

From Columns to Industrial Heaps: Critical Design Considerations for Heap Leach Pilot Plants

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Abstract: Heap leaching has become a strategic approach for processing low-grade and mineralogically complex nickel ores; however, the transition from laboratory testing to full-scale industrial heaps remains one of the least structured and most risk-prone stages in hydrometallurgical project development. This review critically evaluates the role of pilot heap leach plants in reducing scale-up uncertainty, emphasizing that bottle-roll and column tests, while useful for estimating kinetics and acid consumption under controlled conditions, do not reproduce the hydraulic heterogeneity, permeability evolution, mechanical compaction, solution retention, and long-term hydro-geochemical feedback mechanisms that govern industrial heap performance. Key engineering variables influencing pilot behavior are examined, including heap geometry, stacking strategy, agglomeration practices, irrigation system design, acid management, solution recycling, hydro-mechanical monitoring, and integration with downstream processing. Recurrent failure mechanisms—undersized pilots, short operational campaigns, insufficient instrumentation, simplified irrigation layouts, and incomplete water–acid balance closure—are identified as major contributors to scale-up errors. Persistent gaps in long-term pilot data reporting and in the validation of reactive transport models against field measurements are also discussed. A structured best-practice framework is proposed that integrates geometallurgical characterization, reactive transport modeling, extended-duration pilot operation, and comprehensive monitoring, advancing the central thesis that pilot heaps must be designed as dynamic hydro-geochemical reactors rather than as enlarged laboratory columns to reduce technical, economic, and environmental risks in industrial nickel heap leaching.

Keywords. Pilot plant design; Scale-up; HeapLeaching; Hydro-mechanical behavior; Reactive transport; Acid management; Agglomeration; Hydrometallurgy; Process integration; Industrial risk reduction

Highlights

- Pilot heaps often underestimate hydraulic heterogeneity and permeability evolution.
- Short-duration pilots systematically overestimate nickel recovery.
- Irrigation design and solution recycle are major sources of scale-up error.
- Integrated hydro-geochemical monitoring is essential for reliable extrapolation.
- A structured engineering framework reduces uncertainty in industrial heap leaching projects.

Graphical abstract



I. Introduction

Nickel has become a strategic metal in the transition to electrification and energy storage. Demand for battery-grade nickel has increased pressure on primary resources and intensified the search for cost-effective and lower-impact processing routes (Caetano et al., 2025; Roy et al., 2025). Lateritic ores account for a large share of global nickel resources, and their hydrometallurgical processing has been widely investigated (Stanković et al., 2020; Pandey et al., 2023; Li et al., 2023). Recent advances have expanded the technological options available for laterite treatment, including atmospheric leaching, chloride systems, and hybrid flowsheets (Pandey et al., 2024; O'Sullivan & Williams, 2024).

Heap leaching offers an alternative to high-pressure acid leaching for certain laterite deposits, especially when capital costs or ore characteristics favor simpler methods (Gavrilov et al., 2022; Petersen & van Staden, 2025). While heap operations are proven robust for other commodities when geotechnical, hydraulic, and chemical factors are well managed (Dunne, 2025), applying this to nickel laterites is challenging due to high acid use, iron hydrolysis, clay textures, and permeability changes during leaching (Pandey et al., 2023; Stanković et al., 2020).

In the development of a heap leach project, the pilot plant is crucial. The process typically includes: (i) mineralogical and geometallurgical characterization; (ii) bottle roll tests for kinetics and

acid demand; (iii) column tests for leaching; (iv) pilot heap trials; and (v) industrial implementation. Each step adds realism but also complexity and cost.

Column tests provide valuable data on extraction trends and reagent use but are limited by simplified conditions: primarily one-dimensional flow, limited boundary effects, and restricted mechanical loading. As a result, scale-dependent phenomena like preferential flow, agglomerate degradation, heterogeneous permeability, and evolving precipitation fronts may not be fully captured.

Pilot heaps are often designed as larger columns, with unchanged conceptual models despite changes in geometry. Simplified irrigation, limited instrumentation, and minimized operational variability can underestimate hydraulic heterogeneity and overestimate recovery stability at the scale of interest.

Given nickel's importance and the rising interest in heap leaching, a review of pilot-plant design is needed. It assesses how pilot heaps are conceived, instrumented, and interpreted as lab data are translated into industry applications. The focus is on scale-dependent hydro-geochemical and mechanical processes that challenge typical scale-up assumptions.

This article identifies gaps in pilot heap design and proposes a framework to reduce uncertainty during scale-up. It highlights the limitations of column-based extrapolation and aims

to improve the reliability of industrial heap leaching for nickel ores.

The following section describes the methodology adopted for literature selection, thematic classification, and critical analysis.

II. Methodology

This review was conducted in accordance with the PRISMA 2020 guidelines for systematic reviews (Page et al., 2021). The framework was adopted to ensure transparent identification, screening, eligibility assessment, and inclusion of relevant literature in heap leaching and pilot-scale engineering.

A search in Scopus, Web of Science, and Google Scholar used keywords like nickel laterites, heap leaching, pilot heaps, column tests, scale-up, agglomeration, permeability, geotechnical stability, and reactive transport. Reference lists of key papers were also checked for additional sources.

Publications were included if they addressed (i) heap leaching of nickel or transferable systems, (ii) pilot-scale design or scale-up methodology, or (iii) hydro-geochemical and geotechnical aspects relevant to heap performance. Purely laboratory studies without scale implications were excluded.

After screening and eligibility assessment, 85 references were consolidated and form the basis of the present review. These sources were grouped into thematic categories aligned with the engineering challenges discussed in subsequent sections.

To ensure transparency of the selection process, a PRISMA flow diagram is presented in Figure 1.

Figure 1 summarizes the literature identification, screening, eligibility, and inclusion process followed in this review.

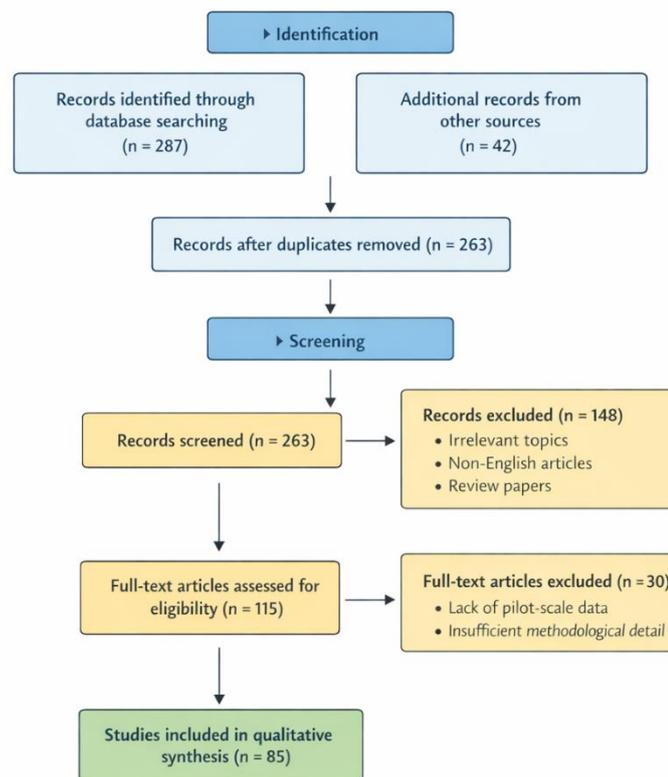


Figure 1. PRISMA 2020 flow diagram illustrating the literature selection process adopted in this review (adapted from Page et al., 2021).

The following section defines the objectives of a heap leach pilot plant and clarifies the performance criteria that must be demonstrated beyond laboratory column data.

III. Objectives of a Heap Leach Pilot Plant

The pilot heap isn't a larger column; it's the first scale where hydraulic, chemical, and

mechanical processes interact under realistic conditions. It confirms extraction trends and validates integrated behavior under semi-industrial conditions.

Column tests assess intrinsic kinetics and acid demand. Pilot heaps must verify performance amid variable flow, permeability changes, and stacking loads. Risks exist in extrapolating kinetics without considering reactive transport and scale effects (Winarko et al., 2023; Osten & Harrison, 2023; Kumara, 2020). Data-driven methods and geometallurgical models enhance predictability but depend on assumptions about flow and mineral heterogeneity (Flores & Leiva, 2021; Preece et al., 2023; Herrera et al., 2023). Validation at an intermediate scale is essential for process compression and flowsheet simplification (Lakshmanan et al., n.d.).

For clarity, pilot objectives can be grouped into four categories.

3.1 Metallurgical Objectives

The main goal is to determine realistic metal recovery under semi-industrial conditions, reflecting hydraulic variability rather than idealized flow. Kinetic behavior should be assessed at relevant heap heights. Reaction rates may differ from column trends due to oxygen limitations, acid redistribution, or precipitation barriers. Reagent consumption over time should be quantified. Acid use in pilot heaps often differs from column predictions because of iron hydrolysis and secondary phase formation.

Table 1 summarizes the key metallurgical performance indicators to monitor during pilot heap campaigns.

Table 1. Core metallurgical performance indicators for pilot heap validation. Adapted from Winarko et al., 2023; Kumara, 2020.

Indicator	Unit	Measurement Method	Why It Matters for Scale-Up	Typical Risk if Ignored
Nickel recovery	%	PLS assay + residue analysis	Defines economic viability	Overestimation of project value
Cobalt recovery	%	PLS assay	Selectivity assessment	Impurity misbalance
Extraction rate constant (k)	day ⁻¹	Kinetic modeling	Time-to-recovery forecast	Incorrect heap cycle time
Acid consumption (total)	kg H ₂ SO ₄ /t ore	Cumulative acid balance	OPEX estimation	Underestimated operating cost
Acid retained in heap	kg H ₂ SO ₄ /t ore	Moisture + residual acidity	Long-term balance closure	Acid inventory distortion
PLS nickel grade	g/L	Solution sampling	SX design basis	Undersized recovery circuit
Impurity loading (Fe, Mg, Al, Si)	g/L	ICP/OES or equivalent	Precipitation and scaling risk	Downstream instability
Percolation rate	L/m ² ·h	Flow measurement	Irrigation optimization	Channeling misinterpretation
Residence time	days	Tracer testing	Reactive transport calibration	Incorrect kinetic extrapolation
Solid-liquid ratio	–	Mass balance	Acid distribution modeling	Reaction inefficiency

Metallurgical validation must consider kinetic behavior, acid balance, and solution chemistry, not just extraction percentage. These

should be evaluated cumulatively and over time, as early trends alone do not validate scale-up.

3.2 Hydraulic Objectives

Hydraulic stability is vital for pilot validation, as it ensures stable self-weight percolation, differentiating pilot heaps from lab columns. It detects preferential flow and channel formation; uniform wetting isn't guaranteed. Stacked ore compaction influences void ratio and permeability. Hydraulic conductivity changes gradually and non-linearly over time.

Reactive transport modeling has shown that small variations in permeability can amplify concentration gradients at the system scale (Winarko et al., 2023; Osten & Harrison, 2023).

Figure 2 illustrates the transition from one-dimensional column flow to heterogeneous flow fields typical of pilot heaps.

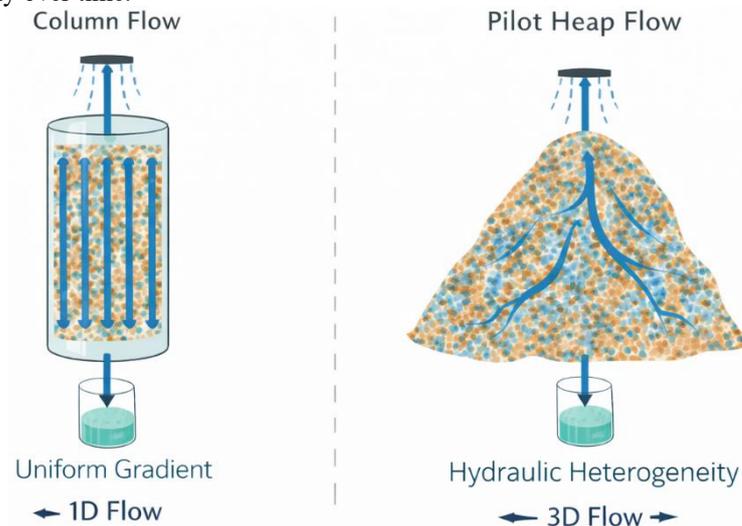


Figure 2. Conceptual comparison between column flow and heterogeneous pilot heap flow fields. Adapted from Winarko et al., 2023.

The figure emphasizes that hydraulic objectives extend beyond measuring total flow rate. Internal distribution is equally critical.

3.3 Chemical Objectives

The evolution of pregnant leach solution (PLS) chemistry must be monitored continuously. Concentration profiles over time offer insight into reaction fronts and secondary precipitation. Reprecipitation of iron and aluminum phases may change porosity and acid distribution. These processes are rarely fully captured in column tests.

Controlling pH and Eh conditions is required to maintain dissolution selectivity. Reactive transport simulations and geometallurgical frameworks support interpretation, but field data remain essential (Kumara, 2020; Preece et al., 2023).

Figure 3 shows a representative temporal evolution of PLS composition during pilot operation.

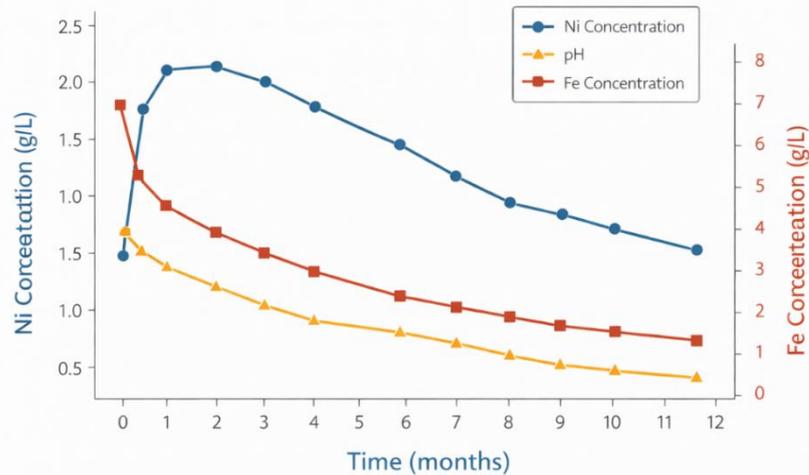


Figure 3. Example of temporal evolution of Ni concentration, pH, and Fe in PLS during pilot heap operation. Adapted from (Flores & Leiva, 2021; Herrera et al., 2023).

Temporal coupling between metal extraction and solution chemistry often reveals scale-dependent constraints that are not observed in short-column tests.

3.4 Operational Objectives

Pilot heaps should emulate industrial irrigation by accounting for flow rates, emitter spacing, and application methods for uniform

wetting. Manage solution inventory and recycling with closed mass balances. Solid handling, including agglomeration and stacking, must mirror industrial procedures. Ensuring operational realism is crucial. A technically controlled pilot that reduces variability might hide scale risks.

Figure 4 outlines the integration of metallurgical, hydraulic, chemical, and operational objectives in pilot design.

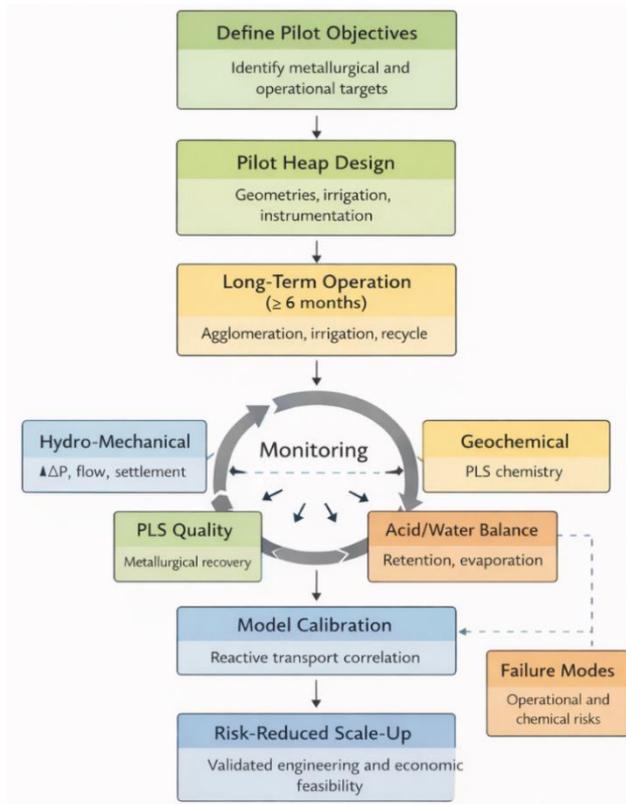


Figure 4. Integrated validation framework for pilot heap leach plants. Adapted from Lakshmanan et al., n.d.; Preece et al., 2023.

The framework highlights that pilot evaluation must integrate variables rather than assess them independently.

A pilot heap should validate system behavior, not simply confirm extraction efficiency. Recovery without hydraulic and chemical stability is insufficient evidence of industrial readiness.

The next section examines how heap scale and geometry influence these objectives and defines the physical constraints under which pilot validation occurs.

IV. Scale and Geometry of Pilot Heaps

Scale defines behavior. Geometry defines boundary conditions. Together, they determine whether a pilot heap can reproduce the coupled hydro-mechanical and geochemical responses expected at an industrial scale.

Many pilot programs underestimate the influence of height, footprint, and internal volume on the evolution of permeability and flow redistribution. As a result, hydraulic uniformity is often overestimated.

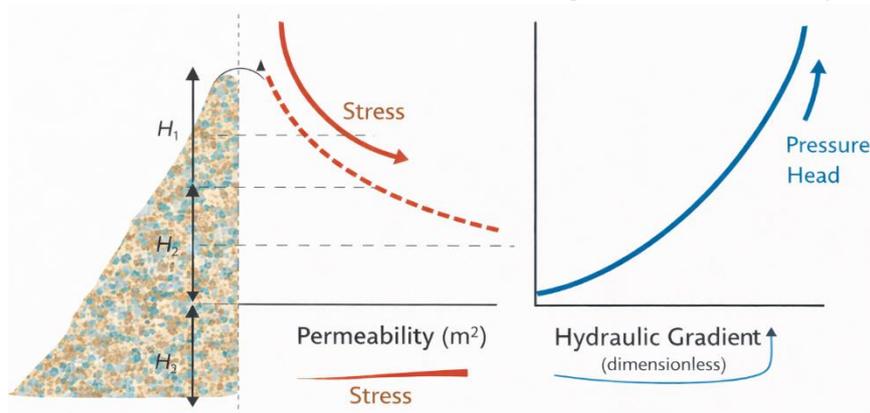


Figure 5. Conceptual representation of stress-dependent permeability and vertical hydraulic gradients as a function of heap height. Adapted from Pourverdi et al., 2025; Smith & Sinha, 2022.

The figure emphasizes that insufficient height limits the development of realistic compaction-driven changes in permeability.

4.2 Heap Area

Footprint area influences the redistribution of lateral flow and edge effects. Small pilot heaps exhibit strong boundary control. Sidewall friction and proximity to drainage can artificially stabilize flow.

Edge-dominated systems suppress the development of preferential flow channels. In

4.1 Heap Height

Heap height controls vertical gradients in stress, saturation, temperature, and solution chemistry. Columns typically operate under limited mechanical loading. Pilot heaps must reproduce self-weight compaction and its effect on pore structure.

Heights below 3 m tend to behave like enlarged columns. They do not generate sufficient vertical stress to induce a reduction in permeability or agglomerate degradation. Practical experience indicates that pilot heights of 3-6 m are necessary to capture realistic hydraulic gradients and compaction effects.

Coupled hydro-mechanical analyses show that stress-dependent permeability can evolve during leaching (Pourverdi et al., 2025). Liquefaction potential and shear instability are also influenced by heap height and internal pore pressure (Smith & Sinha, 2022; Huallanca & Quispe, n.d.).

Figure 5 illustrates the relationship between heap height and the development of vertical gradients in stress and hydraulic conductivity.

contrast, larger footprints allow internal heterogeneity to manifest.

Studies of waste rock and heap structures show that lateral confinement and drainage geometry influence hydraulic response (Dwumfour et al., 2020; Abbasi et al., 2020). Underdrain design and base configuration also modify flow fields (Hull et al., n.d.).

Table 2 compares geometric parameters typically reported for column, pilot, and industrial heaps.

Table 2. Comparison of characteristic geometric parameters across laboratory, pilot, and industrial

heaps Adapted from Hull et al., n.d.; Abbasi et al., 2020

Parameter	Laboratory Column	Pilot Heap	Industrial Heap	Engineering Implication
Height	0.3–2.0 m	3–6 m (minimum recommended)	6–15 m (typical lifts)	Gradient development depends strongly on height
Footprint area	< 0.05 m ²	10–200 m ²	10,000–500,000 m ²	Edge effects decrease with scale
Volume	< 0.1 m ³	50–1,000 m ³	> 100,000 m ³	Heterogeneity scales with volume
Compaction mechanism	Manual packing	Controlled stacking / limited equipment	Full-scale conveyor stacking	Stress-dependent permeability differs
Hydraulic dimensionality	1D flow	Transitional 2D–3D flow	Fully 3D heterogeneous flow	Column tests underestimate complexity
Edge influence	Dominant	Moderate	Negligible	Small systems overestimate uniformity
Drainage system	Simplified outlet	Engineered underdrain	Multi-layer drainage network	Drainage capacity affects stability
Irrigation method	Top drip/spray	Simplified grid	Engineered drip network	Distribution uniformity critical
Stress profile	Low confining stress	Moderate self-weight	High vertical stress	Permeability evolves with depth
Residence time variability	Minimal	Moderate	High spatial variability	Affects metal recovery distribution

Geometric scale directly influences hydraulic gradients, compaction, and the evolution of permeability. Laboratory columns cannot reproduce the stress-dependent flow behavior observed in pilot- and industrial-scale heaps. Pilot geometry must therefore exceed minimum thresholds to capture realistic hydro-mechanical conditions.

The comparison highlights how a reduced footprint can constrain hydraulic variability.

4.3 Minimum Representative Volume

Representative volume must allow: Real compaction under self-weight; Redistribution of flow paths; Development of internal heterogeneity.

Macro-pore formation and channelization emerge only when sufficient volume exists for preferential paths to coalesce. Simplified water-balance models demonstrate that macro-pore flow can dominate under certain geometries (Hull et al., n.d.).

Geostatistical modeling of ore bodies shows that heterogeneity is inherently non-stationary (Veliz et al., 2023). When pilot heaps are too small, geological variability is artificially homogenized.

Hydraulic disturbances during operation, such as irrigation variation or localized saturation, may amplify structural weaknesses. Case studies of heap instability indicate that small-scale testing may fail to capture such amplification mechanisms (Abbasi et al., 2020; Pourverdi et al., 2025).

Figure 6 presents a conceptual relationship between heap volume and the emergence of permeability variability.

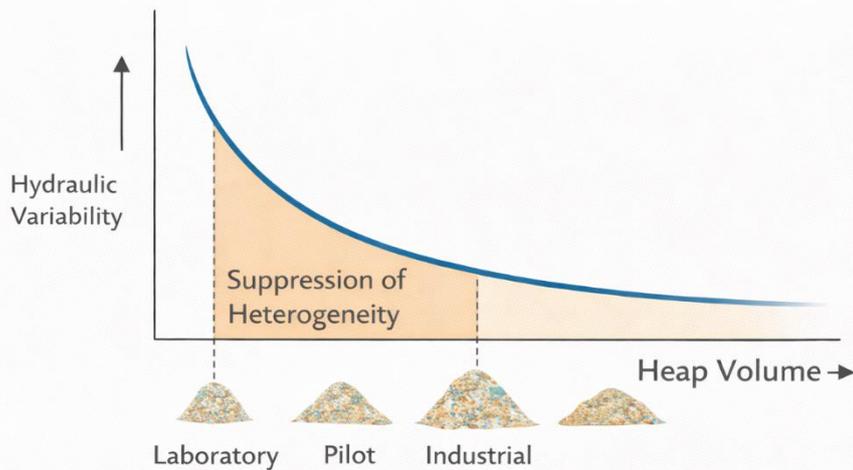


Figure 6. Conceptual relationship between heap volume and hydraulic variability, illustrating suppression of heterogeneity in small pilot systems. Adapted from Veliz et al., 2023; Hull et al., n.d.

The graph underscores a recurring issue: undersized pilots tend to overestimate hydraulic uniformity.

Pilots that are too small in height or footprint behave predictably. Industrial heaps do not. Underrepresentation of internal variability leads to optimistic recovery forecasts and underestimated risk.

The following section examines how ore preparation and stacking strategy further influence permeability evolution and hydraulic behavior at pilot scale.

V. Ore Preparation and Stacking Strategy

Ore preparation defines initial permeability. Stacking defines its evolution. Many pilot campaigns focus on solution chemistry and overlook solids engineering. This omission affects hydraulic stability and the reliability of extraction.

Granulometry, agglomeration chemistry, stacking method, and segregation control must be treated as design variables. They are not secondary operational details.

5.1 Representative Particle Size Distribution

Pilot heaps must reproduce the PSD expected at industrial scale. Over-screening improves short-term permeability but misrepresents fines migration and long-term compaction. Fines influence pore connectivity and agglomerate integrity. The removal of excessive fines creates artificially stable systems.

Table 3 summarizes the impact of particle size distribution on permeability and mechanical behavior in heap systems.

Table 3. Influence of particle size distribution on permeability and agglomerate stability in heap leaching. Adapted from Chen et al., 2020; Yin et al., 2021

PSD Characteristic	Permeability Behavior	Agglomerate Stability	Operational Consequence	Scale-Up Risk
Coarse-dominated (>10 mm)	High initial permeability	Low structural cohesion	Rapid percolation	Poor solution–solid contact
Well-graded (broad PSD)	Moderate, stable permeability	Good mechanical interlocking	Balanced flow and recovery	Preferred configuration
Excess fines (<1 mm >20%)	Reduced permeability	High cohesion but prone to swelling	Flow restriction	Clogging and ponding
High clay fraction	Strong permeability reduction	Weak under saturation	Slumping and channeling	Structural instability

Agglomerated fines	Improved permeability	Enhanced structural strength	Controlled percolation	Binder-dependent durability
Over-agglomerated material	Reduced void space	Dense, rigid pellets	Slow drainage	Acid diffusion limitation
Segregated PSD during stacking	Local permeability contrast	Heterogeneous bonding	Preferential flow paths	Channeling amplification

Particle size distribution governs both hydraulic conductivity and mechanical integrity. Excess fines reduce permeability and promote clogging, while insufficient fines reduce structural cohesion. Controlled agglomeration mitigates both extremes but requires validation under realistic irrigation and stress conditions.

The data indicate that minor variations in fines content can alter hydraulic response and the kinetics of metal extraction.

5.2 Agglomeration: Chemical and Mechanical Aspects

Agglomeration aims to improve permeability and structural stability. Its

Figure 7 illustrates agglomerate degradation pathways under hydraulic stress.

effectiveness depends on binder chemistry, moisture control, and curing conditions.

Chemical binders influence particle bonding and resistance to degradation during leaching (Chen et al., 2020; Yin et al., 2021). Mechanical integrity affects attrition under irrigation (Wang et al., 2024).

Industrial practice shows that inadequate agglomeration leads to fines migration and channel formation (Fiscor, 2023). Scale-dependent improvements have been reported when agglomeration intensity is optimized (Guzman et al., 2024).

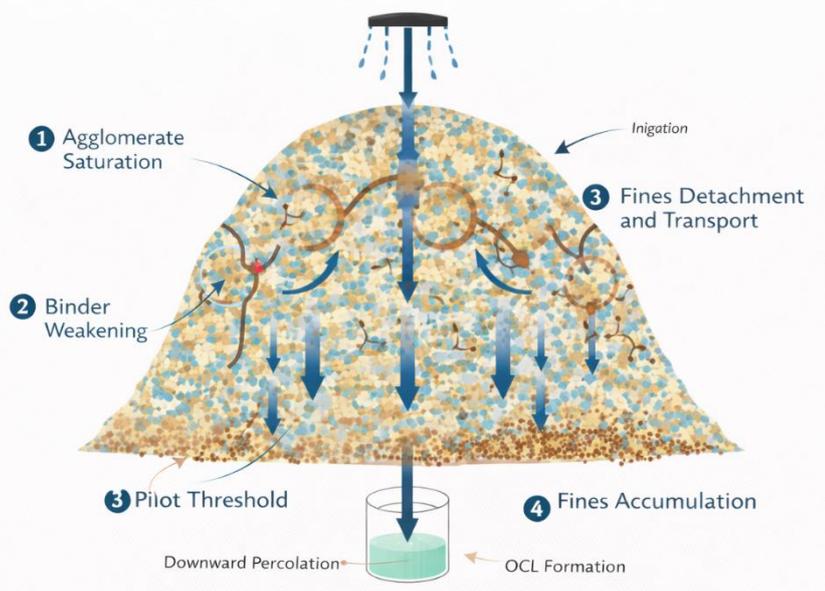


Figure 7. Mechanisms of agglomerate degradation and fines migration under irrigation. Adapted from Wang et al., 2024; Guzman et al., 2024.

Agglomerate breakdown alters pore structure. The effect becomes more pronounced at greater heap heights.

Mechanical activation has also been proposed to intensify leaching by modifying mineral structure and surface area (Acquah et al., 2025; Miah, 2024). While promising, these approaches

require pilot validation to assess structural consequences under stacking loads.

5.3 Stacking Method: Layered vs Dumped

Stacking method influences density and internal heterogeneity. Layered stacking provides controlled lift thickness. Dumped stacking creates variable density zones.

Manual stacking in pilot programs often results in uniform compaction. Industrial stacking generates differential loading, localized segregation, and uneven moisture distribution.

Figure 8 compares bulk density variability associated with layered and dumped stacking approaches.

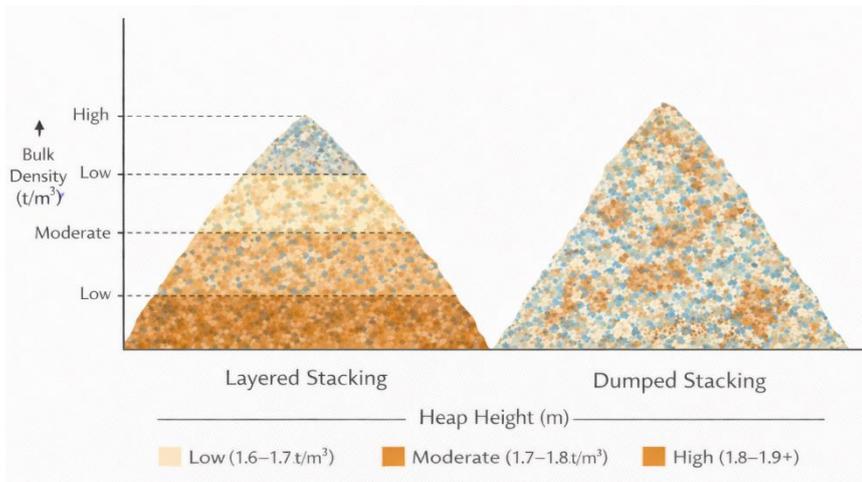


Figure 8. Conceptual comparison of bulk density variability under layered and dumped stacking. Adapted from Fiscor, 2023.

Uniform density in pilot heaps may mask the development of preferential flow paths.

5.4 Segregation Control

Particle segregation during stacking alters permeability distribution. Coarse particles tend to migrate outward. Fines concentrate in the lower or central zones.

Without segregation control, internal flow becomes uneven. Pilot heaps built with controlled feed blending may not reflect industrial variability.

Manual stacking does not reproduce the mechanical compaction and segregation observed in conveyor-based industrial stacking. As a result, hydraulic uniformity is often overestimated.

Ore preparation and stacking strategy determine initial structural conditions. These conditions govern the evolution of permeability and the distribution of solutions. If preparation is idealized, pilot performance becomes non-representative.

The next section examines how irrigation system design interacts with ore preparation to control solution distribution and hydraulic stability.

VI. Irrigation System Design and Geochemical Evolution

Irrigation controls reaction progress. It governs solution distribution, residence time, oxygen availability, and precipitation dynamics. In pilot heaps, irrigation design is often simplified. This simplification distorts hydraulic and chemical behavior.

Distribution is not a secondary variable. It defines the internal reactor environment.

6.1 Type of Irrigation

Drip irrigation promotes localized infiltration, reduces evaporation, and improves control, but may cause channel development if emitters are spaced inadequately. Spray irrigation increases surface wetting and evaporation, increasing the risk of crust formation. Intermittent irrigation alters saturation cycles, affecting oxygen transport and precipitation fronts, especially in bioleaching systems (Gericke et al., 2022; Jia et al., 2024).

Bio-oxidative transport depends on oxygen diffusion and solution renewal (Khachatryan et al., 2023; Tambwe, 2025). Inadequate irrigation can suppress microbial activity and alter iron cycling (Mäkinen et al., 2020).

Table 4 compares the hydraulic and geochemical implications of different irrigation modes in pilot heaps.

Table 4. Comparison of irrigation modes and their impact on solution distribution, oxygen transport, and precipitation behavior. Adapted from Gericke et al., 2022; Jia et al., 2024

Irrigation Mode	Solution Distribution Pattern	Oxygen Transport	Precipitation Tendency	Operational Sensitivity	Scale-Up Implication
Continuous Drip	Relatively uniform if grid properly designed	Moderate diffusion through partially saturated zones	Moderate; localized if flow becomes preferential	Sensitive to emitter clogging	Preferred for controlled pilots
Spray Irrigation	Surface wetting; prone to uneven infiltration	Enhanced aeration at surface	Higher risk of surface precipitation crusts	Wind and evaporation sensitive	Requires careful distribution testing
Intermittent Irrigation	Cyclic wet–dry fronts	Improved oxygen penetration during dry phase	Increased risk of salt accumulation at evaporation fronts	Timing critical	Must simulate industrial cycling
Flood / High-Rate Application	Rapid infiltration along preferential paths	Reduced oxygen in saturated zones	Promotes iron hydrolysis and clogging	High channeling risk	Not representative unless monitored
Pulsed Irrigation	Controlled infiltration fronts	Improved oxygen renewal	May reduce continuous precipitation zones	Requires automation	Suitable for bioleaching systems
Drip with Recycle PLS	Chemically variable distribution	Dependent on Fe ²⁺ /Fe ³⁺ ratio	Increased secondary phase formation if poorly controlled	Strong chemistry–hydraulics coupling	Must validate acid and iron balance

Irrigation strategy affects flow uniformity, redox changes, and precipitation. Pilot systems' simplified irrigation can mask flow and oxygen transport issues. Validation of distribution and redundancy is needed before scaling up. The table shows that the irrigation strategy influences the evolution of permeability and chemical stability.

6.2 Distribution Parameters

Uniformity, pressure, and redundancy define irrigation performance. Low pressure can cause uneven wetting, while excessive pressure may lead to erosion and fines migration. Emitter spacing controls infiltration overlap. Small pilots achieve

more uniformity, but larger systems face greater variability. Distribution is often the most underestimated aspect in pilot design.

Poor distribution accelerates preferential flow. Uneven acid delivery promotes localized precipitation of iron and aluminum phases (Mbedzi, 2020; Shayakhmetova et al., 2025). Secondary-phase formation can reduce permeability and alter flow paths (Chepushtanova et al., 2020).

Hydrochloric systems and atmospheric leaching pathways exhibit distinct precipitation patterns, thereby affecting internal porosity (Top et al., 2020; Faris et al., 2023; Neira et al., 2021; Mokmeli & Parizi, 2022).

Figure 9 illustrates the formation of precipitation fronts under non-uniform irrigation conditions.

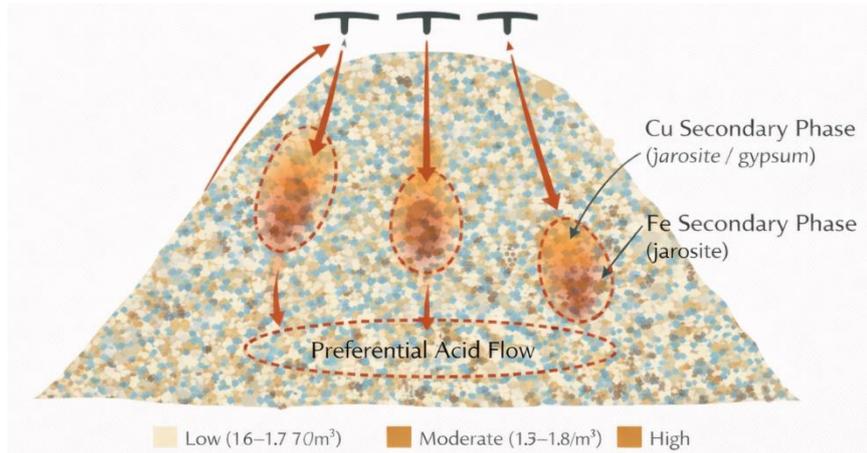


Figure 9. Conceptual development of secondary phase precipitation fronts induced by uneven acid distribution. Adapted from Chepushtanova et al., 2020; Mbedzi, 2020.

Localized acid excess may trigger iron hydrolysis. Acid deficiency zones reduce dissolution efficiency. The interaction produces migrating precipitation fronts.

6.3 Coupling Irrigation and Geochemistry

Solution residence time determines reaction extent. High flow rates may reduce contact time. Low flow rates may intensify precipitation.

Reactive systems do not respond linearly to irrigation adjustments. Minor changes in flow can shift redox balance, oxygen availability, and iron speciation.

Figure 10 shows the conceptual relationship between irrigation rate and the evolution of PLS composition.

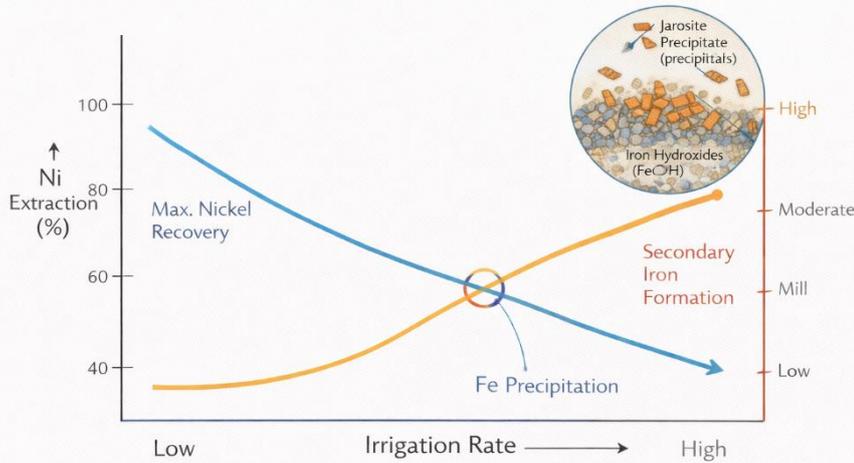


Figure 10. Conceptual influence of irrigation rate on Ni extraction and Fe precipitation dynamics. Adapted from Shayakhmetova et al., 2025; Gericke et al., 2022.

The graph emphasizes that hydraulic control directly affects chemical stability.

Many pilot programs design irrigation simply, assuming uniform wetting and neglecting internal distribution, without measuring it. This masks heterogeneity and delays the detection of permeability loss due to precipitation. Irrigation design should be a key engineering factor that

affects ore prep, stacking density, and acid management.

The next section examines how hydro-mechanical monitoring can detect changes in permeability and structural changes during pilot operation.

VII. Hydro-Mechanical Monitoring and Acid Management

Pilot heaps require instrumentation similar to that used in reactors under load because hydraulic and mechanical responses change during operation. Without monitoring, these changes remain hidden, making the pilot behave like a large column with limited diagnostic value. Instrumentation is essential; it ensures accurate interpretation of scale-up.

7.1 Hydro-Mechanical Monitoring

Permeability evolves due to compaction, fines migration, and precipitation. These processes alter internal flow distribution. They cannot be inferred solely from outlet flow rate.

Essential monitoring elements include:

Table 5. Recommended hydro-mechanical instrumentation for pilot heap monitoring. Adapted from Nagar, 2021; Meng et al., 2023.

Instrument / Sensor	Parameter Measured	Installation Location	Monitoring Frequency	Purpose in Pilot Validation	Risk if Omitted
Differential pressure sensors (ΔP)	Vertical hydraulic gradient	Multiple depths (top–mid–base)	Continuous	Detect permeability loss and clogging	Channeling undetected
Flow meters	Inlet and outlet flow rate	Irrigation line and PLS discharge	Continuous	Close water balance	Mass balance error
Moisture probes (TDR or capacitance)	Volumetric water content	Vertical profiles	Daily / continuous	Identify saturation zones	Misinterpretation of kinetics
Settlement plates / markers	Vertical displacement	Surface and intermediate layers	Weekly	Track compaction	Structural instability
Load cells (base layer)	Stress development	Heap base	Continuous	Correlate stress with permeability	No stress–flow linkage
Hydraulic tracer ports	Residence time distribution	Injection at top, sampling at base	Periodic tests	Validate reactive transport models	Incorrect kinetic extrapolation
Piezometers	Pore pressure	Lower third of heap	Continuous	Detect local ponding	Drainage failure unnoticed
Temperature sensors	Thermal gradient	Multi-depth array	Continuous	Identify exothermic zones	Hidden hot spots
Drainage collection cells	Localized discharge	Base drainage grid	Continuous	Detect uneven flow	Edge-dominated bias

- Differential pressure sensors (ΔP) along the vertical profile
- Continuous flow measurement at inlet and outlet
- Moisture sensors within the heap
- Settlement monitoring to detect compaction
- Hydraulic tracers to identify preferential pathways

ΔP trends reveal a loss of permeability before extraction declines. Settlement data indicate stress redistribution and agglomerate degradation. Tracer tests help quantify channelization and residence time.

Table 5 summarizes the minimum instrumentation required for hydro-mechanical monitoring in pilot heaps.

Data logging system	Integrated monitoring	Central control unit	Continuous	Enable time-resolved interpretation	Fragmented data
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Hydro-mechanical behavior cannot be inferred solely from extraction data. Instrumentation must capture the evolution of stress, flow, moisture, and pressure over time. Without continuous monitoring, a pilot heap

behaves as an enlarged column, masking heterogeneity and scale-dependent failure mechanisms.

The absence of distributed monitoring reduces interpretative reliability. Outlet chemistry alone cannot diagnose internal hydraulic evolution.

Figure 11 presents a schematic illustrating the evolution of differential pressure during pilot operation.

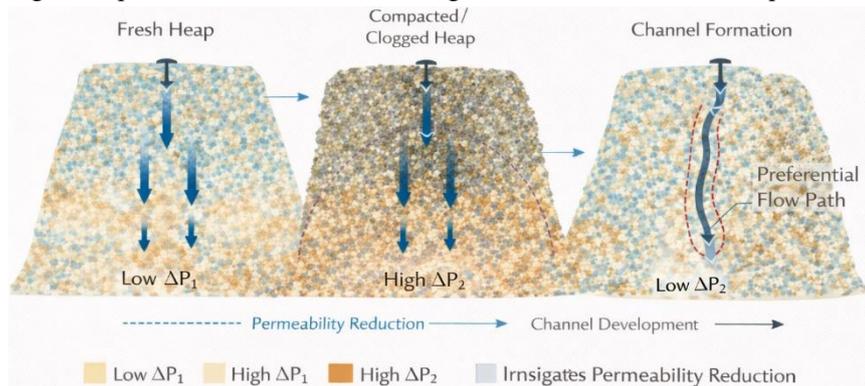


Figure 11. Conceptual evolution of differential pressure (ΔP) during permeability reduction and channel formation. Adapted from Nagar, 2021.

Rising ΔP may indicate pore blockage. Sudden drops can signal channel breakthrough.

Without this level of monitoring, pilot heaps fail to capture scale-dependent hydraulic instability.

7.2 Acid Consumption and Solution Chemistry

Acid consumption is dynamic. It depends on mineral dissolution, iron hydrolysis, secondary precipitation, and solution recycle.

Selective precipitation and impurity control modify acid balance (Astuti et al., 2023). Membrane-based separations and solution purification may alter recycle chemistry (Manis et al., 2021). Emerging approaches for magnesium and hydroxide recovery also influence solution alkalinity (Battochio et al., 2024).

Figure 12 illustrates cumulative acid consumption during pilot operation.

Short-term acid demand differs from cumulative consumption. Pilot heaps allow evaluation of acid retention and regeneration strategies.

Techno-economic assessments show that reagent cost is highly sensitive to scale-dependent consumption patterns (Nagar, 2021). Regeneration approaches and lixiviant recycling can mitigate acid demand (Meng et al., 2023).

Downstream solvent extraction performance depends on stable PLS composition (Mbao et al., n.d.). Variability in iron or impurity levels increases reagent consumption and affects phase separation.

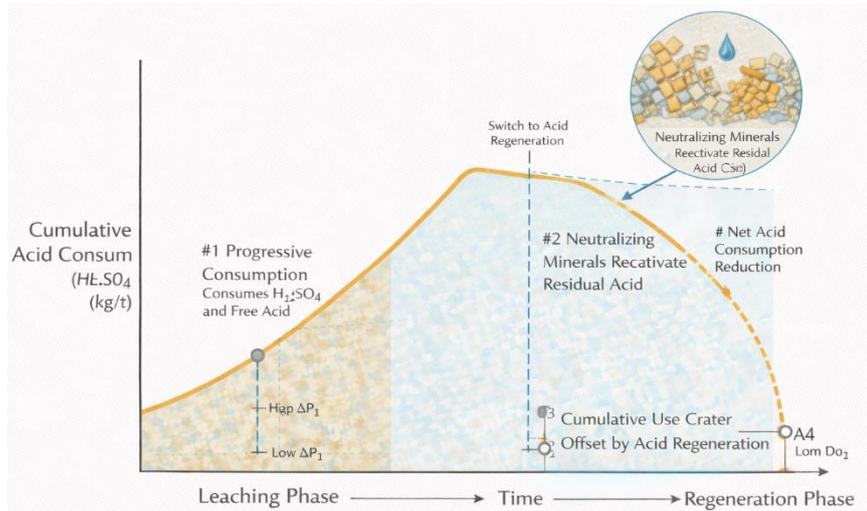


Figure 12. Conceptual cumulative acid consumption profile and regeneration effects during pilot leaching. Adapted from Nagar, 2021; Meng et al., 2023.

Non-linear trends reflect evolving mineral reactivity and precipitation behavior.

Figure 13 presents a simplified acid mass balance framework for pilot heaps.

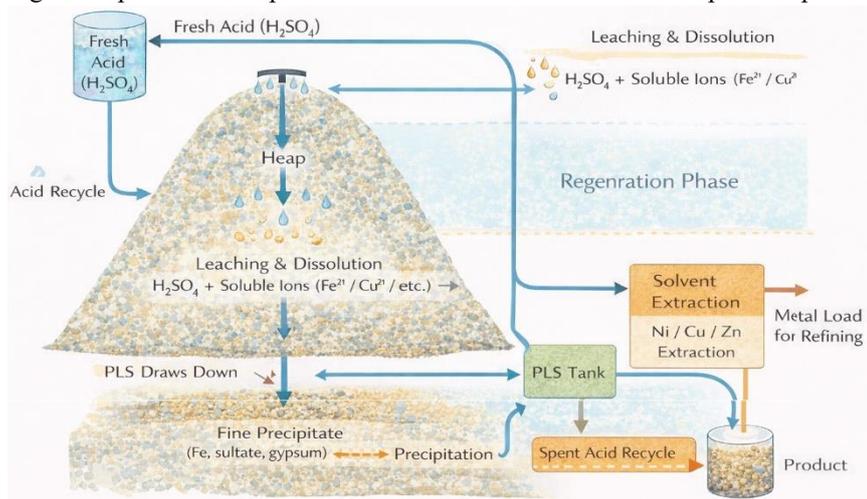


Figure 13. Simplified acid mass balance including dissolution, precipitation, recycle, and downstream extraction. Adapted from Manis et al., 2021; Battochio et al., 2024.

Closing the acid balance is essential. Unaccounted losses distort scale-up projections.

Hydro-mechanical monitoring and acid management are interdependent. Permeability loss modifies residence time. Residence time influences

The next section examines detailed geochemical monitoring and the interpretation of PLS evolution under dynamic pilot conditions.

VIII. Geochemical Monitoring and Geotechnical Stability

acid consumption. Acid distribution affects precipitation and compaction.

If monitoring is incomplete, these couplings remain undetected. The pilot then confirms extraction trends without validating structural stability.

Pilot heaps must be monitored as reactive systems. Metal extraction alone does not describe internal evolution. Solution chemistry reflects the simultaneous occurrence of dissolution, precipitation, oxidation, and transport processes.

Continuous monitoring is required for:

- Ni and Co; Fe²⁺ / Fe³⁺; Mg; Al; Si; pH; Eh; Electrical conductivity

Absolute values are informative. Temporal evolution is more critical. Transient shifts often precede hydraulic or structural instability.

8.1 Chemical Evolution in Pilot Heaps

Nickel and cobalt concentrations define metallurgical performance. Iron speciation indicates redox balance and hydrolysis risk. Magnesium

Table 6. Key geochemical monitoring parameters and their diagnostic significance in pilot heap operation. Adapted from Smith & Sinha, 2022; Bar & Teleu, 2023

Parameter	Measurement Location	Monitoring Frequency	Diagnostic Significance	Typical Warning Signal	Operational Implication
Ni (g/L)	PLS discharge	Daily	Metal dissolution efficiency	Plateau or decline	Permeability loss or acid depletion
Co (g/L)	PLS discharge	Daily	Selectivity assessment	Disproportionate recovery vs Ni	Mineralogical variability
Fe ²⁺ / Fe ³⁺ ratio	PLS discharge	Daily	Redox control	Rising Fe ³⁺ fraction	Iron hydrolysis risk
Total Fe (g/L)	PLS discharge	Daily	Secondary precipitation risk	Sudden decrease	Jarosite / ferric precipitation
Mg (g/L)	PLS discharge	Weekly	Acid consumption indicator	Progressive increase	High gangue dissolution
Al (g/L)	PLS discharge	Weekly	Precipitation and scaling risk	Elevated Al with low pH	Risk of basic aluminum sulfate formation
Si (mg/L)	PLS discharge	Weekly	Silica gel formation risk	Gradual increase	Potential pore clogging
pH	Inlet and outlet solution	Continuous	Acid availability	Upward drift	Acid depletion
Eh (mV)	PLS discharge	Continuous	Oxidation state control	Drop in Eh	Limited oxygen transport
Electrical conductivity	PLS discharge	Continuous	Ionic strength evolution	Rapid fluctuation	Dilution or recycle imbalance
Sulfate (SO ₄ ²⁻)	PLS discharge	Weekly	Acid mass balance control	Unexpected decrease	Precipitation or retention
Temperature (°C)	Multi-depth in heap	Continuous	Reaction intensity	Local hot zones	Oxidative acceleration

reflects acid consumption in lateritic systems. Aluminum and silica signal precipitation tendencies.

Fluctuations in Fe³⁺/Fe²⁺ ratio affect dissolution kinetics and precipitation fronts. pH drift can trigger secondary phase formation. Conductivity trends reflect cumulative ion buildup.

Table 6 links monitored chemical parameters to operational interpretation in pilot heaps.

Temporal trends are more informative than single measurements. Monitoring must capture both concentration and redox evolution. Many pilot failures arise from ignoring early deviations in Fe

speciation, pH drift, or conductivity changes, which precede visible hydraulic problems.

Integrated interpretation requires correlating chemical trends with hydraulic data.

Isolated measurements may lead to incorrect conclusions.

Figure 14 illustrates a representative temporal shift in iron speciation and pH during pilot operation.

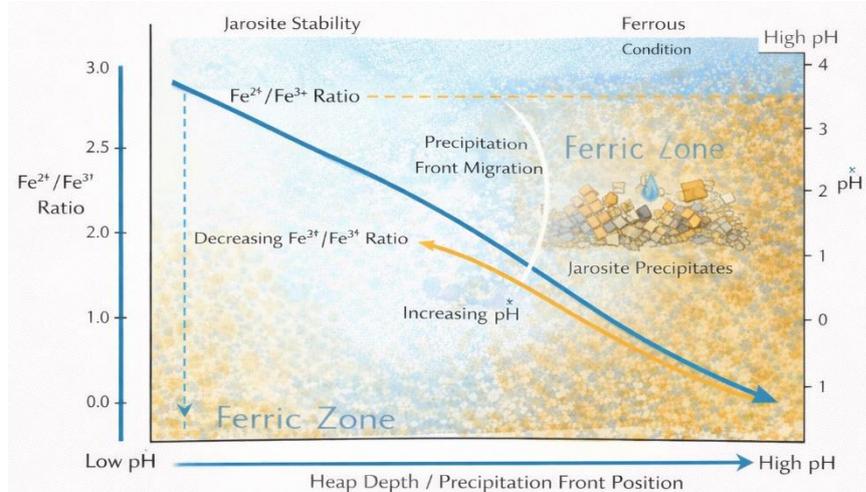


Figure 14. Conceptual evolution of Fe^{2+}/Fe^{3+} ratio and pH during precipitation front migration. Adapted from Solanki, 2020; Tuomela et al., 2021.

Early detection of pH drift can prevent uncontrolled precipitation and permeability reduction.

8.2 Coupling Chemistry with Structural Stability

Chemical evolution influences geotechnical stability. Iron precipitation and silica formation modify pore structure. Reduced permeability increases pore pressure. Elevated pore pressure reduces effective stress.

Interface shear strength between geomembranes and underlying layers must be considered in design (Solanki, 2020; Zúñiga & León, 2024). Strain response of geomembranes under loading can evolve over time (Clinton & Rowe, 2025). Chemical durability of liner materials must also be verified (Abdelaal & Samea, 2024; Silva et al., 2021).

Drainage efficiency controls pore pressure buildup. Base liner design and seepage control are essential to stability (Tuomela et al., 2021; Smith & Sinha, 2022).

Slope stability and shear interface behavior require proper geotechnical evaluation (Bar & Teleu, 2023). Failure forecasting tools, including remote sensing approaches, have been explored for large-scale facilities (Szakolczai et al., n.d.).

Valley-fill configurations introduce additional hydraulic and geomechanical complexity (Bridge, 2024). Case studies from gold and base metal operations highlight the need for conservative stability margins (Surimbayev et al., 2025).

Figure 15 presents the coupling between geochemical evolution and structural stability in pilot heaps.

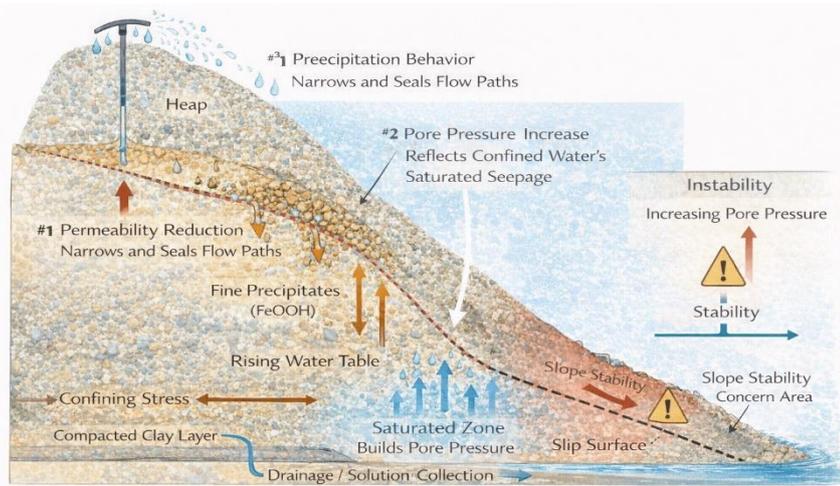


Figure 15. Interaction between precipitation-induced permeability reduction, pore pressure increase, and slope stability in heap structures. Adapted from Smith & Sinha, 2022; Bar & Teleu, 2023.

The schematic illustrates how chemical processes can amplify geotechnical risk.

Geochemical monitoring must be integrated with hydro-mechanical data. Chemical signals often precede structural symptoms. Ignoring these trends delays corrective action.

Pilots that focus only on extraction may overlook stability degradation. Long-term reliability depends on coupled interpretation.

The following section addresses acid management and solution-recycle strategies, linking chemical monitoring to mass-balance control and process optimization.

IX. Acid Management, Recycle and Pilot-Scale Case Evidence

Acid management determines economic viability. It also reflects internal reaction efficiency. In pilot heaps, acid balance is often simplified. This leads to optimistic scale-up projections.

Cumulative acid balance must be closed. Inlet, outlet, retention, and loss terms must be quantified. Without this control, reagent consumption cannot be reliably extrapolated.

9.1 Acid Mass Balance

Cumulative acid consumption includes:

- Acid consumed by mineral dissolution
- Acid neutralized by gangue reactions
- Acid lost to precipitation
- Acid retained in pore solution

Solution retention in the heap can be significant. Moisture trapped in low-permeability zones increases apparent consumption. Evaporation losses alter concentration and ionic strength.

Concentration control is essential. Recycle streams progressively accumulate dissolved species. Ionic buildup modifies activity coefficients and precipitation thresholds.

Common error:

Failure to close both water and acid balances during pilot operation.

Figure 16 illustrates the main acid and water balance components in a pilot heap system.

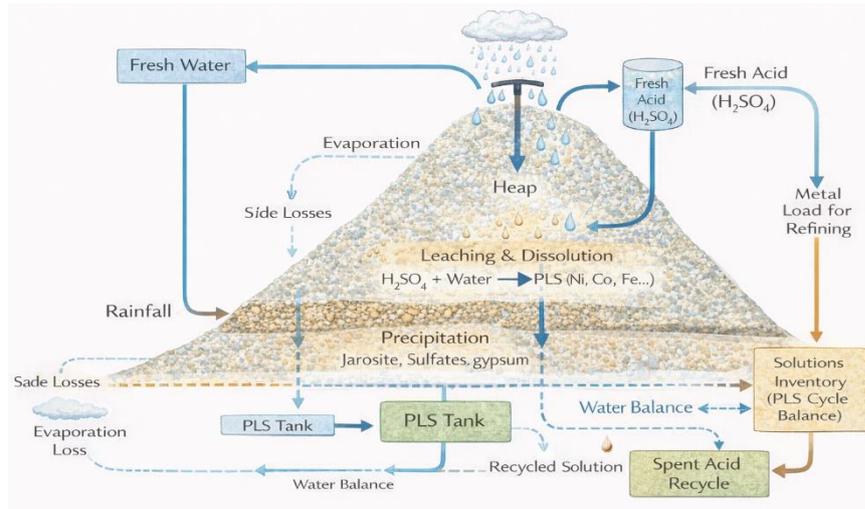


Figure 16. Simplified acid and water mass balance framework for pilot heap leaching. Adapted from Agatzini-Leonardou et al., 2021; Carr et al., 2008.

The framework highlights the need to quantify solution inventory and internal retention.

Figure 17 shows a representative relationship between cumulative acid input and nickel extraction.

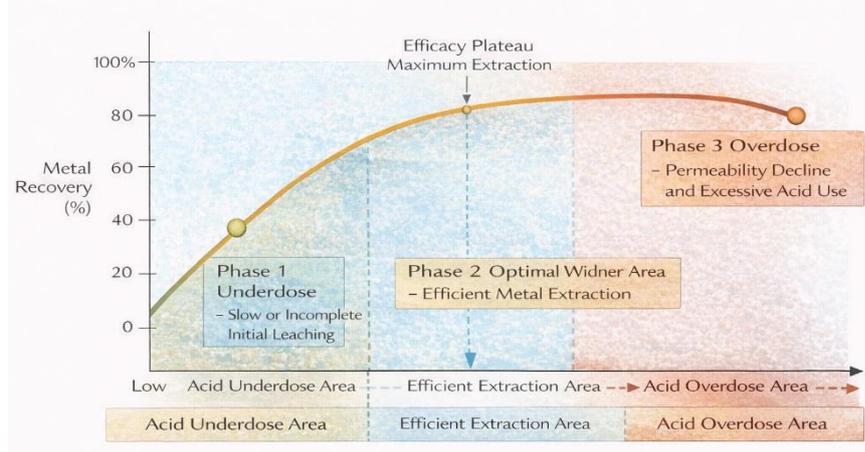


Figure 17. Conceptual relationship between cumulative acid input and metal recovery in pilot operation. Adapted from Oxley et al., 2025; Thomas et al., 2024.

Non-linear trends indicate evolving mineral reactivity and precipitation effects.

9.2 Lessons from Pilot-Scale Applications

Pilot campaigns in lateritic systems have demonstrated variable acid efficiency depending on ore mineralogy and stacking practice (Agatzini-Leonardou et al., 2021; Oxley et al., 2025). Case studies emphasize the importance of operational realism.

Recovery of critical metals from unconventional feedstocks also shows that recycle chemistry must be stabilized before industrial deployment (Thomas et al., 2024; Nawab & Honaker, 2023). Integrated pilot circuits for rare-earth recovery underscore the importance of

coupling leaching with downstream processing (Honaker et al., 2021; Honaker et al., 2022).

Earlier industrial development programs highlighted that underestimating the complexity of solution management led to economic and operational challenges (Carr et al., 2008).

For sulfide systems, pilot investigations confirm that acid demand and redox control differ from oxide ores (Arpalahti, 2021; Porvali et al., 2024). These differences affect the stability of the recycle and iron management.

Table 7 summarizes key findings from selected pilot-scale case studies relevant to acid management and recycle stability.

Table 7. Selected pilot-scale case observations related to acid balance and solution recycle . Adapted from Agatzini-Leonardou et al., 2021; Oxley et al., 2025; Arpalahiti, 2021.

Case / Ore Type	Leaching Medium	Pilot Duration	Acid Balance Behavior	Solution Recycle Strategy	Key Observation	Engineering Implication
Laterite (saprolite-dominant)	H ₂ SO ₄	120–180 days	Progressive acid consumption increase due to Mg dissolution	Partial raffinate recycle	Acid demand underestimated during early stages	Long-term monitoring required before industrial projection
Laterite (limonite-rich)	H ₂ SO ₄	>180 days	Acid losses via Fe ³⁺ hydrolysis and jarosite formation	Closed-loop recycle with bleed control	Iron precipitation altered acid efficiency	Acid balance must include secondary phase formation
Mixed laterite feed	H ₂ SO ₄	90–150 days	Variable cumulative acid retention in heap inventory	Intermittent recycle adjustment	Solution inventory fluctuated with rainfall events	Water balance integration is critical for acid projection
Sulfide ore (secondary Ni sulfides)	Acidic ferric solution	>180 days	Partial acid regeneration via Fe ³⁺ /Fe ²⁺ cycling	Continuous recycle with aeration	Oxidative regeneration reduced net acid demand	Redox control impacts overall acid consumption
Low-grade oxide ore	H ₂ SO ₄	60–120 days	Acid overdosing led to permeability decline	Limited recycle during early test phase	Excess acid caused precipitation front formation	Acid addition must be linked to permeability monitoring
Laterite pilot with high evaporation	H ₂ SO ₄	150–210 days	Concentration increase due to evaporative losses	Compensated by fresh water addition	Acid concentration spikes affected metal recovery	Climatic factors must be incorporated into pilot design
Industrial-scale validation trial	H ₂ SO ₄	>1 year	Acid balance stabilized after steady-state recycle achieved	Full raffinate recycle with purge	Stable cumulative acid profile achieved after 6–8 months	Short pilots fail to capture steady-state acid regime

Case evidence confirms that pilot systems frequently underestimate cumulative acid demand when recycle chemistry is not rigorously controlled.

Acid management cannot be treated as a secondary accounting exercise. It defines operating cost, precipitation risk, and long-term stability.

Pilots that do not rigorously close water and acid balances generate unreliable scale-up data. This limitation becomes more pronounced over extended operating periods.

The following section examines long-term operation, where cumulative effects on permeability, chemistry, and structural stability become fully apparent.

X. Long-Term Operation and Pilot Validation

Short pilot campaigns provide partial answers. Long-term operation reveals system

Figure 18 illustrates a representative extraction curve highlighting early rapid dissolution and late-stage kinetic decline.

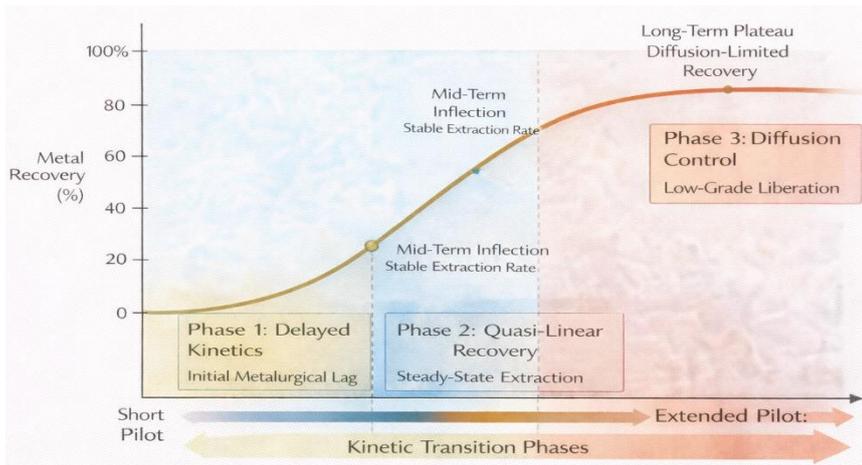


Figure 18. Conceptual extraction curve during extended pilot operation showing kinetic transition phases. Adapted from Agatzini-Leonardou et al., 2021; Arpalahti, 2021.

Late-stage slopes often determine economic feasibility. Short campaigns may misrepresent this phase.

10.2 Progressive Clogging and Permeability Loss

Colmatation develops gradually. Precipitation of iron and aluminum phases may block pores. Fine migration can accumulate in lower zones.

Extended operation allows detection of these mechanisms. Pilot programs shorter than 120

stability. Many scale-up errors emerge only after extended leaching.

A pilot heap should operate for at least 180 days. Ideally, it should complete the projected industrial leach cycle. Early extraction data do not represent late-stage behavior.

10.1 Late-Stage Kinetics

Reaction rates decline over time. Mineral accessibility changes. Diffusion limitations increase as pore structure evolves.

Lateritic systems may exhibit declining acid efficiency at advanced stages (Agatzini-Leonardou et al., 2021; Oxley et al., 2025). In sulfide systems, redox evolution can modify dissolution behavior (Arpalahti, 2021; Porvali et al., 2024).

days rarely capture cumulative reductions in permeability.

Industrial case histories indicate that early hydraulic stability can deteriorate over time (Carr et al., 2008). Recent pilot studies confirm that permeability evolution must be monitored beyond initial extraction peaks (Thomas et al., 2024; Oxley et al., 2025).

Figure 19 presents a schematic evolution of permeability during long-term pilot leaching.

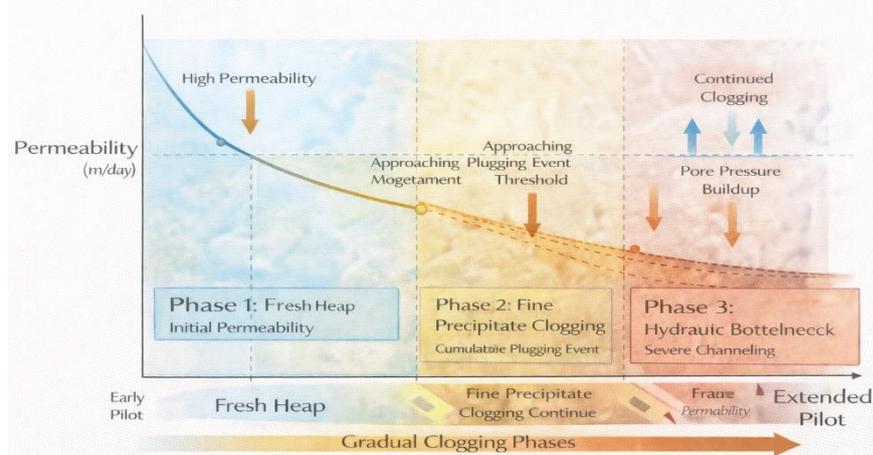


Figure 19. Conceptual permeability evolution during extended heap operation, including gradual clogging phases. Adapted from Thomas et al., 2024; Carr et al., 2008.

Delayed permeability loss can alter residence time and acid distribution.

10.3 Stability of Pregnant Leach Solution (PLS)

PLS composition evolves during long-term operation. Ionic buildup may increase scaling risk. Impurity accumulation affects downstream performance.

Pilot-scale studies involving integrated circuits show that long-term stability is critical for continuous operation (Nawab & Honaker, 2023; Honaker et al., 2021; Honaker et al., 2022).

In sulfide systems, iron management and redox control become more complex over time (Arpalahti, 2021; Porvali et al., 2024).

Table 8 summarizes key indicators to evaluate during extended pilot campaigns.

Table 8. Indicators of long-term operational stability in pilot heap leaching.; Adapted from Nawab & Honaker, 2023; Oxley et al., 2025

Indicator	Measurement Method	Typical Monitoring Frequency	Stability Signal	Instability Signal	Engineering Interpretation
Ni Recovery Rate (%)	Cumulative metal balance	Weekly / Monthly	Gradual plateau with minor fluctuations	Sudden decline or oscillations	Indicates kinetic transition or flow redistribution
PLS Flow Rate (m ³ /h)	Continuous flowmeter	Continuous	Stable within ±5–10%	Progressive decline or sharp variation	Possible clogging or channel development
Differential Pressure (ΔP)	Pressure sensors (vertical profile)	Continuous	Stable gradient	Increasing ΔP or localized spikes	Permeability reduction or pore blockage
Fe ²⁺ /Fe ³⁺ Ratio	Chemical analysis	Weekly	Controlled redox window	Sharp oxidation/reduction swings	Risk of uncontrolled precipitation
pH Profile (inlet vs outlet)	In-line probes	Continuous	Gradual, predictable shift	Abrupt increase or drop	Acid depletion or overdosing

Acid Consumption (kg/t ore)	Cumulative mass balance	Monthly	Converging toward steady-state	Increasing without recovery gain	Secondary phase formation or acid loss
Solution Inventory (m ³ retained)	Water balance calculation	Weekly	Stable inventory	Progressive retention increase	Heap saturation or drainage restriction
Temperature Profile (°C)	Thermocouples	Continuous	Moderate gradient	Localized hot spots	Enhanced reaction zones or bio-oxidation effects
Electrical Conductivity	In-line sensor	Continuous	Stable trend correlated with dissolution	Erratic variation	Precipitation or concentration effects
Settling / Recalque (mm)	Settlement plates	Monthly	Gradual, predictable compaction	Accelerated settlement	Structural instability or internal void formation
Metal Grade in Raffinate	Laboratory assay	Weekly	Stable composition	Unexpected impurity accumulation	Downstream recycle imbalance

Stability must be demonstrated, not inferred from early trends.

Long-term operation transforms pilot heaps into realistic reactors. Time reveals cumulative effects that short campaigns conceal.

Projects that shorten pilot duration reduce cost. They also increase uncertainty.

The next section examines how pilot leach data must be integrated into downstream processing to validate full-flow sheet performance.

XI. Downstream Integration and Process Intensification

Pilot heaps generate a solution. They do not generate product. Validation must therefore extend beyond leaching performance.

Downstream integration determines whether extracted metals can be recovered efficiently and economically. Omitting this step results in incomplete feasibility assessments.

11.1 Integration with Recovery Circuits

The pilot leach solution should be used to conduct recovery tests under realistic conditions. These include: Solvent extraction (SX); Precipitation routes; Impurity removal steps; Recycle simulations

PLS composition in pilot heaps evolves. Metal concentration, iron loading, magnesium buildup, and the presence of silica affect phase separation and reagent consumption.

Failure to test PLS under representative impurity levels is a common oversight. Selective extraction performance may decline when ionic strength increases.

Critical error:

Validating leaching without validating PLS treatability.

Table 9 summarizes key PLS parameters influencing downstream recovery performance.

Table 9. Influence of PLS composition on solvent extraction and precipitation performance. Adapted from O’Sullivan & Williams, 2024; Caetano et al., 2025

PLS Parameter	Typical Range in Pilot PLS	Impact on Solvent Extraction (SX)	Impact on Precipitation / Downstream Recovery	Operational Risk	Engineering Control Strategy
Ni Concentration (g/L)	1–10 (laterites)	Higher loading improves SX efficiency and phase continuity	Higher Ni tenor improves precipitation selectivity	Low tenor increases O/A ratio and solvent inventory	Adjust irrigation intensity and recycle to stabilize tenor
Co Concentration (mg/L–g/L)	0.05–1	May co-extract depending on extractant selectivity	Affects downstream Co recovery route	Impurity carryover into Ni circuit	Selective stripping and staged extraction
Fe ³⁺ (g/L)	0.5–10	Causes third-phase formation and extractant degradation	Promotes jarosite/goethite precipitation	Organic phase contamination	Pre-reduction (Fe ³⁺ →Fe ²⁺) or iron removal stage
Fe ²⁺ /Fe ³⁺ Ratio	Variable	Influences redox behavior and phase stability	Controls secondary precipitation kinetics	Instability in SX if the redox fluctuates	Redox monitoring and aeration control
Mg (g/L)	5–40 (laterites)	Increases ionic strength; limited extraction but affects phase disengagement	Raises neutralization demand in precipitation	High lime/neutralizer consumption	Partial bleed or selective impurity removal
Al (g/L)	0.5–5	Competes in some extractant systems	Forms Al-hydroxides during neutralization	Scaling and sludge generation	Controlled pH adjustment before SX
Si (mg/L–g/L)	0.05–1	Emulsion risk in SX	Silica gel formation in precipitation	Fouling and poor solid-liquid separation	Clarification and anti-scaling measures
Free Acid (g/L H ₂ SO ₄)	5–50	Affects the distribution coefficient and phase ratio	Controls pH window for precipitation	Over-acidic raffinate reduces precipitation efficiency	Tight acid balance control
Chloride (if present)	<1–10 g/L	Alters the extraction chemistry and corrosion risk	Influences precipitate morphology	Materials compatibility issues	Alloy selection and chloride monitoring
Suspended Solids (mg/L)	Variable	Causes crud formation	Impacts precipitation purity	Organic losses and filtration issues	Efficient clarification before SX

Temperature (°C)	20–50	Affects kinetics and phase separation	Influences precipitation rate and crystal growth	Instability at low temperature	Thermal management of PLS circuit
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Recovery efficiency depends not only on metal grade but also on impurity balance and solution chemistry.

11.2 Recycle Simulation

Recycling alters system chemistry. Acid strength, redox potential, and impurity accumulation shift over time.

Pilot programs must simulate closed-loop operation. Fresh-acid-only testing does not reflect industrial reality.

Figure 20 presents an integrated pilot configuration that links heap leaching, metal recovery, and solution recycling.

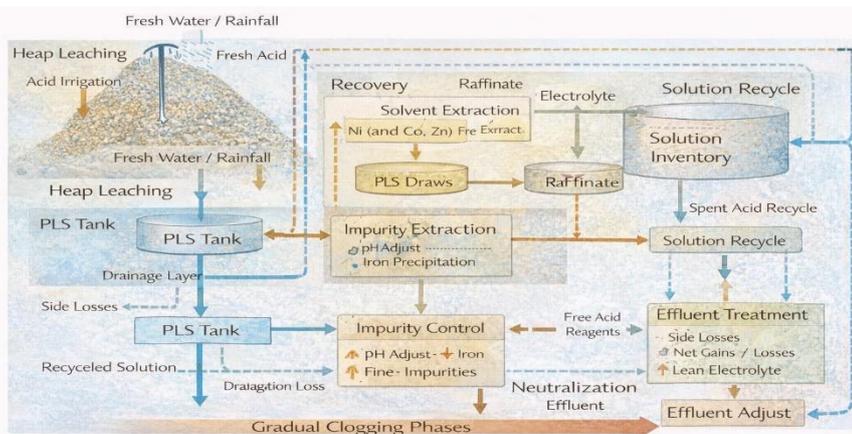


Figure 20. Integrated pilot flowsheet including leaching, recovery, impurity control, and solution recycle. Adapted from O’Sullivan & Williams, 2024.

Closed-loop evaluation reveals cumulative effects not visible in open systems.

11.3 Process Intensification and Innovation

Emerging technologies aim to reduce waste and increase resource efficiency. Process intensification strategies include selective precipitation, by-product recovery, and valorization of gangue minerals.

Valorization of mine waste and tailings offers new integration pathways (Stander, 2023). Artificial laterite formation from ultramafic leachates offers an alternative method for metal enrichment (Wang et al., 2025). Nickel leaching innovations aim to reduce waste and enhance sustainability (O’Sullivan & Williams, 2024). Early-stage strategic processing routes for laterites emphasize the integration of flowsheets (Caetano et al., 2025).

Figure 21 illustrates selected intensification and valorization pathways integrated with pilot leach operations.

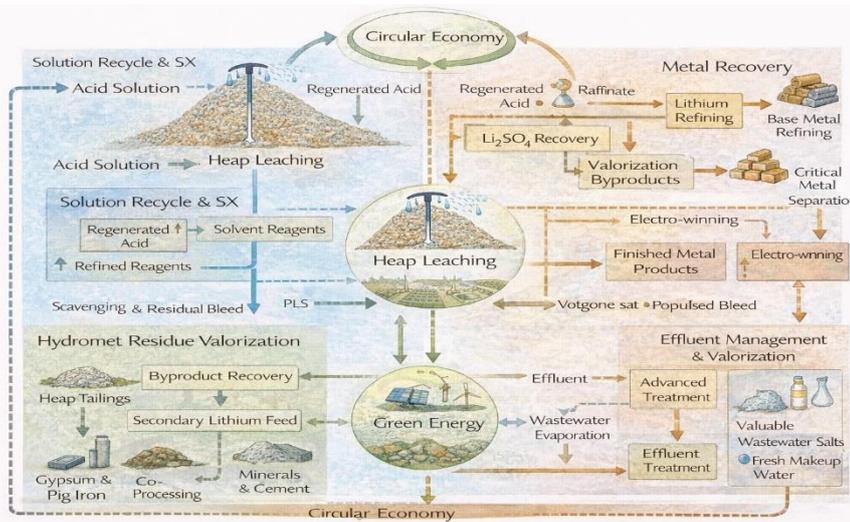


Figure 21. Emerging process integration and valorization routes linked to pilot heap leaching. Adapted from Stander, 2023; Wang et al., 2025.

Innovation requires compatibility with leach chemistry. Downstream constraints often limit implementation.

Pilot heaps must be evaluated as part of a complete flowsheet. Metal extraction without downstream validation creates false confidence.

Integrated testing reduces technical and economic uncertainty.

The next section addresses environmental and safety considerations associated with pilot heap operation and scale-up.

XII. Sustainability, Environmental, and Safety Considerations

Heap leaching is often presented as a lower-capex alternative. This does not automatically translate into lower environmental impact. Sustainability must be evaluated across reagent use,

waste generation, water balance, and long-term stability.

12.1 Low-Residue Production and Life Cycle Perspective

Low-residue production is increasingly required for battery-grade nickel supply chains. Near-zero waste production remains technically challenging in base metal systems (Reijnders, 2022). Improvements in process granularity and life cycle inventory quality highlight the sensitivity of impact indicators to acid consumption and energy intensity (Roy et al., 2025).

Systematic reviews of heap leaching operations show that operational variables strongly influence environmental footprint (León et al., 2025). Acid efficiency, water recycle, and impurity control affect both emissions and downstream waste streams.

Table 10 summarizes key sustainability drivers associated with pilot heap operation.

Table 10. Sustainability drivers and environmental risk factors in pilot heap leaching. Adapted from Reijnders, 2022; Roy et al., 2025; León et al., 2025

Sustainability Dimension	Key Driver	Environmental Risk Factor	Monitoring Indicator	Engineering Mitigation Strategy	Long-Term Implication
Acid Efficiency	Minimize acid consumption per tonne	Excess neutralization	kg H ₂ SO ₄ / t ore	Optimized irrigation rate;	Lower OPEX and reduced

		reactions (Mg, Al dissolution)		staged acid dosing	sulfate discharge
Water Use	Closed-loop recycle	Solution inventory accumulation; overtopping risk	Water balance closure (%)	Real-time inventory control; evaporation ponds	Improved water footprint performance
Residue Stability	Reduced secondary waste generation	Precipitation of unstable phases (jarosite, gypsum scaling)	Solid phase characterization	Controlled pH window; periodic permeability testing	Enhanced geochemical stability of spent heap
Energy Consumption	Low pumping and circulation demand	Over-irrigation increases pumping energy	kWh / m ³ circulated	Irrigation optimization; variable frequency drives	Reduced indirect carbon footprint
Metal Recovery Efficiency	Maximize Ni/Co recovery	Diminishing returns at high acid input	Recovery vs acid input curve	Dynamic acid optimization	Higher resource efficiency
Air Emissions	Control acid mist and vapors	H ₂ SO ₄ aerosols; HCl vapors (if chloride present)	Air quality monitoring	Covered irrigation; vapor suppression	Improved worker safety and compliance
Solution Containment	Prevent seepage and leakage	Liner failure; drainage clogging	Leak detection system	Double-liner systems; drainage redundancy	Reduced groundwater contamination risk
Slope Stability	Maintain structural integrity	Pore pressure buildup due to clogging	Piezometer readings; settlement plates	Controlled heap height; drainage design	Lower geotechnical failure probability
Climate Sensitivity	Adaptation to rainfall and evaporation	Dilution or concentration spikes	Acid concentration variability	Seasonal operational adjustment	Operational resilience
Byproduct Valorization	Secondary metal or salt recovery	Impurity accumulation in recycle	Impurity concentration trend	Bleed stream control; impurity extraction	Circular economy alignment
Regulatory Compliance	Alignment with environmental permits	Exceedance of discharge thresholds	Effluent chemistry	Integrated effluent treatment	Reduced permitting risk

The table shows that acid efficiency and solution management dominate life cycle sensitivity.

Figure 22 presents a conceptual breakdown of the environmental impacts of heap-based nickel production.

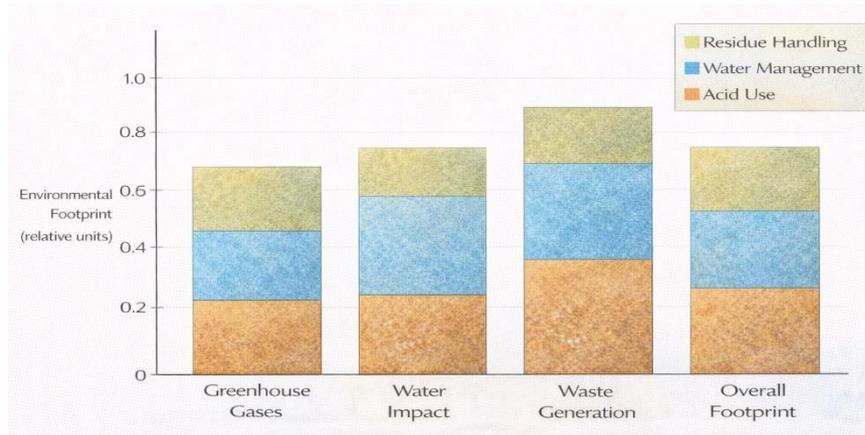


Figure 22. Conceptual contribution of acid use, water management, and residue handling to overall environmental footprint. Adapted from Roy et al., 2025.

Acid consumption remains a primary driver of environmental intensity.

12.2 Environmental Control and Containment

Pilot heaps must incorporate full solution containment systems. Liner integrity and underdrain performance are essential. Leakage during pilot testing can distort both environmental compliance and water balance calculations.

Drainage control prevents pore pressure buildup and slope instability. Poor drainage increases hydraulic head and the risk of failure.

Vapor monitoring is required when evaluating chloride systems. HCl volatilization may occur under certain conditions. Pilot testing must quantify emissions under realistic climatic exposure.

Geotechnical stability must be continuously assessed. Structural failure during pilot operation undermines both safety and data reliability.

Figure 23 outlines the environmental control components required in pilot heap operation.

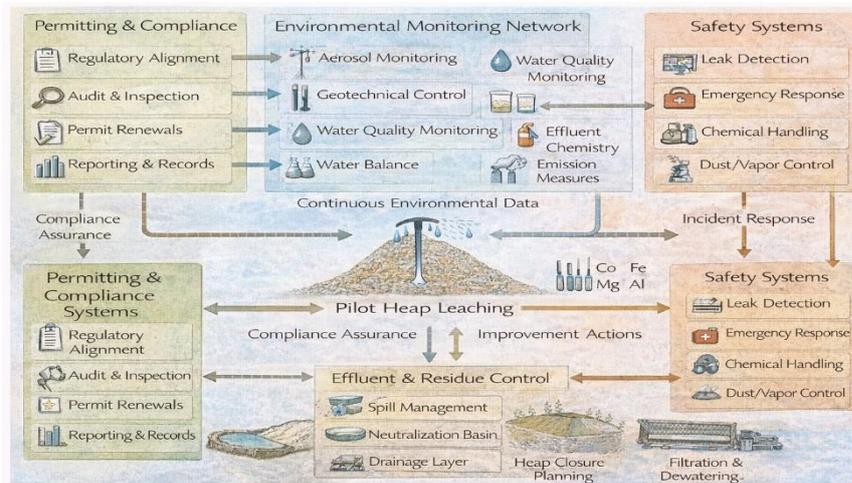


Figure 23. Environmental and safety control framework for pilot heap leaching systems. Adapted from León et al., 2025.

Environmental safeguards must be embedded in pilot design, not added after performance validation. Sustainability evaluation must be integrated from the pilot stage. Environmental controls influence hydraulic behavior, water balance, and acid management. Pilot

heaps that ignore containment, drainage, and vapor monitoring generate incomplete technical assessments.

The next section synthesizes common pilot plant failures and identifies recurring design blind spots.

XIII. Engineering Framework Proposal and Common Pilot Plant Failures

Pilot heaps fail for predictable reasons. The causes are technical, not random. Recurrent errors arise from oversimplified design and incomplete integration.

An engineering framework must combine geometallurgical characterization, reactive transport modeling, and staged validation. Heap behavior cannot be extrapolated from extraction curves alone.

13.1 Integrated Engineering Framework

Geometallurgy defines mineral distribution and acid demand variability. Reactive transport Table 11. Recurring pilot plant design failures and associated technical consequences. Adapted from Osten & Harrison, 2023; Winarko et al., 2023.

Error	Consequence
Scale too small	Underestimates heterogeneity
Short duration	Overestimates recovery
Lack of instrumentation	Incorrect interpretation
No recycle simulation	Acid balance error
Simplified irrigation	Undetected channeling

Small-scale pilots suppress hydraulic variability. Short campaigns conceal late-stage kinetics. Poor instrumentation limits diagnosis. Fresh-acid testing distorts reagent projections. Simplified irrigation masks preferential flow.

These failures are cumulative. One design weakness amplifies another.

Pilot heaps should function as dynamic reactors. Without integration of modeling, monitoring, and recycle simulation, scale-up risk remains high.

Engineering discipline, not metallurgical optimism, determines reliability.

The following section examines persistent data gaps in the literature and identifies research priorities for future pilot design.

XIV. Data Gaps in the Literature

Figure 24 illustrates the typical duration of laboratory, pilot, and industrial studies reported in the literature.

modeling links dissolution, precipitation, and flow evolution (Kumara, 2020; Winarko et al., 2023).

Recent studies emphasize scale-aware modeling and kinetic extrapolation (Preece et al., 2023; Osten & Harrison, 2023). Coupled hydro-geochemical simulation provides more realistic predictions than isolated rate constants (Lakshmanan et al., n.d.).

13.2 Common Pilot Plant Failures

Most pilot shortcomings follow identifiable patterns.

Table 11 summarizes common pilot plant errors and their consequences.

Despite extensive literature on heap leaching, critical gaps remain. Many publications focus on laboratory columns or short pilot campaigns. Few provide long-term, instrumented pilot datasets.

14.1 Limited Long-Term Pilot Data

Campaigns longer than 12 months are rarely reported in detail. Kinetic stabilization, permeability decline, and late-stage acid consumption are therefore poorly documented. Some pilot-scale demonstrations exist (Agatzini-Leonardou et al., 2021; Oxley et al., 2025), yet most reports emphasize recovery rather than hydraulic evolution.

Bioheap studies also highlight scale challenges, but long-duration hydraulic datasets remain limited (Jia et al., 2024; Gericke et al., 2022).

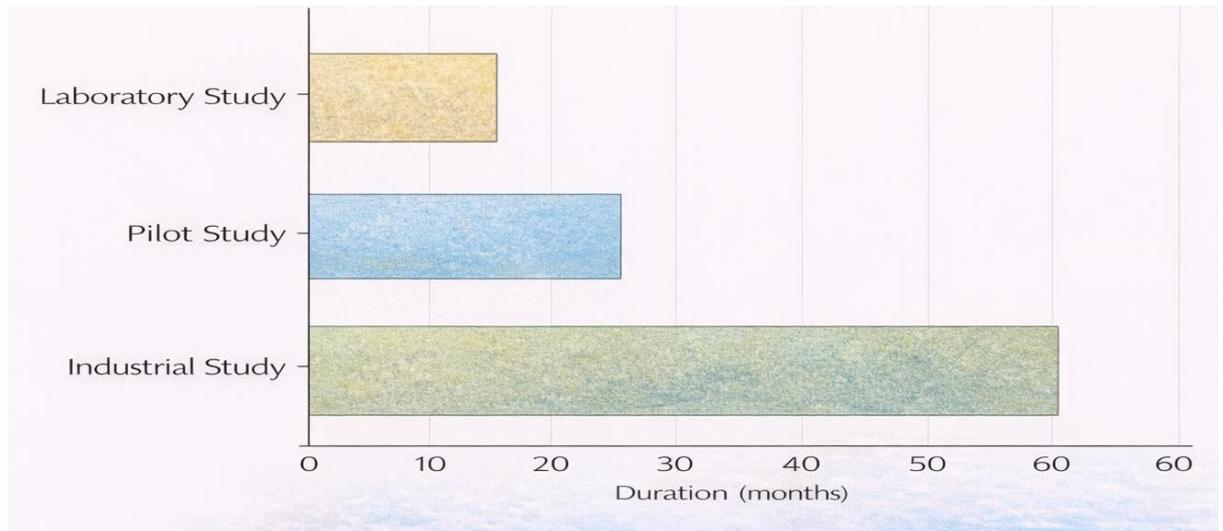


Figure 24. Comparative duration of column, pilot, and industrial heap leaching studies based on published reports. Adapted from Agatzini-Leonardou et al., 2021; Jia et al., 2024; Oxley et al., 2025.

The imbalance toward short-duration tests limits predictive confidence for late-stage behavior.

14.2 Insufficient Instrumentation Reporting

Many studies do not report internal pressure profiles, moisture gradients, or settlement data. Hydraulic diagnostics are often absent.

Geotechnical analyses emphasize the importance of interface shear strength and pad stability (Bar & Teleu, 2023; Zúñiga & León, 2024). However, these are rarely integrated with metallurgical monitoring.

Remote sensing approaches are emerging (Szakolczai et al., n.d.), but validation at the pilot scale remains scarce.

Table 12 summarizes commonly reported versus rarely reported pilot parameters.

Table 12. Frequency of reported pilot monitoring variables in the literature. Adapted from Bar & Teleu, 2023; Zúñiga & León, 2024; Szakolczai et al., n.d.

Discipline	Primary Objective	Key Performance Indicators (KPIs)	Measurement Tools	Validation Timeframe	Failure Signal	Decision Impact
Metallurgy	Demonstrate realistic metal recovery	Ni recovery (%), Co recovery (%), extraction rate (kg/m ² ·day)	PLS assays, cumulative mass balance	≥180 days	Early plateau or unstable recovery trend	Redesign ore preparation or irrigation
Hydraulics	Maintain stable percolation	Flow rate stability, ΔP profile, permeability index	Flowmeters, pressure sensors	Continuous	Rising ΔP, channelization evidence	Adjust irrigation or heap geometry
Geochemistry	Control precipitation and acid balance	Fe ³⁺ concentration, Fe ²⁺ /Fe ³⁺ ratio, pH,	In-line probes, laboratory assays	Weekly / Continuous	Precipitation front migration	Modify acid dosing strategy

		sulfate balance				
Geotechnical	Ensure structural stability	Settlement (mm), pore pressure, slope factor of safety	Settlement plates, piezometers	Monthly	Accelerated settlement or pore pressure spike	Reduce heap height or improve drainage
Environmental	Minimize environmental footprint	Acid losses (kg/t), water balance closure (%), effluent chemistry	Water balance models, effluent sampling	Monthly	Water imbalance, discharge exceedance	Redesign recycle or containment
Safety	Prevent chemical exposure and instability	Acid mist levels, leak detection events	Air monitors, liner sensors	Continuous	Leak detection alarm or aerosol increase	Immediate corrective action
Process Integration	Validate downstream treatability	SX efficiency (%), impurity carryover, raffinate quality	SX pilot tests, impurity assays	Campaign-based	Third phase formation, impurity buildup	Adjust impurity control stage
Economic	Confirm cost projections	Acid consumption (kg/t), water usage (m ³ /t), energy (kWh/t)	Cost tracking model	End of pilot	Rising variable cost without recovery gain	Re-evaluate economic viability
Sustainability	Align with ESG targets	CO ₂ intensity proxy, waste generation rate	LCA screening model	End of pilot cycle	High residue intensity	Redesign residue management
Data & Modeling	Validate predictive model	Model deviation (%), permeability evolution fit	Reactive transport modeling	Iterative	Poor model fit	

The lack of hydro-mechanical data prevents robust model calibration.

14.3 Lack of Integrated Model Validation

Reactive transport models are increasingly applied (Winarko et al., 2023; Osten & Harrison, 2023). Geometallurgical modeling frameworks exist (Kumara, 2020; Preece et al., 2023).

However, few studies validate coupled hydro-geochemical models against instrumented pilot heaps. Model assumptions are rarely stress-tested under real heterogeneity.

Without pilot-calibrated validation, scale-up remains empirical.

14.4 Limited Quantitative Column → Pilot → Industrial Comparisons

Direct comparisons across scales are uncommon. Recovery trends are often reported, but permeability evolution and deviations in acid balance are rarely quantified simultaneously.

Recent reviews highlight operational variables and sustainability metrics (León et al., 2025; Petersen & van Staden, 2025). Yet

quantitative scale transition factors remain underdeveloped.

Figure 25 conceptualizes the amplification of uncertainty during the scale transition.

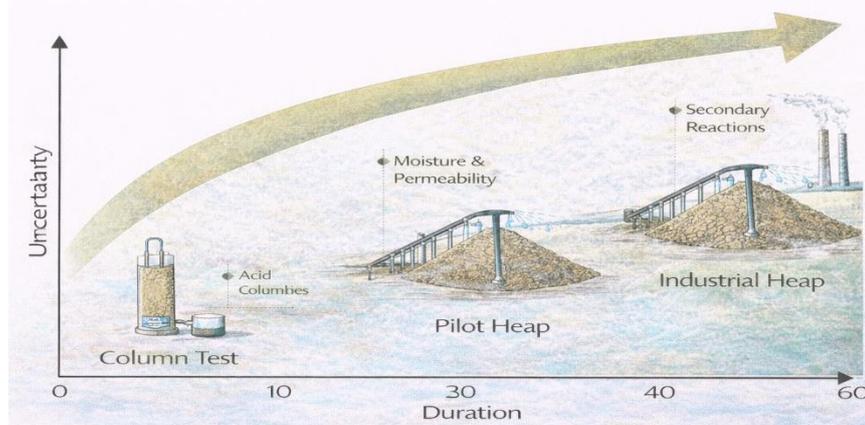


Figure 25. Amplification of uncertainty from column tests to pilot and industrial heaps due to hydraulic and geochemical complexity. Adapted from Winarko et al., 2023; Petersen & van Staden, 2025.

The absence of structured cross-scale datasets is a major blind spot.

The literature is rich in kinetic data. It is weaker in hydraulic diagnostics. It is fragmented into integrated validation.

Long-duration, instrumented pilots with transparent data reporting remain rare. This limits reproducibility and engineering reliability.

The next section proposes a structured best-practice design framework to address these deficiencies and reduce the risk of scale-up.

XV. Proposed Best-Practice Design Framework

Pilot heaps require structure. Not expansion of column tests, but staged engineering validation.

Table 13 presents a structured objective-definition matrix for the pilot heap design.

Table 13. Multidisciplinary objective matrix for pilot heap validation. Adapted from Petersen & van Staden, 2025; León et al., 2025

Dimension	Primary Objective	Key Questions	Typical Indicators	Risk if Not Addressed
Metallurgical	Validate realistic metal recovery	Does recovery reflect semi-industrial kinetics?	Ni recovery (%), Co recovery (%), extraction curve shape, lag phase duration	Overestimation of ultimate recovery
Hydraulic	Ensure representative	Is the flow uniform at scale?	Irrigation rate (L/m ² ·h), ΔP profile,	Undetected channeling;

This section proposes a practical framework derived from recurring technical gaps and documented failure modes.

Step 1 – Definition of Objectives

Objectives should be clear and multidimensional, covering Metallurgical aspects (such as realistic recovery and reagent demand), Hydraulic factors (including percolation stability and permeability changes), and Economic considerations (like acid cost, water balance, and solution management).

Pilot programs often prioritize extraction. Hydraulic validation is neglected.

	percolation behavior		moisture distribution, tracer dispersion	suppressed heterogeneity
Geochemical	Monitor solution chemistry evolution	Are secondary phases forming?	pH, Eh, Fe ²⁺ /Fe ³⁺ ratio, Mg, Al, Si trends	Precipitation fronts; permeability loss
Geotechnical	Confirm structural stability	Does settlement affect flow paths?	Bulk density variation, settlement rate, slope deformation	Stability failure; altered hydraulic regime
Operational	Reproduce industrial operating mode	Is irrigation and recycling realistic?	On/off irrigation cycles, solution inventory, recycle ratio	Misleading acid balance; unrealistic consumption
Economic	Estimate reagent and infrastructure costs	Is acid consumption scalable?	kg H ₂ SO ₄ /t ore, solution inventory, pumping energy	Underestimated OPEX
Environmental	Evaluate containment and water balance	Is water retention quantified?	Solution retention (%), evaporation rate, drainage chemistry	Unclosed mass balance; environmental risk
Downstream Integration	Validate PLS treatability	Is impurity profile compatible with SX/precipitation?	Ni tenor (g/L), Fe load, impurity ratios	Recovery circuit mismatch
Modeling & Scale-Up	Support predictive simulation	Can pilot data calibrate reactive transport models?	Fitted kinetic constants, hydraulic conductivity evolution	Poor extrapolation to industrial heap

Clear objectives prevent scope drift and unrealistic extrapolation.

Step 2 – Minimum Representative Scale

Minimum geometric thresholds are required:

- Height ≥ 3–6 m
- Sufficient footprint to reduce edge effects
- Volume enabling compaction and flow redistribution

Small pilots suppress heterogeneity. They overestimate hydraulic uniformity.

Figure 26 illustrates the relationship between heap height and the development of hydraulic and chemical gradients.

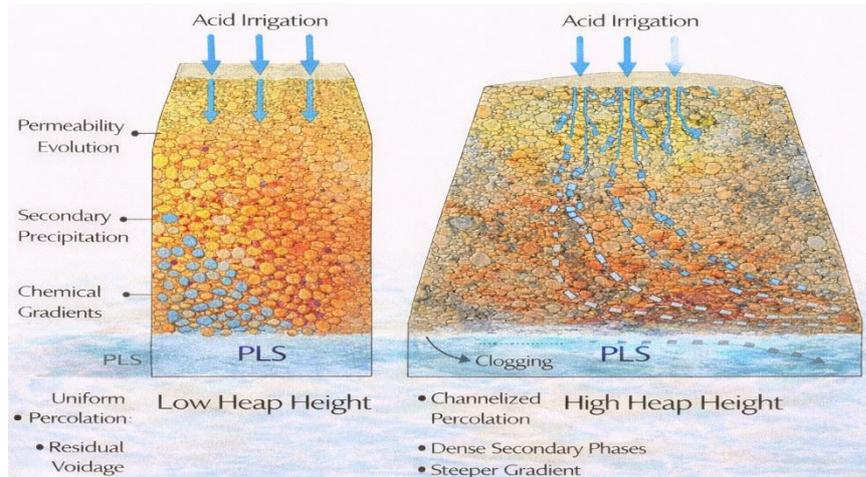


Figure 26. Effect of heap height on the evolution of permeability and the formation of chemical gradients. Adapted from Pourverdi et al., 2025; Abbasi et al., 2020.

Below the critical height, gradients do not fully develop.

Step 3 – Complete Instrumentation

Instrumentation must include: ΔP sensors, moisture probes, flow meters, settlement monitoring, and tracer testing

Without this, interpretation remains speculative.

Step 4 – Long-Term Operation

Duration should exceed 180 days. Preferably, a full leaching cycle.

Short campaigns mask: Late-stage kinetics, progressive clogging, and acid retention.

Step 5 – Integrated Modeling

Modeling must combine: Geometallurgy, reactive transport, acid balance, and hydraulic calibration.

Model validation should rely on instrumented pilot data, not only extraction curves.

Economic Considerations

Pilot design influences cost accuracy. Acid consumption, irrigation rates, and solution recycle strongly affect OPEX.

Statistical cost estimation approaches for heap pads provide early capital guidance (Sánchez et al., 2022). Case studies show reagent consumption can dominate operating cost projections (Nagar, 2021).

Failure to close water and acid balances distorts feasibility studies.

Blind Spots and Failure Mechanisms

Industrial case discussions reveal common blind spots. Overconfidence in early recoveries has led to underdesigned pads (Washbourne, 2023).

Hydro-mechanical instability can escalate rapidly when drainage and compaction are mischaracterized (Pourverdi et al., 2025). Operational modifications, such as hydraulic interventions, may compromise pad integrity if not properly engineered (Abbasi et al., 2020).

Table 14 summarizes representative industrial warning cases and associated engineering lessons. Table 14. Industrial warning cases highlighting pilot-scale blind spots (adapted from Washbourne, 2023; Pourverdi et al., 2025; Abbasi et al., 2020).

Industrial Context	Pilot-Scale Blind Spot	Observed Consequence at Scale	Engineering Lesson
Rapid production ramp-up	Insufficient pilot duration	Late-stage permeability collapse	Operate the pilot through the full leach cycle

Pad modification during operation (e.g., hydraulic intervention)	No simulation of operational disturbance	Localized instability and flow redistribution	Include operational stress scenarios in pilot
High irrigation rates to accelerate recovery	No ΔP monitoring	Channeling and uneven saturation	Monitor hydraulic gradients continuously
Aggressive acid addition strategy	Acid balance is not rigorously closed	Secondary precipitation and clogging	Perform a cumulative acid mass balance
Underestimated self-weight compaction	Manual stacking in pilot	Settlement and drainage impairment	Replicate the industrial stacking method
Drainage underdesign	Limited drainage testing	Solution ponding and slope stress increase	Design conservative drainage capacity
Edge-dominated pilot geometry	No representative footprint	Artificial hydraulic uniformity	Ensure a minimum representative area

Industrial failures are rarely caused by unexpected chemistry. They stem from unvalidated hydraulic and mechanical assumptions at the pilot scale. These warning cases underscore the need for integrated monitoring, realistic geometry, and long-duration validation before industrial implementation. A best-practice pilot is defined not by size alone but by integration, depth of monitoring, and duration. When these elements are absent, scale-up risk increases nonlinearly.

The following section concludes the review and synthesizes the key engineering implications for industrial nickel heap-leaching development.

XVI. Conclusion

Heap-leach pilot plants occupy a pivotal position between laboratory testing and industrial implementation. However, they are often designed as enlarged columns. This reductionist approach ignores hydraulic heterogeneity, permeability evolution, geochemical feedback, and mechanical behavior under load.

The literature demonstrates strong advances in nickel hydrometallurgy (Caetano et al., 2025; Pandey et al., 2023; Stanković et al., 2020). It also shows progress in modeling and scale-up methodologies (Winarko et al., 2023; Osten & Harrison, 2023). However, integration between geometallurgy, hydro-mechanics, and long-term pilot validation remains limited.

Three key structural weaknesses recur: lack of sufficient scale to replicate real gradients, brief operational duration, and limited instrumentation,

along with incomplete acid/water balances. These issues distort the interpretation of kinetics and economic forecasts.

Pilot heaps must be treated as dynamic hydro-geochemical reactors.

They require: minimum representative geometry, comprehensive hydraulic and geochemical monitoring, long-term operation, integrated modeling calibrated with field data, closed acid and water balances, and downstream validation of PLS treatability.

Economic and sustainability considerations reinforce this need. Acid consumption and solution management influence life-cycle performance (Roy et al., 2025; León et al., 2025). Poorly designed pilots propagate uncertainty into capital allocation and environmental risk.

The central thesis of this review is therefore direct:

A pilot heap that does not reproduce hydraulic, chemical, and operational complexity cannot be used as a reliable scale-up platform.

Future research should focus on several key areas: collecting long-duration (>12 months) instrumented pilot datasets, ensuring transparent reporting of hydro-mechanical parameters, developing validated reactive transport models, and conducting quantitative comparisons across scales (column to pilot to industrial).

Reducing scale-up uncertainty is not primarily a metallurgical challenge. It is an engineering systems challenge.

Industrial reliability depends on recognizing that distinction.

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Conflicts of Interest

The author declares no conflict of interest.

Author Contributions

The author solely conceived, structured, analyzed, and wrote this review.

Data Availability

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