when thresholds link to specific actions rather than being reported only for compliance.

Table 4. Environmental Failure Modes, Indicators, and Mitigation Priorities for ISR

Failure mode	Early indicator	Primary consequence	Priority mitigation
Off-pattern lixiviant migration	Tracer or conductivity excursion; pressure imbalance	Groundwater contamination beyond capture zone	Reduce injection, increase recovery, re-balance pattern, verify barriers
Persistent target/impurity mobility	Slow decline or rebound after flushing	Extended restoration and monitoring	Geochemical immobilization, targeted flushing, or reactive treatment
Residual ammonium/sulfate	Elevated major ions after production	Water-quality impact and nutrient loading	Reagent recovery, selective purge, treatment, and source-zone flushing
Plugging and pressure escalation	Falling injectivity at constant pressure or rising pressure at constant rate	Fracture growth, bypass, and loss of sweep	Control saturation, solids, pH/Eh, and flow; rehabilitate wells
Unrecognized preferential pathway	Early tracer breakthrough and asymmetric chemistry	Loss of reagent and containment	Reconfigure pattern, isolate interval, adjust hydraulic capture
Incomplete restoration	Plateau above baseline/criterion	Long-term liability and delayed closure	Design restoration during pilot stage; use reactive-transport scenario testing

Note. Adapted conceptually from de Boissezon et al. (2020), Huang et al. (2021), Pereira (2026b), Reimus et al. (2022), Ruiz et al. (2019), Saunders et al. (2016), and Seigneur et al. (2024).

Techno-Economic Performance and Industrial Maturity

The CAPEX Advantage and Its Hidden Counterweights

ISR can reduce mining, hauling, crushing, and surface waste handling and can therefore offer an economic advantage. However, the relevant comparison is not “no mining” versus “mining”; it is the full life-cycle cost of a controlled subsurface recovery system versus a conventional flowsheet. Project evaluation must include drilling density, well replacement, pumping, water treatment, reagent use, surface separation, monitoring, restoration, and uncertainty allowances. Economic literature consistently indicates that ISR attractiveness is deposit-specific (Seredkin et al., 2016). Similar logic applies to gold ISR, for which benefits depend on avoiding deep underground development without incurring excessive permeability-creation and solution-management costs (Kuhar, Breuer, et al., 2018).

For copper, the challenge is balancing low-grade resource access with acid use, kinetics, and hydraulic reach. Studies show that good economics depend on recoverable geometry and manageable gangue reactions (Sinclair & Thompson, 2015; H. Wang et al., 2022). For uranium, flow reversal, wellfield design, and hydraulic control influence production and cost, linking economics to control strategy (Y. Li et al., 2024; Shayakhmetov et al., 2023).

Maturity Is Commodity- and Deposit-Specific

Industrial maturity should be assigned to a defined deposit–lixiviant–wellfield configuration rather than to ISR as a generic technology. Sandstone uranium occupies the most established maturity domain because commercial practice, large-scale reactive-transport modeling, restoration experience, and operational optimization are all documented (Collet et al., 2022; Lagneau et al., 2019; Li & Yao, 2024). Ion-adsorption REE systems also have industrial-scale evidence, including electrokinetic and bio-assisted variants, but environmental performance and regional ore characteristics remain critical (X. Meng et al., 2026; G. Wang et al., 2025).

Copper ISR has advanced beyond purely conceptual studies through Kapunda modeling and extensive mineralogical and process investigations, but broad commercial transferability remains less established than for uranium (Ortega-Tong, Jamieson, Kuhar, et al., 2023; H. Wang et al., 2022). Gold ISR retains a strong economic rationale for deep resources and a plausible chemical basis, yet field-scale evidence remains comparatively limited (Kuhar, Breuer, et al., 2018; Oraby et al., 2019). Low-permeability electrokinetic uranium and copper concepts are also advancing, but they remain emerging because energy demand, electrode-scale effects, and long-distance field behavior require further demonstration (C. Li et al., 2025; Martens et al., 2021).

Figure 4 presents a qualitative maturity–uncertainty map. It is not a quantitative technology ranking. Maturity is interpreted from demonstrated scale, duration, hydraulic control, integration with surface recovery, and restoration evidence; uncertainty reflects geological heterogeneity, transport predictability, site dependence, and confidence in environmental control. A technology can therefore be relatively mature while retaining substantial site-specific uncertainty, whereas a less mature technology may be attractive where it directly addresses the dominant geological constraint.

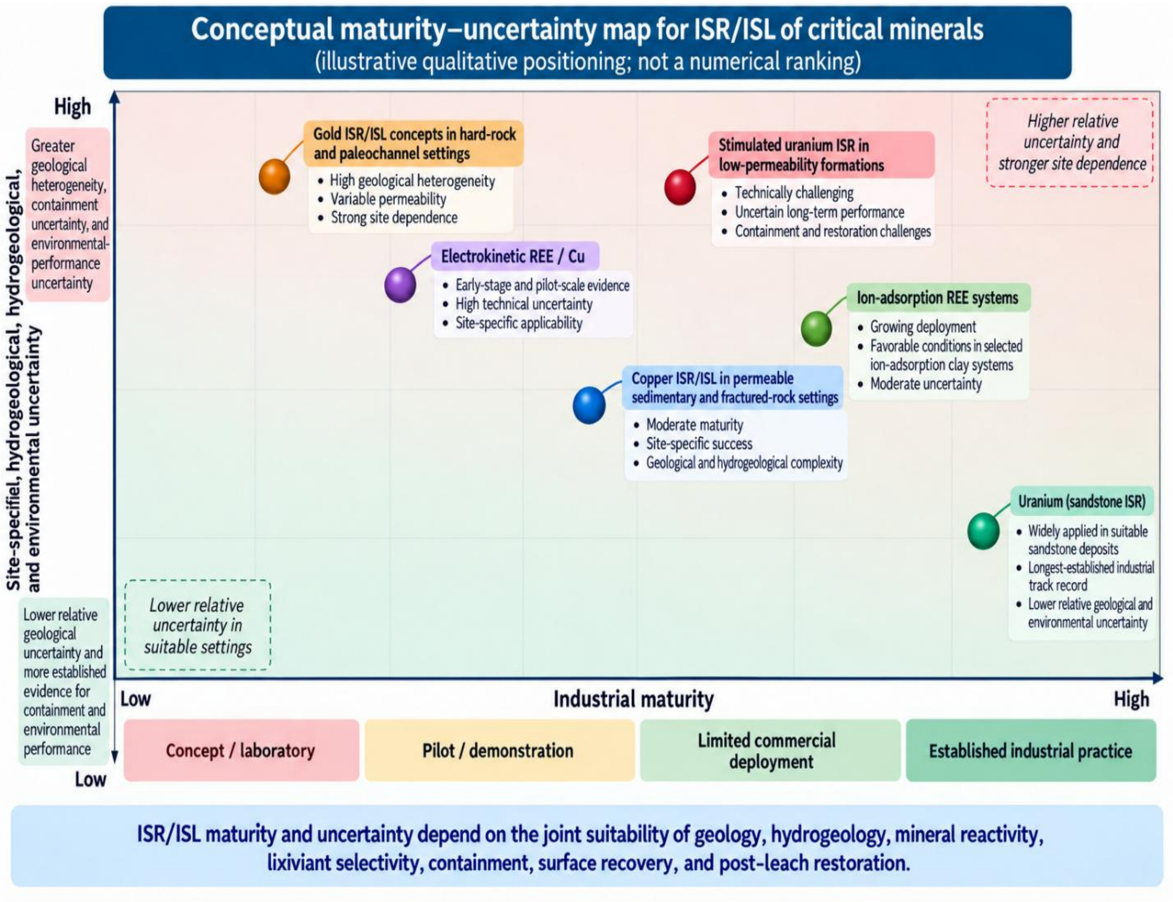

Figure 4. *Conceptual Maturity–Uncertainty Map for Selected ISR/ISL Application Domains*

Note. Author's qualitative synthesis based on Kuhar, Breuer, et al. (2018), Li and Yao (2024), C. Li et al. (2025), X. Meng et al. (2026), Seredkin et al. (2016), H. Wang et al. (2022), and G. Wang et al. (2025). Axis positions are schematic ordinal placements based on the evidence criteria described in the text; they are not measured scores.

Cross-Commodity Case Evidence: Successes, Constraints, and Transferable Lessons

Sandstone-Hosted Uranium: The Benchmark ISR System

Sandstone-hosted uranium provides the benchmark because it combines favorable deposit types, decades of operational experience, wellfield-scale modeling, and a substantial restoration literature. Industrial deployment of reactive-transport simulation and three-dimensional modeling demonstrates how site characterization can be translated into production forecasts (Collet et al., 2022; Lagneau et al., 2019). Stochastic streamline and resource-estimation approaches further show how uncertainty can be incorporated into production planning (Aizhulov et al., 2022). Recent studies of wellfield hydraulics, periodic injection, and stagnation-point delineation indicate a shift from static design toward adaptive flow management (M. Chen et al., 2024; Y. Li et al., 2024; C. Zhang et al., 2025).

The same uranium evidence also reveals why maturity should not be confused with simplicity. Plugging, evolving permeability, contaminant transport, and restoration remain active research topics (T. Chen et al., 2024; T. He et al., 2024; Seigneur et al., 2024). Uranium therefore illustrates the mature-state lesson for other commodities: successful ISR requires sophisticated control of a complex process rather than elimination of complexity.

Copper: Strong Mechanistic Basis, More Difficult Hydraulic Domain

Copper ISR is attractive because large, low-grade resources may be inaccessible to conventional economics, but sulfide and gangue mineralogy can impose slow kinetics, high oxidant demand, and precipitation. Process-scheme studies show how bioleaching may generate favorable redox conditions in situ, while multistage reaction studies quantify the competing effects of extraction, acid consumption, and gangue alteration (Hidalgo et al., 2020; Vargas et al., 2020). Kapunda modeling provides an important bridge toward field-scale design, and mineralogical model-based analysis has clarified how ore composition controls recovery pathways (Ortega-Tong, Jamieson, Kuhar, et al., 2023; H. Wang et al., 2022).

Electrokinetic work extends this domain by enabling transport through lower-permeability intact ore. However, secondary-phase formation and coupled electrochemical fronts can reduce efficiency or redirect transport, so permeability enhancement must be evaluated together with geochemical stability (Martens et al., 2021; Ortega-Tong, Jamieson, Bostick, et al., 2023; Tang et al., 2025). The transferable lesson is that solving a transport limitation with an additional driving force does not remove the need to control reaction products.

Ion-Adsorption REE: High Chemical Accessibility, High Environmental Sensitivity

Ion-adsorption REE deposits are chemically favorable for ISR because target elements can be exchanged from clay surfaces, but this clay-rich architecture creates sensitivity to seepage, swelling, particle migration, and residual salts. Studies of pore structure, seepage evolution, and newly formed clay particles demonstrate that hydraulic behavior evolves throughout the leach cycle (X. Chen et al., 2021; Yin et al., 2021; L. Zhang et al., 2024). Reactive-transport modeling with ammonium sulfate provides a means of linking ion exchange to field-scale transport (Guo & Zhuang, 2023).

Environmental performance is inseparable from lixiviant choice. $MgSO_4$ and compound leaching systems have been developed partly to reduce ammonia-nitrogen impacts, whereas residual-ammonium recovery and mother-liquor reuse target closed-loop operation (Feng et al., 2024; Wu et al., 2024; Xiao et al., 2015; Yan et al., 2018). Industrial-scale electrokinetic and bioleaching studies show that the technology space is moving from solution-injection optimization toward integrated control of recovery, reagent movement, and ecological effects (X. Meng et al., 2026; G. Wang et al., 2025).

Gold and Other Emerging Targets: Chemistry Ahead of Field Evidence

Gold illustrates a recurring ISR development pattern in which compelling project logic and promising chemistry precede field-scale proof. Deep hard-rock gold may benefit economically if mineralized zones can be contacted without underground development, but permeability creation and hydraulic containment become central uncertainties (Kuhar, Breuer, et al., 2018). Glycine-leaching studies show that a selective, relatively mild lixiviant can mobilize gold under controlled conditions, including paleochannel materials relevant to heap and in situ concepts (Azadi et al., 2019; Oraby et al., 2019). The remaining question is not whether glycine can leach gold, but whether a heterogeneous orebody can be contacted, swept, monitored, and restored at competitive recovery rates and acceptable reagent consumption.

Other emerging targets, including lignite-associated REEs, similarly require evidence beyond solution chemistry. In situ solvent-extraction concepts are innovative because they may combine extraction and separation, but they introduce additional questions regarding phase contact, losses, selectivity, and subsurface compatibility (Feole & Folkedahl, 2025). Such concepts should be evaluated with the same evidence hierarchy as conventional ISR rather than granted a lower burden of proof because they are chemically novel.

Emerging Hybrid ISR Routes and Process Intensification

Electrokinetic ISR

Electrokinetic ISR is an important emerging direction because it directly addresses the permeability limitation that excludes many hard-rock and low-permeability resources. Electric fields can drive ionic migration and electroosmotic flow, potentially enabling lixiviant transport where pressure-driven flow is inadequate. Laboratory and conceptual studies have established a mechanistic basis across critical-metal systems (Dushyantha et al., 2024; Martens et al., 2021). Demonstration in low-permeability uranium ore and industrial-scale REE applications indicates that the concept is progressing beyond proof of principle (C. Li et al., 2025; G. Wang et al., 2025).

Electrokinetic intensification shifts the bottleneck rather than eliminating it. Electrode reactions create pH and redox fronts; electric fields interact with ionic strength and mineral surfaces; and secondary phases can form where chemical fronts converge (Ortega-Tong, Jamieson, Bostick, et al., 2023; Tang et al., 2025). Energy efficiency and electrode spacing must therefore be treated as components of the reaction–transport system. The technology is most promising where hydraulic permeability is the dominant limiting factor and where electrochemical side reactions can be actively managed.

Bio-Assisted and Stimulation-Enabled ISR

Bio-assisted ISR offers another route to process intensification by generating oxidants, reductants, acids, or other reactive species through microbial metabolism. Copper bioleaching schemes and REE bioleaching studies illustrate the breadth of this approach (X. Meng et al., 2026; Vargas et al., 2020). Its principal attraction is the possibility of lower external chemical intensity and partially self-sustaining reaction chemistry, but biological kinetics, nutrient transport, temperature, and ecological impacts introduce additional state variables into an already heterogeneous reactor.

Physical stimulation can improve access where permeability is insufficient. Gas fracturing in low-permeability uranium deposits is an example, but any stimulation strategy must be assessed against containment because the same fracture network that improves contact can create off-pattern migration (Y. Zhang et al., 2024). Stimulation should therefore be optimized for controlled connectivity rather than maximum fracture generation.

Evidence-Gated Scale-Up

Emerging ISR routes are particularly vulnerable to scale-up overconfidence because proof of mechanism can be obtained in small systems long before field heterogeneity, recycle chemistry, restoration, and economics are adequately constrained. Figure 5 proposes an evidence-gated sequence in which each development stage must reduce defined uncertainties to acceptable levels before progression to the next scale is justified.

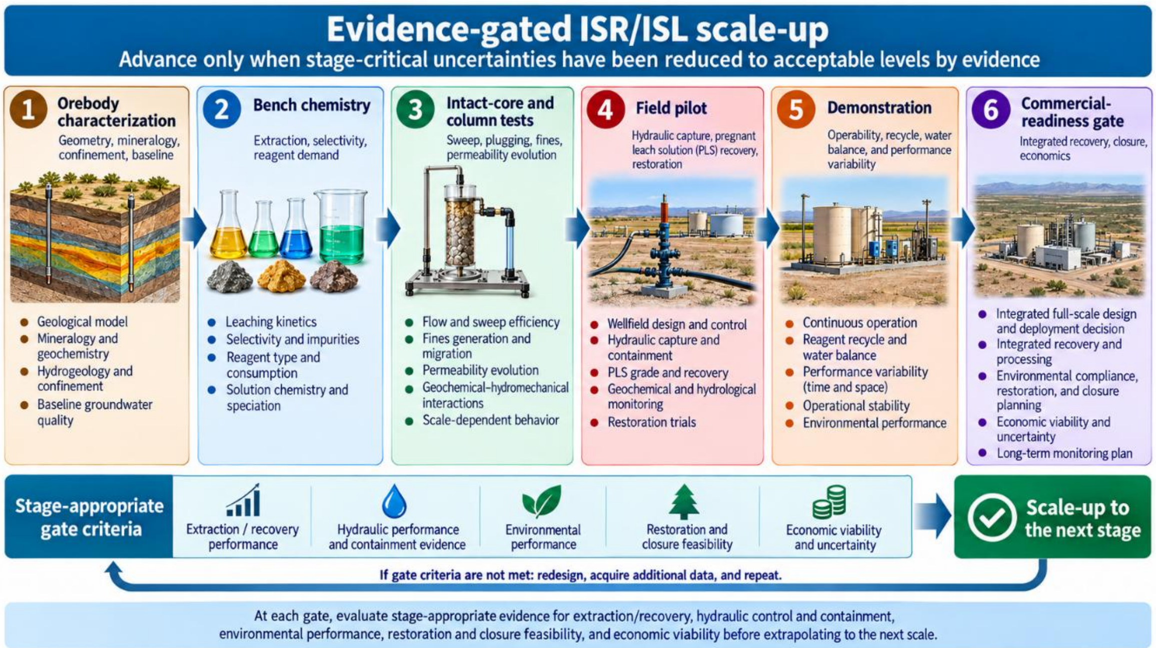

Figure 5. *Evidence-Gated Scale-Up Roadmap for ISR From Orebody Characterization to Demonstration-Scale Operation*

Note. Framework developed in this review and informed by staged amenability, modeling, field-control, and restoration approaches described by M. Chen et al. (2024), Kuhar, Bunney, et al. (2018), Lagneau et al. (2019), Seigneur et al. (2024), and H. Wang et al. (2022).

The sequence in Figure 5 is intentionally more rigorous than a progression from favorable bottle tests directly to economic projection. Bench tests should quantify not only extraction but also impurity release and reagent demand; intact-core and column tests should preserve natural structure and reveal plugging, fines migration, and transport nonuniformity; field pilots should demonstrate hydraulic capture and restoration; and demonstration-scale work should quantify recovery variance, operability, and complete water and reagent balances. Commercial economics can then be grounded in observed process behavior rather than assumed scale invariance.

Research Gaps and Future Priorities

Standardized Performance Metrics

The first research priority is to standardize performance metrics. “Recovery” may refer to metal dissolved from a sample, metal collected in production wells, or metal recovered as a saleable product; these quantities are not equivalent. Future studies should report, at minimum, the fraction of the orebody hydraulically contacted, target extraction from contacted material, surface recovery of the dissolved target, overall product recovery, reagent consumption per unit of product, impurity loading, water inventory, and restoration performance. This distinction would reduce the risk of comparing column extraction directly with field production.

Dynamic Permeability and Heterogeneity

The second priority is to represent permeability as an evolving field rather than as a pre-mining constant. Evidence across REE and uranium systems shows that dissolution, swelling, fines migration, precipitation, and fracture evolution can materially change permeability during operation (T. He et al., 2024; Niu et al., 2025; X. Wang et al., 2018; L. Zhang et al., 2024). Research should couple mineralogical alteration to porosity and permeability through calibrated constitutive relationships and should quantify the conditions under which those relationships remain transferable across scales.

Model Validation Under Field Uncertainty

The third priority is model validation using measurements that are independent of the calibration target. Reactive-transport models can fit concentration histories while still representing the permeability architecture incorrectly. Stronger validation should combine tracer data, pressure response, mineralogical change, isotopic indicators, and post-leach core or borehole information. Surrogate and machine-learning models should report their domain of validity and propagate uncertainty rather than report only predictive accuracy on held-out data (Ji et al., 2024; Qiu et al., 2025; Z. Liu et al., 2025).

Restoration, Closure, and Long-Term Liability

The fourth priority is to elevate restoration from an environmental appendix to a primary design parameter. Field restoration studies and reactive-transport remediation models provide a technical basis, but the literature still contains far fewer quantified closure trajectories than extraction studies (Reimus et al., 2022; Ruiz et al., 2019; Seigneur et al., 2024). Future pilots should include a planned restoration phase with predefined success criteria, rebound monitoring, and a mass balance of residual reagents and mobilized species.

Techno-Economic and Life-Cycle Boundaries

The fifth priority is consistency in economic and environmental system boundaries. ISR should not receive credit for avoided comminution while additional wells, pumping, water treatment, reagent recycle, monitoring, and closure are omitted. Conversely, comparisons with conventional mining should include waste-rock, tailings, and comminution burdens. A useful future standard would report cost and environmental intensity per unit of final product under at least base-case, adverse-hydrology, and adverse-geochemistry scenarios.

Actionable Research Matrix

Table 5 consolidates the principal gaps into testable research questions. The purpose is to move the discussion from broad calls for “more research” toward evidence that directly changes project decisions.

Table 5. Actionable Research Gaps and Evidence Required to Advance ISR Maturity

Gap	Research question	Required evidence	Decision enabled
Effective permeability	How does permeability evolve under representative chemistry and stress?	Time-resolved intact-core/column tests linked to mineralogy and imaging	Whether injectivity and sweep remain viable over project life
Heterogeneity	What fraction of the orebody is actually contacted?	Tracer tests, stochastic models, distributed pressure/chemistry, and field calibration	Well spacing, recovery uncertainty, and reserve conversion
Chemical selectivity	Can target extraction be maintained without excessive gangue dissolution or precipitation?	Speciation, saturation, impurity extraction, and recycle-loop testing	Lixiviant window and surface-plant design
Digital prediction	Does the model predict independent field variables?	Out-of-sample tracer, pressure, mineralogical, and recovery validation	Confidence limits for adaptive control
Restoration	Can the post-leach state reach stable closure criteria?	Pilot restoration, rebound monitoring, and residual-mass balance	Closure liability and permitting readiness
Economics	Does the project remain attractive under adverse but credible scenarios?	Integrated CAPEX/OPEX, recovery variance, water/reagent balance, and closure cost	Commercial go/no-go decision
Emerging intensification	Does electrokinetic, bio-assisted, or physical stimulation solve the dominant constraint without creating a larger one?	Energy/reagent balance, secondary-phase behavior, containment, and field-pilot evidence	Selection of hybrid ISR route

Note. Author's synthesis informed by cross-cutting evidence from Dushyantha et al. (2024), Escario et al. (2023), Lagneau et al. (2019), Martens et al. (2021), Seigneur et al. (2024), and Seredkin et al. (2016).

Environmental-footprint modeling provides a useful bridge among Sections 6, 7, and 11 because it translates process design into predicted off-pattern and post-operational impacts. Reactive-transport models developed explicitly to estimate the environmental footprint of uranium ISR show how the same numerical framework can support both production and closure decisions (Escario et al., 2023). This integration should become standard practice: the model used to maximize recovery should also be tested for its ability to predict contaminant migration and remediation response.

Conclusions

ISR/ISL should be understood as controlled subsurface processing rather than as mining without excavation. Its principal advantage is the possibility of recovering value while avoiding much of the rock movement, comminution, and surface-residue generation associated with conventional mining. Its defining limitation is that the reactor cannot be directly mixed, visually inspected, or easily repaired. Geological uncertainty, hydraulic connectivity, reaction selectivity, permeability evolution, containment, and restoration therefore become first-order process variables.

The evidence reviewed for 2015–2026 supports a differentiated view of technological maturity. Sandstone-hosted uranium provides the clearest benchmark for industrial ISR, whereas ion-adsorption REE systems show that high chemical accessibility can coexist with substantial environmental and hydraulic sensitivity. Copper, gold, electrokinetic, bio-assisted, and stimulation-enabled systems broaden the opportunity space but require stronger deposit-specific evidence before broad commercial transferability can be assumed. Across all commodities, laboratory extraction should not be used as a surrogate for wellfield recovery, and pre-leach permeability should not be treated as constant.

The most defensible development strategy is evidence-gated scale-up. Orebody characterization should precede chemistry optimization; intact-structure tests should precede field-recovery claims; field pilots should demonstrate hydraulic containment and restoration; and demonstration-scale operation should quantify recovery variability, recycle chemistry, water balance, operability, environmental performance, and cost. Under this framework, ISR is neither a universal replacement for conventional mining nor a niche curiosity. It is a high-potential technology for deposits that occupy a rigorously defined feasibility window and for projects that treat subsurface uncertainty and closure performance as design requirements from the outset.

Declarations

Funding

This review received no specific external funding.

Conflict of Interest

The author declares no conflict of interest.

Data Availability

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

Author Contributions

Conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation: Antonio Clareti Pereira.

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