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Do Tall Columns Truly Represent Industrial Heaps? A Critical Review of Nickel Heap Leach Testwork

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ABSTRACT: Tall column tests are widely used as an intermediate step between laboratory-scale experiments and industrial heap leaching, aiming to improve the reliability of scale-up predictions by capturing hydro-mechanical and geochemical processes under more representative conditions. However, their predictive value remains inherently limited. This review critically evaluates the extent to which tall columns (2–6 m) reproduce key mechanisms governing industrial heap performance, including progressive compaction, unsaturated flow, preferential pathways, and coupled transport–reaction phenomena. Evidence shows that while tall columns can partially capture vertical chemical gradients, permeability evolution, and delayed reagent consumption, they still fail to represent large-scale heterogeneity, long flow paths, and structural evolution typical of industrial heaps. As a result, the observed extraction kinetics reflect system-dependent effective rates rather than intrinsic reaction kinetics, and direct extrapolation to recovery, hydraulic stability, or long-term performance is unreliable. The analysis also identifies systematic limitations in experimental design, including insufficient column diameter, limited instrumentation, and short test durations, which further constrain data interpretation. A scale-aware framework is proposed that integrates mineralogical characterization, staged testing (from bottle roll to pilot), and coupled hydro-geochemical modeling to improve decision-making and reduce scale-up risk. Tall column tests are therefore best interpreted as diagnostic tools for mechanistic understanding and trend identification, rather than standalone predictors of industrial heap leaching performance.

KEYWORDS: Heap leaching, Hydro-geochemical coupling, Mass transfer, Nickel laterite, Tall column tests, Scale-up.

Highlights

✓ Tall columns capture hydro-geochemical gradients but remain scale-limited.
✓ Observed kinetics reflect transport-coupled behavior, not intrinsic rates.
✓ Structural heterogeneity and channeling are not fully reproduced.
✓ Reliable scale-up requires integrated testing and coupled modeling.

Graphical abstract

1. INTRODUCTION

Heap leaching is a mature, large-scale processing route for low-grade ores, typically involving heap heights of 5–30 m, irrigation rates of 5–15 $L \cdot m^{-2} \cdot h^{-1}$, and operational cycles ranging from 120 to 400 days depending on ore characteristics. Its economic attractiveness stems from lower capital costs, often 40–70% lower than alternative routes, albeit at the expense of longer residence times and a strong dependence on coupled transport phenomena and structural evolution within the heap. Consequently, reliable process design requires experimental methodologies that capture the key mechanisms governing fluid flow, reaction kinetics, and permeability evolution.

Experimental evaluation follows a hierarchical framework. Bottle roll tests estimate intrinsic kinetics under fully mixed conditions, typically using fine particles (<150 µm), high liquid-to-solid ratios (>5:1), and short durations (<48 h). Short-column tests (0.1–0.3 m) introduce percolation and allow preliminary assessment of hydraulic behavior and reagent consumption. Tall columns (2–6 m, 90–300 days) partially reproduce gravity-driven flow and chemical gradients, while pilot heaps (>6 m) and full industrial heaps incorporate large-scale heterogeneity, environmental factors, and operational variability (Segura, 2026; Pereira, 2026e; Jia et al., 2024).

Tall column tests are widely used because they capture key features absent in smaller-scale experiments, including compaction under self-weight, evolving permeability, and delayed geochemical processes. However, their predictive capability remains limited. Their geometry restricts the development of large-scale heterogeneity and complex flow networks typical of industrial heaps. In addition, stress conditions and test durations are generally insufficient to reproduce long-term structural evolution and late-stage kinetic limitations (van Staden & Petersen, 2021; Petersen & van Staden, 2025).

Kinetics from tall columns should be seen as effective, system-dependent parameters, not intrinsic rates. Extrapolating to industrial scale may overestimate recovery and underestimate risks, especially in lateritic nickel systems where mineralogy, pH, and redox sensitivity affect transport and precipitation (León et al., 2025; Pereira, 2026a).

Tall columns are diagnostic tools bridging lab observations and field performance, offering mechanistic insights when combined with testing and modeling. This review assesses how well tall-column tests reflect industrial heap behavior, with a focus on nickel laterite systems.

2. METHODOLOGY

This study critically reviews heap leaching methods, focusing on the link between experimental scale, transport processes, and kinetic interpretation. It follows the PRISMA 2020 principles, adapted for engineering systems in which physical representativeness and experimental design are key.

82 references were consolidated via a multi-stage process to ensure consistency between experimental scope and scale-up relevance. The methodology excludes studies lacking a hydraulic context or operational parameters, thereby addressing a common limitation in previous reviews.

2.1. Hierarchical Experimental Framework

Experimental methods were analyzed within a hierarchical scale framework that reflects the progressive increase in physical complexity and representativeness across testing approaches. At the smallest scale, bottle roll tests operate as well-mixed systems. They are used to estimate intrinsic kinetics under controlled conditions, typically involving fine particles, high liquid-to-solid ratios, and short durations. Short-column tests (0.1–0.3 m) introduce percolation, allowing preliminary evaluation of reagent consumption and flow behavior. Tall columns (2–6 m, typically operated over 90–300 days) further incorporate gravity-driven flow, compaction effects, and the partial development of vertical chemical gradients. At the largest scale, pilot and industrial heaps (>6 m) represent full system complexity, including structural heterogeneity, environmental variability, and long-term evolution.

This hierarchical framework avoids direct comparison across physically incompatible systems and ensures that each experimental method is interpreted within its appropriate domain of validity.

2.2. Selection and Data Consistency Criteria

Studies were included only when key experimental parameters were explicitly reported, ensuring consistency between data quality and interpretability. These parameters comprised well-defined system geometry (height, diameter, and H/D ratio), relevant hydraulic variables (such as irrigation rate and flow stability), controlled chemical conditions (including pH, Eh, or reagent concentration), and time-dependent performance data.

This selection criterion directly addresses a major limitation in the literature, where incomplete datasets are frequently used for kinetic interpretation, leading to ambiguous or non-transferable conclusions

2.3. Interpretation Strategy

Kinetic results were interpreted as scale-dependent effective parameters rather than intrinsic properties when derived from systems in which flow–transport coupling governs system behavior. Particular emphasis was placed on the interaction between reaction and transport processes, the evolution of permeability over time, and the role of precipitation and pore blocking in modifying fluid accessibility. In addition, scale-induced bias in both recovery and reagent consumption was critically evaluated.

Direct extrapolation from column-scale experiments to industrial heaps was avoided unless supported by demonstrable hydraulic and structural similarity, ensuring that interpretations remained consistent with the physical constraints of each system.

2.4. Methodological Scope and Limitations

Despite the structured selection, the dataset faces constraints such as variable experimental protocols, few long-term studies lasting 200–300 days, incomplete hydraulic data, and a lack of validated scale-up correlations. These constraints are considered in the analysis to prevent overinterpretation and to keep conclusions aligned with data quality and scope.

The literature review, conducted in accordance with PRISMA 2020 and adapted for engineering systems, follows a structured workflow (Figure 1) designed to ensure transparency and minimize selection bias. The analysis emphasizes hydraulic behavior, transport phenomena, and scale-up implications, thereby addressing key shortcomings commonly observed in reviews based on incomplete or non-representative datasets.

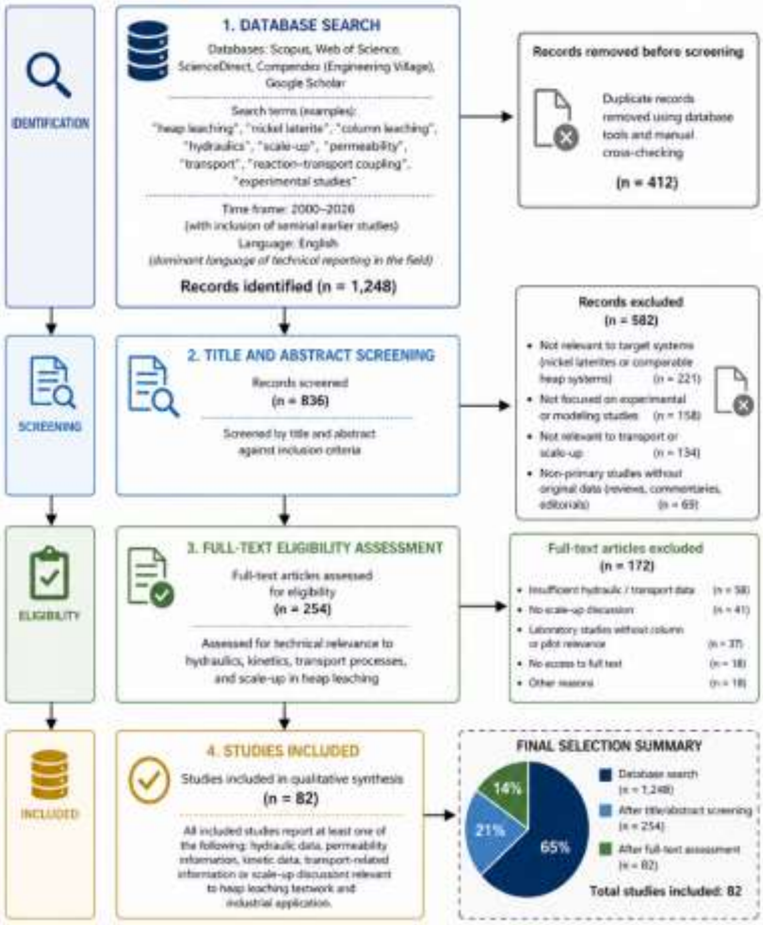


Figure 1. PRISMA-based selection workflow adapted for engineering review of heap leaching methodologies, including database search, screening, eligibility, and final inclusion of studies with hydraulic and scale-up relevance. Adapted from Page et al. (2021).

The selection workflow yielded a final dataset of 82 studies, representing a progressive refinement of an initial pool of 1,248 records. Exclusion at the screening stage was primarily driven by a lack of relevance to transport-controlled systems or by an absence of experimental or modeling rigor. At the full-text level, studies were further excluded when key variables—such as hydraulic conditions, permeability evolution, or time-dependent performance—were not reported.

This structured filtering ensures that the analysis is based on physically meaningful and scale-relevant data. Rather than emphasizing the volume of the literature, the methodology prioritizes consistency between experimental design and industrial applicability, enabling a critical assessment of how different testing approaches reflect real heap behavior.

3. DEFINING TALL COLUMNS: Geometry, Scale, and Representativeness

Tall column tests are defined by their ability to introduce gravity-driven flow and vertical gradients that are absent in short columns. In practice, these systems typically operate with heights of 2–6 m (occasionally up to 8–10 m) and diameters ranging from 0.1 to 0.5 m, resulting in height-to-diameter (H/D) ratios between approximately 5 and >20. These dimensions approach the lower bound of industrial heap heights (typically >10 m and up to 30 m), but remain strongly constrained in lateral scale (Agatzini-Leonardou et al., 2021; Komnitsas et al., 2023; Segura, 2026). However, height alone is not a sufficient criterion for representativeness.

A key geometric parameter is the height-to-diameter ratio (H/D), which governs the balance between vertical gradient development and wall confinement effects. While high H/D ratios promote the formation of vertical gradients, narrow diameters increase wall-confinement effects, where boundary friction alters stress distribution, porosity, and flow patterns. Experimental studies consistently indicate that diameters below 0.2–0.3 m are insufficient to suppress these effects, leading to artificially enhanced permeability (often by a factor of 2–10, depending on fines content and compaction) and non-representative flow regimes (Arellano et al., 2022; Larrabure et al., 2024).

Granulometry and fines content are equally critical. Representative tests typically use top particle sizes of 10–25 mm, with fines fractions of 5–20 wt% below 1 mm. Simplified or truncated size distributions can significantly overestimate permeability, suppress fines migration, and reduce the likelihood of preferential flow and pore clogging, particularly in systems prone to precipitation and structural evolution (Larrabure et al., 2025; Pereira, 2026e).

Test duration in tall columns generally ranges from 90 to 300 days, enabling observation of slower processes such as secondary mineral precipitation and permeability decline. Even extended tests do not fully capture long-term behavior observed in industrial heaps, where leaching cycles commonly extend beyond 200–400 days and may reach several years (Segura, 2026; Komnitsas et al., 2023).

Despite these improvements, representativeness remains fundamentally constrained by ore mass. Tall columns typically process 10^2–10^3 kg of ore, whereas industrial heaps involve 10^5–10^7 tonnes, corresponding to differences of 3–5 orders of magnitude. This scale gap limits the development of large-scale heterogeneity and preferential flow networks, resulting in more uniform flow paths than those observed in field conditions (Larrabure et al., 2024; Segura, 2026).

The scale gap between experimental systems and industrial heaps can be quantified by comparing key geometric and operational parameters across testing methodologies, as summarized in Table 1.

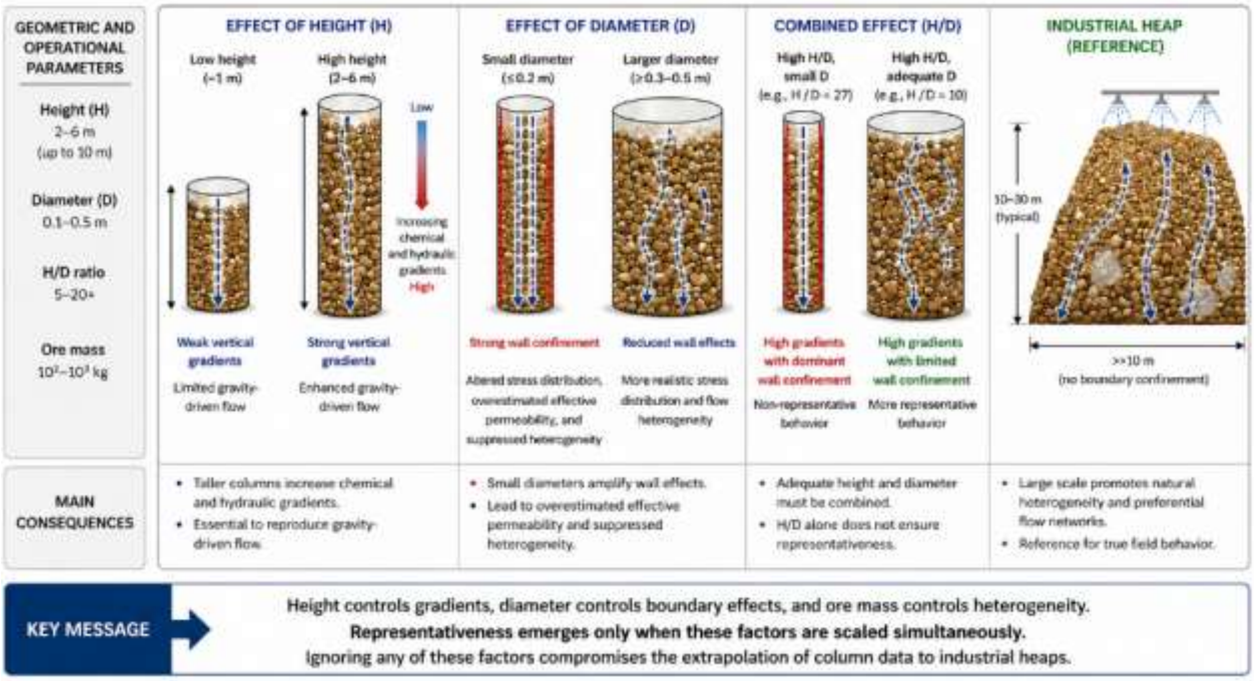
Table 1. Key parameters controlling representativeness in tall column tests and their typical Key parameters controlling representativeness in tall column tests and their typical

Parameter	Typical Range (Tall Columns)	Industrial Heaps	Main Effect on Representativeness
Height	2–6 m (up to 10 m)	10–30 m	Controls vertical gradients
Diameter	0.1–0.5 m	Large-scale (no confinement)	Governs wall effects and flow uniformity
H/D ratio	5–20+	Variable	Controls trade-off between gradients and confinement
Particle size (top)	10–25 mm	10–50 mm	Affects permeability and flow distribution

Fines content	5–20 wt% (<1 mm)	Highly variable	Controls clogging and preferential flow
Duration	90–300 days	200–400+ days (or longer)	Captures slow processes
Ore mass	10^2–10^3 kg	10^5–10^7 tonnes	Controls heterogeneity and scale effects

Table 1 quantifies the scale gap between test methods and industrial heaps. Despite improvements over smaller tests, tall columns remain several orders of magnitude smaller, limiting heterogeneity and preferential flow development.

The influence of column geometry on representativeness can be conceptually understood by separating the effects of height and diameter. While increasing column height enhances vertical chemical and hydraulic gradients, diameter controls the extent of boundary confinement and the development of realistic flow patterns. These factors are not independent: high height-to-diameter (H/D) ratios may improve gradient formation but can simultaneously amplify wall effects if the column diameter is insufficient. As a result, representativeness cannot be achieved by scaling a single parameter in isolation; rather, it emerges from the combined scaling of height, diameter, and ore mass, as illustrated in Figure 2.



- Taller columns increase chemical and hydraulic gradients.
- Essential to reproduce gravity-driven flow.

- Small diameters amplify wall effects.
- Lead to overestimated effective permeability and suppressed heterogeneity.

- Adequate height and diameter must be combined.
- H/D alone does not ensure representativeness.

- Large scale promotes natural heterogeneity and preferential flow networks.
- Reference for true field behavior.

Height controls gradients, diameter controls boundary effects, and ore mass controls heterogeneity.
Representativeness emerges only when these factors are scaled simultaneously.
Ignoring any of these factors compromises the extrapolation of column data to industrial heaps.

Figure 2. Column geometry versus representativeness in heap leaching testwork. Height controls gradients, diameter controls confinement, and ore mass controls heterogeneity. Adapted from Arellano et al. (2022), Larrabure et al. (2024), and Segura (2026).

Figure 2 shows that column height alone is insufficient to ensure representative behavior. While increased height enhances vertical gradients and gravity-driven flow, small diameters impose boundary constraints that suppress heterogeneity. Conversely, larger diameters reduce wall effects, but without sufficient height, vertical gradients remain limited.

This interaction highlights a fundamental limitation of tall column testing: representativeness requires multidimensional scaling. Height controls gradient development, diameter governs boundary effects, and ore mass determines heterogeneity and preferential flow. Only their combined scaling allows column behavior to approach industrial conditions.

Neglecting this coupling leads to systematic bias in the estimation of permeability evolution, flow distribution, and effective kinetics, contributing to the frequent overestimation of performance when extrapolating column data to industrial heaps. Reliable interpretation, therefore, requires simultaneous consideration of H/D ratio, particle size distribution, ore mass, and test duration, with leaching kinetics treated as system-dependent rather than intrinsic parameters (Pereira, 2026e; Segura, 2026).

4. HYDRO-MECHANICAL BEHAVIOR UNDER SELF-WEIGHT

Tall-column tests introduce gravity-driven stresses absent in short columns and bottle-roll systems. Even at moderate heights (2–6 m), self-weight creates vertical stress gradients that affect porosity, permeability, and flow. Vertical stress is approximated as $\sigma_v = \rho \cdot g \cdot H$, where ρ is the density and g is the acceleration due to gravity. Under typical conditions ($\rho = 1.5\text{–}2.0\ \mathrm{t \cdot m^{-3}}$; $H \leq 6$ m), stresses reach 50–100 kPa, lower than industrial heaps with overburden pressures of 200–300 kPa at depths of 20–30 m (Erskine et al., 2025; Robertson et al., 2021). This limits the range of experimental compaction and structural changes.

These stress effects are further influenced by column diameter, which controls lateral confinement and stress redistribution. Narrow columns amplify wall effects, reducing the effective transmission of vertical stress and altering compaction behavior relative to large-scale systems.

4.1. Progressive Compaction

Under self-weight, the packed bed undergoes progressive compaction, particularly in lower sections where stress is highest. This results in reduced void fraction, increased bulk density, and redistribution of fines. Compaction is inherently non-uniform, with localized densification zones arising from particle rearrangement, breakage, and stress heterogeneity (Erskine et al., 2025; Chen et al., 2025).

Porosity reductions typically range from 5–15%, depending on ore type, particle-size distribution, and saturation conditions. Moisture content plays a critical role: at intermediate saturation levels (20–60%), capillary forces enhance inter-particle cohesion, accelerating compaction and reducing permeability. Despite these effects, the overall magnitude of densification remains lower than in industrial heaps, where sustained loading, operational traffic, and repeated wetting–drying cycles intensify structural evolution (Ghadiri, 2020). As a result, tall columns tend to underestimate long-term compaction and its impact on flow resistance.

4.2. Permeability Evolution

Permeability evolves continuously during leaching through coupled mechanical and geochemical processes, including compaction, fines migration, precipitation of secondary phases, and changes in saturation. Initial permeability of crushed ores typically ranges from 10^{-11} to 10^{-9} m², but may decrease by one to two orders of magnitude during operation due to the combined effects of structural and chemical transformations (Robertson et al., 2021; Wang et al., 2020).

Column tests often show apparently stable bulk flow rates in the early stages, followed by a gradual decline. However, this apparent stability can be misleading. Limited heterogeneity and boundary effects may sustain global flow even as the internal pore structure evolves. In contrast, industrial heaps exhibit more pronounced and spatially heterogeneous permeability loss, driven by localized clogging, fines accumulation, and channeling—phenomena that are not fully reproduced at the column scale (Gibson, 2020; Zheng, 2026).

4.3. Vertical Gradients and Flow Regimes

The interaction between self-weight and fluid flow generates vertical gradients in both hydraulic and chemical conditions along the column. Conceptually, this behavior can be divided into three characteristic zones. The upper region (0–1 m) is dominated by high irrigation rates, elevated oxygen availability, and short residence times, typically associated with higher reagent concentrations. The intermediate zone (approximately 1–4 m) represents the primary leaching domain, where partial saturation prevails and transport limitations become increasingly significant. In the lower section (>4 m), longer residence times, reduced permeability, and the onset of reprecipitation processes contribute to progressive flow restriction.

This zonation is conceptual and dependent on column height and operating conditions, reflecting the coupling between fluid flow and reaction processes. As fluid velocity generally decreases with depth while contact time increases, residence time distributions broaden along the column height, indicating non-ideal flow behavior (Gibson, 2020; Zheng, 2026).

The combined effects of compaction, permeability evolution, and flow redistribution under self-weight are conceptually synthesized in Figure 3, which integrates mechanical and hydraulic processes along the column height.

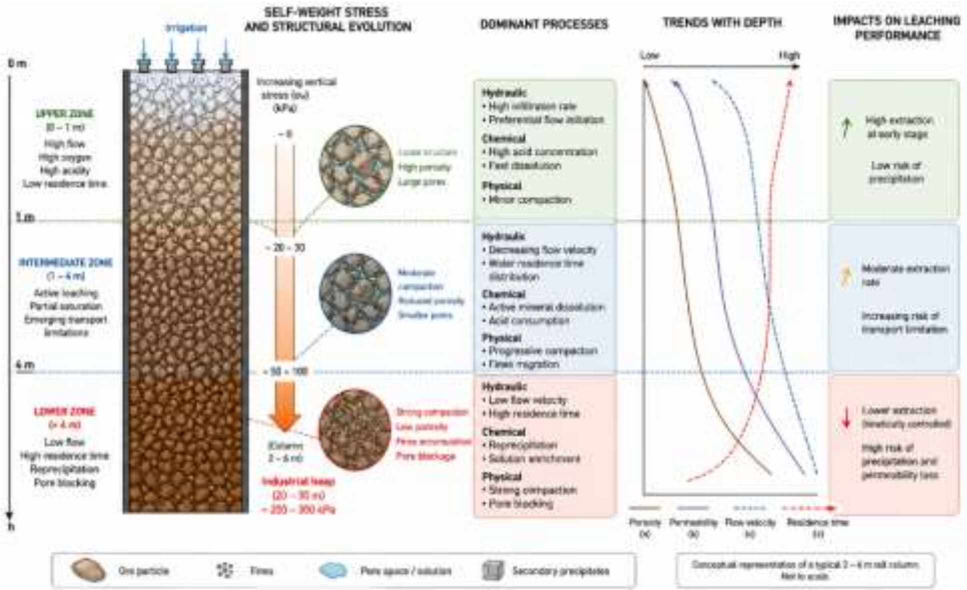


Figure 3. Conceptual representation of hydro-mechanical evolution in tall columns. Self-weight induces progressive compaction, reducing porosity and permeability with depth. Flow velocity decreases, leading to increased residence time and development of vertical reaction zones. Adapted from Erskine et al. (2025), Robertson et al. (2021), and Wang et al. (2020).

Figure 3 shows that hydro-mechanical behavior in tall columns is governed by the progressive coupling of compaction, permeability loss, and flow redistribution. These processes are captured qualitatively, though with reduced intensity and spatial variability compared to industrial heaps.

4.4. Scale Limitations in Hydro-Mechanical Behavior

The effects of compaction, permeability evolution, and flow redistribution show that tall columns mimic the hydro-mechanical coupling onset but under constrained stress and boundaries. Limited stress similarity to industrial heaps restricts large-scale features like extensive flow networks, heterogeneous stress fields, and long-term structural changes.

Tall columns offer a simplified analog with key mechanisms present but less intense, resulting in smoother and more uniform gradients than at the field scale, which simplifies flow behavior and moderates leaching kinetics.

This reduced complexity originates from incomplete mechanical and geometric similitude, which limits the amplification of feedback mechanisms between compaction, permeability loss, and flow redistribution. In industrial heaps, these interactions occur over larger spatial and temporal scales, producing stronger heterogeneity and non-linear system responses.

The hydro-mechanical framework established here defines the boundary conditions for chemical evolution and secondary phase formation. The following section, therefore, examines hydro-geochemical coupling, with emphasis on solution evolution, precipitation, and their impact on leaching performance.

5. HYDRO-GEOCHEMICAL COUPLING AND VERTICAL CHEMICAL GRADIENTS

Leaching in tall columns depends on the interaction between fluid flow and chemical reactions, not just kinetics. As the solution moves through the medium, pH, redox potential (Eh), ionic strength, and dissolved species change, influencing mineral dissolution and the formation of secondary phases. This feedback, known as hydro-geochemical coupling, involves transport controlling reactions and vice versa (Ansah et al., 2023; Ansah et al., 2025).

In tall columns (2–6 m), residence time rises from minutes at the top to hours at depth, depending on permeability (10^{-11}–10^{-9} m²) and irrigation rate (5–15 $L \cdot m^{-2} \cdot h^{-1}$). This gradient causes vertical chemical stratification, though less than in industrial heaps. Consequently, different reaction regimes develop along the column. Typically, pH increases from <1 in the upper zone to ~2–4 at depth, and Eh decreases from >600 mV (oxidizing) to <400 mV (less oxidizing/more reducing), influenced by mineralogy and oxygen availability.

5.1. Sulfate Systems (H_2SO_4)

In sulfuric acid systems, commonly used for copper and nickel laterites, solution chemistry evolves rapidly due to the dissolution of gangue minerals and iron-bearing phases. Secondary reactions include jarosite formation, ferric hydroxide precipitation, and gypsum formation, which consume reactive species, alter pH and redox conditions, and reduce metal solubility and recovery.

These reactions are spatially distributed along the column. The upper zone maintains high acidity (pH < 1–1.5), favoring dissolution; the intermediate zone is marked by active iron cycling and progressive acid consumption; and the lower zone tends to accumulate precipitates. Precipitation can reduce local porosity by approximately 5–20%, significantly affecting permeability and flow distribution (Wang et al., 2021; Ansah et al., 2025). However, the spatial extent and intensity of these processes remain limited compared with those in industrial heaps.

5.2. Chloride Systems (HCl)

In chloride systems, hydrogeochemical behavior is strongly influenced by high ionic strength and distinct metal speciation. Key processes include silica gel formation, $FeCl_3$ hydrolysis, and salt accumulation, such as $MgCl_2$. These mechanisms increase solution viscosity, reduce effective diffusivity, and can lead to rapid pore blockage under elevated residence times.

Compared to sulfate systems, chloride systems are more prone to localized clogging due to silica polymerization and salt accumulation, particularly in deeper regions where flow velocity is reduced. These effects intensify transport limitations and strengthen the coupling between chemical evolution and flow behavior (Das & Li, 2023; Gunaratnam, 2022).

The main hydro-geochemical processes controlling leaching behavior in tall columns and their limitations relative to industrial heaps are summarized in Table 2.

Table 2. Hydro-geochemical processes controlling leaching behavior in tall columns and their impact on representativeness. Adapted from Ansah et al. (2023, 2025), Wang et al. (2021), and Das & Li (2023).

System	Process	Mechanism	Effect in Tall Columns	Limitation vs Industrial Heaps
H_2SO_4	Jarosite formation	Fe^{3+} + SO_4^{2-} precipitation	Moderate precipitation (limited spatial extent)	Underestimated accumulation
	Ferric hydroxide	Hydrolysis / pH increase	Local precipitation	Limited spatial variability
	Gypsum	Ca^{2+} + SO_4^{2-} reaction	Partial clogging	Less severe than field
HCl	Silica gel formation	Si polymerization	Rapid pore blockage	Underestimated heterogeneity
	$FeCl_3$ hydrolysis	Acid generation / buffering	Alters pH profile	Less pronounced gradients
	Salt accumulation	$MgCl_2$, ionic strength	Increased viscosity, reduced diffusivity	Limited large-scale effect
General	Precipitation	Supersaturation	Porosity reduction (5–20%)	Reduced spatial variability
	Ionic strength increase	Dissolution products	Lower diffusion rates	Underestimated feedback
	Flow–reaction coupling	Transport–reaction feedback	Gradual evolution	Reduced non-linearity

Table 2 shows that tall columns capture the dominant reaction mechanisms but systematically underestimate their spatial variability, intensity, and feedback strength relative to industrial heaps.

The vertical evolution of solution chemistry and reaction regimes along the column height can be described conceptually, as illustrated in Figure 4.

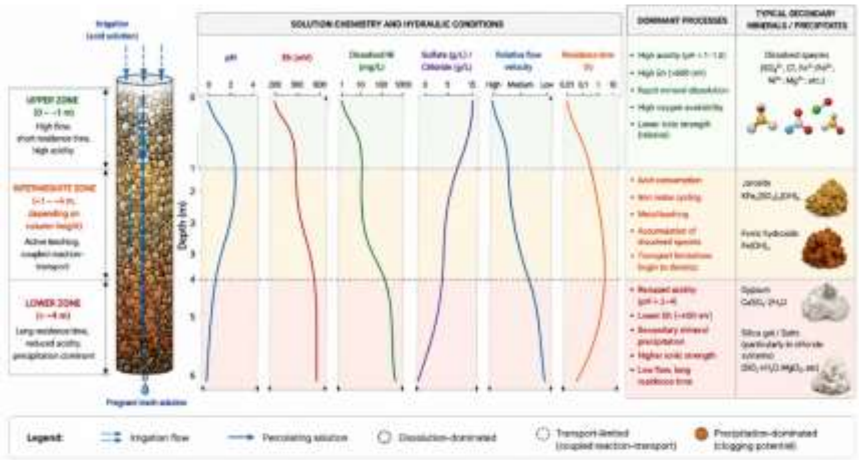


Figure 4. Vertical hydro-geochemical gradients in tall column leaching. Dissolution dominates in the upper zone, coupled reaction–transport behavior in the intermediate zone, and precipitation processes dominate in the lower zone. Adapted from Ansah et al. (2023), Ram et al. (2020), and Wang et al. (2021).

Figure 4 shows that chemical gradients develop progressively with depth, controlling dissolution, transport, and precipitation. However, their magnitude and spatial variability remain limited compared to industrial systems.

5.3. Feedback Mechanisms and Non-Linear Behavior

Hydro-geochemical coupling introduces non-linear, path-dependent system behavior through feedback loops between transport and reaction. For example, dissolution increases ionic strength, reducing diffusion rates, while precipitation decreases porosity, lowering flow velocity and increasing residence time. These changes promote further precipitation, reinforcing permeability loss and modifying flow pathways.

Such feedback explains the progressive deviation from initial conditions even under constant irrigation. However, in tall columns, these effects are attenuated due to limited scale, reduced heterogeneity, and incomplete development of localized supersaturation conditions.

5.4. Scale Limitations and Implications for Kinetics

Although tall columns capture the onset of hydro-geochemical coupling, they underestimate its intensity and spatial variability. Limited height restricts the development of strong chemical gradients, while structural uniformity reduces localized precipitation and feedback amplification.

This behavior shows incomplete chemical and transport similarity between column and heap systems. Consequently, leaching kinetics are driven by changing chemical gradients linked to flow and should be treated as system-dependent effective parameters rather than intrinsic reaction rates. In industrial heaps, increased coupling and heterogeneity intensify transport limitations and non-linear effects, resulting in different kinetic behavior (Hardee et al., 2025; Rosemann et al., 2025).

These coupled effects directly influence flow stability and the evolution of hydraulic regimes over time. The next section, therefore, examines hydraulic stability and flow regimes, focusing on flow decay, pressure evolution, and the onset of channeling and clogging phenomena.

6. HYDRAULIC STABILITY AND FLOW REGIMES OVER TIME

Hydraulic stability in tall columns is governed by the temporal evolution of flow distribution, pressure drop (ΔP), and saturation, all of which respond to changes in pore structure and fluid properties. Flow behavior in these systems can be described by unsaturated Darcy's law, in which hydraulic conductivity is a nonlinear function of saturation. As a result, small changes in saturation or pore structure can produce disproportionately large variations in flow distribution.

Unlike short-duration tests, tall columns (90–300 days) enable observation of transient flow regimes, in which initially stable conditions progressively evolve into non-uniform flow, partial saturation, and hydraulic instability. These dynamics are governed by the coupling between permeability evolution and fluid transport (Chaitanya & Gupta, 2023; Robertson & Petersen, 2024) and are strongly influenced by compaction and precipitation processes described in Sections 4 and 5.

Typical operating conditions involve irrigation rates of 5–15 $L \cdot m^{-2} \cdot h^{-1}$, producing superficial velocities on the order of 10^{-6}–10^{-5} $m \cdot s^{-1}$. Under these conditions, flow is predominantly unsaturated, occurring through partially saturated pathways, including films and preferential rivulets. Because hydraulic conductivity depends non-linearly on saturation—typically following exponential or power-law relationships—even moderate permeability changes (10–50%) can significantly alter flow distribution (Maghsoudy et al., 2022; Majdalani & Guinot, 2023).

6.1. Evolution of Hydraulic Regimes

During column operation, hydraulic behavior evolves through distinct flow regimes that reflect the progressive coupling between transport processes and structural changes within the porous medium. The initial stage is characterized by relatively uniform flow, typically occurring within the first 10–30 days depending on ore type and operating conditions. In this regime, flow distribution remains approximately homogeneous, the flow rate (Q) is stable, and structural alteration is minimal.

As leaching progresses, the system transitions to a regime of increasing heterogeneity, marked by declining flow rates—often on the order of 20–60%—rising pressure drop (ΔP), and the onset of preferential flow pathways. These changes are driven by fines migration, precipitation of secondary phases, and compaction, which progressively modify the pore structure and flow distribution.

At later stages, a channelized flow may develop, with preferential pathways dominating fluid transport. These pathways cause large bed areas to be poorly contacted, making flow localization the key hydraulic behavior. Studies show that 60–80% of flow can pass through less than 20% of the area in homogeneous systems, emphasizing flow localization (Ju et al., 2021; Odidi et al., 2024).

Under specific conditions, additional regimes may emerge. A clogging-dominated regime is characterized by a pronounced reduction in permeability and substantial increases in ΔP (typically 50–200%), driven by precipitation and compaction processes. Alternatively, a bypass flow regime may develop, in which bulk flow remains relatively stable but effective ore–solution contact is significantly reduced, resulting in lower recovery despite apparent hydraulic stability.

The evolution of these hydraulic regimes, together with their diagnostic indicators and underlying mechanisms, is summarized in Table 3.

Table 3. Hydraulic regimes, diagnostic indicators, and underlying mechanisms of tall-column leaching. Adapted from Ju et al. (2021), Robertson and Petersen (2024), and Maghsoudy et al. (2022).

Regime	Characteristics	Hydraulic Indicators	Dominant Mechanisms	Physical Interpretation	Limitation vs Industrial Heaps
Initial uniform flow	Homogeneous distribution	Stable Q, low ΔP	Minimal structural change	Near-uniform saturation	Overestimates uniformity
Transitional flow	Increasing heterogeneity	Declining Q (20–60%), rising ΔP	Fines migration, precipitation	Instability onset	Underestimates channel development
Channelized flow	Preferential pathways dominate	Localized flow, high ΔP	Flow localization, clogging	Permeability contrast	Less intense than field scale
Clogging-dominated	Reduced permeability zones	Strong ΔP increase (50–200%)	Precipitation, compaction	Pore blocking	Delayed vs industrial heaps
Bypass flow	Poor ore–solution contact	Stable Q, low recovery	Channeling	Flow decoupling	Underestimated severity

Table 3 shows that hydraulic behavior evolves from initially uniform flow to progressively localized and non-linear regimes. However, tall columns systematically underestimate the intensity, spatial variability, and connectivity of flow localization observed in industrial heaps.

The temporal evolution of hydraulic regimes and associated instabilities can be described conceptually, as illustrated in Figure 5.

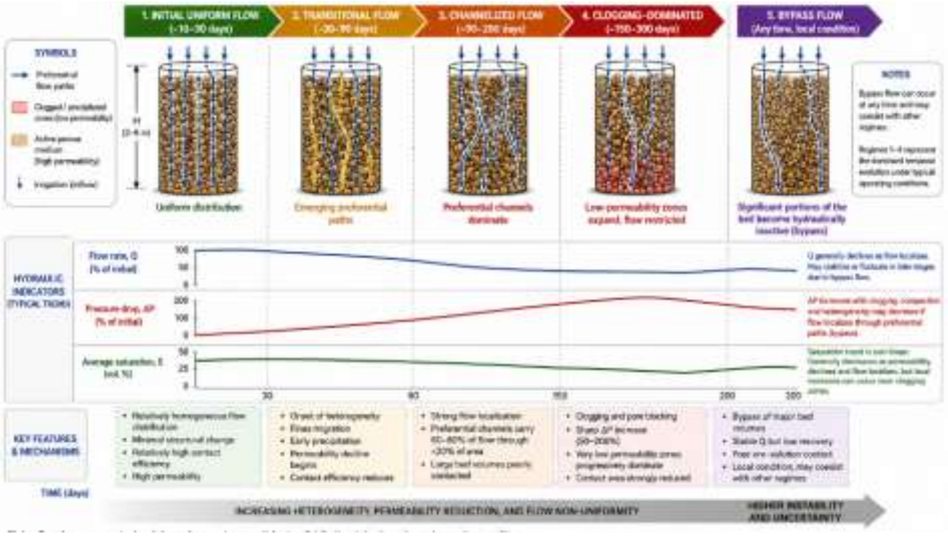


Figure 5. Evolution of hydraulic regimes in tall column leaching. Initially, uniform flow transitions in a progressive and non-linear manner to preferential and channelized regimes as permeability decreases and flow redistributes. Adapted from Ju et al. (2021), Robertson and Petersen (2024), and Maghsoudy et al. (2022).

Figure 5 shows that hydraulic stability is transient, with a progressive and non-linear transition from uniform to preferential flow as permeability evolves and flow redistributes.

6.2. Scale Limitations in Hydraulic Representation

Tall columns indicate hydraulic instability onset, but face limitations like reduced heterogeneity, boundary confinement, and lower stress, which restrict strong channeling and large flow networks. Industrial heaps have tens of meters of flow paths, allowing large-scale connectivity and variability beyond column systems.

This behavior reflects incomplete hydraulic similitude between column and heap systems. Consequently, tall columns tend to delay or attenuate the transition to strongly channelized flow, producing smoother, more uniform apparent behavior than in full-scale systems (Robertson & Petersen, 2024; Chaitanya & Gupta, 2023).

6.3. Critical Interpretation

Hydraulic data from tall columns must be interpreted cautiously. Stable flow doesn't guarantee uniform leaching, and early behavior doesn't predict long-term performance. Small changes in pore structure can cause large effects due to strong coupling of permeability, saturation, and flow.

Consequently, hydraulic behavior in tall columns should be viewed as system-dependent and scale-limited, rather than as a direct representation of industrial flow regimes. Observed stability or uniformity reflects the constraints of experimental conditions and does not capture the full complexity of field-scale behavior.

The evolution of flow regimes directly controls mass transfer and reaction rates within the porous medium. The next section examines effective kinetics in porous media systems, focusing on how transport limitations and structural evolution modify apparent leaching.

7. EFFECTIVE KINETICS IN POROUS MEDIA SYSTEMS

Kinetic behavior in leaching systems depends on the physical environment. Fully mixed systems, like bottle roll tests, reflect intrinsic reaction rates based on mineral surface reactivity and solution chemistry. Tall columns act as porous-media reactors, where observed kinetics result from reaction, mass transfer, and pore structure changes. Under these conditions, apparent kinetics are system-dependent and scale-limited (Faraji et al., 2020; Pereira, 2026c).

This distinction is critical for scale-up. Bottle roll tests typically employ fine particles (<150 µm), high liquid-to-solid ratios (>5:1), and short durations (<48 h), minimizing transport limitations. Tall columns, by contrast, use coarse particles (10–25 mm), low irrigation fluxes (5–15 $L \cdot m^{-2} \cdot h^{-1}$), and extended durations (90–300 days), where mass transfer resistance and structural evolution dominate system behavior (Kang et al., 2026; Shayakhmetova et al., 2025).

7.1. From Intrinsic to Effective Kinetics

Intrinsic kinetics describe reaction rates controlled by surface chemistry under uniform conditions. In porous media, however, reactants must be transported through fluid films, diffuse into the pores of particles, and interact with dynamically evolving surfaces. As a result, the observed rate is governed by the slowest step in a coupled system that varies spatially and temporally.

This transition is characterized by the Damköhler number (Da), which compares the reaction rate to transport rate. As transport limits grow ($Da \gg 1$), the system shifts from reaction-controlled to transport-limited. In tall columns, this shift occurs gradually along the height and over time due to changes in permeability, saturation, and pore accessibility.

The fundamental differences between intrinsic and effective kinetics and their implications for scale-up are summarized in Table 4.

Table 4. Comparison between intrinsic and effective kinetics in leaching systems and implications for scale-up. Adapted from Faraji et al. (2020), Saldaña et al. (2022), and Pereira (2026c).

Aspect	Intrinsic Kinetics (Bottle Roll)	Effective Kinetics (Tall Columns)	Implication for Scale-Up
Controlling mechanism	Surface reaction	Coupled transport–reaction	System-dependent behavior
Particle size	Fine (<150 µm)	Coarse (10–25 mm)	Increased diffusion limitation
Flow conditions	Fully mixed	Unsaturated, non-uniform	Reduced contact efficiency
Mass transfer resistance	Negligible	Significant (film + pore diffusion)	Lower apparent rates
Reaction environment	Uniform	Spatially heterogeneous	Variable kinetics with depth
Structural evolution	Minimal	Strong (precipitation, clogging)	Time-dependent behavior
Diffusion coefficient	Bulk values (~10^{-9} m^2/s)	Reduced (tortuosity, constrictivity)	Slower transport
Model applicability	SCM often valid	SCM physically inconsistent	Poor predictive capability
Rate constants	Transferable	Non-transferable	Cannot be extrapolated
Extraction curve	Smooth, rapid	Slowing + tailing	Overestimation at early stage

Table 4 shows that kinetics in tall columns are governed by coupled transport–reaction processes rather than intrinsic reaction rates. This shift results in non-transferable parameters and limits the predictive capability of models derived from column data.

7.2. Dominant Transport Mechanisms

Effective kinetics in tall columns involve external mass transfer, intraparticle diffusion, and interparticle transport influenced by flow distribution. Diffusion coefficients in aqueous systems are usually 10^{-9}–10^{-10} $m^2 \cdot s^{-1}$, but in porous media, these are lower due to tortuosity and constrictivity (Saldaña et al., 2022).

The relative importance of each mechanism evolves during operation. Early stages may be influenced by external transport, whereas later stages are increasingly controlled by intraparticle diffusion and restricted fluid accessibility due to flow localization and permeability decline.

7.3. Effect of Structural Evolution

Precipitation of secondary phases and migration of fines progressively modify the pore structure, reducing accessible surface area and increasing tortuosity. Even modest reductions in porosity (≈5–10%) can significantly decrease effective diffusivity—often by up to an order of magnitude—shifting the system from reaction-controlled to transport-limited behavior (Shayakhmetova et al., 2025; Kang et al., 2026).

This transition is spatially heterogeneous. Upper regions may remain closer to reaction-controlled conditions, while deeper zones become strongly transport-limited, resulting in variable kinetics within the same system.

The transition from intrinsic to effective kinetics and the progressive influence of transport limitations can be illustrated conceptually, as shown in Figure 6.

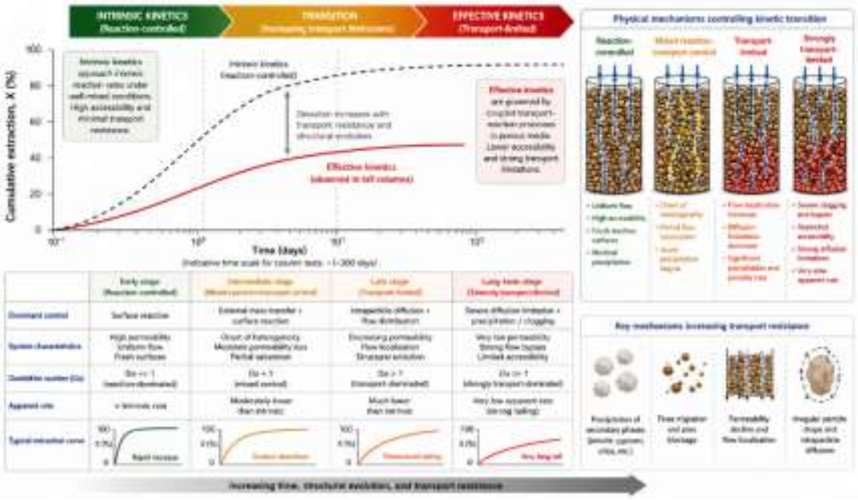


Figure 6. Conceptual comparison between intrinsic and effective kinetics in leaching systems. Apparent rates progressively deviate and transition from reaction-controlled to transport-limited behavior as transport resistance and structural evolution increase. Adapted from Faraji et al. (2020), Saldaña et al. (2022), and Pereira (2026d).

Figure 6 shows that apparent kinetics progressively deviate from intrinsic behavior as transport resistance increases and pore structure evolves.

7.4. Limitations of Kinetic Modeling

A common approach is to fit column data using simplified kinetic models such as the shrinking core model (SCM). However, these models assume uniform particle geometry, well-defined reaction fronts, constant diffusivity, and negligible transport limitations—conditions that are rarely satisfied in porous media systems.

In tall columns, particle irregularity, non-uniform flow, evolving saturation, and continuous structural changes invalidate these assumptions. Consequently, high correlation between model predictions and experimental data does not imply physical validity, and fitted parameters often lack predictive capability when applied to different scales or operating conditions.

7.5. Implications for Scale-Up

The transition from intrinsic to effective kinetics has direct implications for process design and interpretation. Early-stage kinetics are typically overestimated because of minimal transport resistance, whereas diffusion limitations and precipitation dominate long-term behavior.

Extraction curves in tall columns, therefore, show rapid initial recovery, followed by a progressive slowdown and long tailing. These features are often misinterpreted as changes in reaction mechanism, whereas they primarily reflect increasing transport limitations and evolving pore structure.

As a result, apparent rate constants derived from column data are not transferable across scales, reflecting incomplete transport similitude between laboratory and industrial systems. Direct extrapolation to industrial heaps can therefore lead to systematic overestimation of performance.

The evolution of effective kinetics is closely linked to reagent consumption under dynamic flow conditions. The next section examines reagent consumption in tall columns, focusing on cumulative demand and its relationship with transport and chemical processes.

8. REAGENT CONSUMPTION UNDER DYNAMIC FLOW CONDITIONS

Reagent use in heap leaching involves a multi-step, time-dependent process influenced by mineral dissolution, secondary reactions, and fluid flow. Tall columns with continuous irrigation (5–15 $L \cdot m^{-2} \cdot h^{-1}$) provide a more realistic assessment than batch systems. Reagent demand depends on mineralogy, flow regime, and residence time, and is scale-dependent (Thomas, 2021; Toro et al., 2021).

Reagent consumption can be formally expressed through a cumulative mass balance, defined as the difference between total reagent input and output, accounting for dissolved species, precipitation, and retained mass within the porous medium. This framework is essential for distinguishing between apparent consumption (measured in solution) and true consumption, particularly in systems with strong hydro-geochemical coupling.

Unlike bottle roll tests, where consumption is dominated by rapid dissolution under excess solution, tall columns capture the temporal evolution of reagent demand, including delayed reactions that become significant at longer timescales (Prameswara et al., 2024; Pandey et al., 2023).

8.1. Temporal Evolution of Consumption Mechanisms

Reagent consumption evolves through distinct stages:

- **Early stage (≈0–30 days):** dominated by rapid neutralization of gangue minerals (e.g., carbonates, silicates) and surface oxidation reactions, resulting in high consumption rates and rapid depletion of buffering capacity.
- **Intermediate stage (≈30–90 days):** continued dissolution accompanied by the onset of precipitation and increasing influence of residence time and flow distribution.
- **Late stage (≈90–200+ days):** dominated by secondary reactions, including precipitation of jarosite, ferric hydroxides, and gypsum, as well as re-dissolution–reprecipitation cycles.
- **Long-term behavior (>200–300 days):** characterized by hidden consumption associated with low-permeability zones, diffusion-limited regions, and internal redistribution of dissolved species.

Reported acid consumption in lateritic systems ranges from 200 to 600 kg $H_2SO_4 \cdot t^{-1}$, with secondary reactions often accounting for 30–60% of the cumulative acid demand, particularly under conditions of heavy precipitation (Top et al., 2020; Ribeiro et al., 2021).

The main mechanisms, timescales, and magnitudes of reagent consumption in tall-column leaching are summarized in Table 5.

Table 5. Mechanisms, timescales, and magnitude of reagent consumption in tall column leaching. Adapted from Thomas (2021), Ribeiro et al. (2021), and Prameswara et al. (2024).

Stage	Dominant Mechanisms	Typical Timescale	Contribution to Total Consumption	Key Controlling Factors	Economic Impact	Limitation vs Industrial Heaps
Early stage	Neutralization (carbonates, silicates), surface oxidation	0–30 days	40–70%	Mineralogy, acid concentration	Drives initial consumption	Well captured
Intermediate stage	Dissolution + onset of precipitation	30–90 days	20–40%	Residence time, flow distribution	Moderate OPEX impact	Underestimated heterogeneity
Late stage	Precipitation (jarosite, $Fe(OH)_3$, gypsum), reprecipitation cycles	90–200+ days	30–60%	pH, Eh, ionic strength	Major OPEX driver	Underestimated accumulation
Long-term	Hidden consumption (low-permeability zones, redistribution)	>200–300 days	Variable (often significant)	Flow localization, diffusion limitation	Critical for long-term cost	Strongly underestimated

Table 5 shows that reagent consumption evolves from rapid neutralization-dominated processes to slower, precipitation-controlled mechanisms. While early-stage consumption is well captured, later-stage and hidden consumption are systematically underestimated due to the limited development of transport-controlled and precipitation-driven processes.

8.2. Progressive Neutralization and Vertical Gradients

As leaching progresses, acid reacts with gangue minerals and secondary phases, causing progressive neutralization along the column height. This produces vertical gradients in which pH increases and acid concentration decreases with depth. Lower regions may reach pH values of 2–4, even when the feed solution remains strongly acidic (pH < 1), depending on buffering capacity and residence time.

These gradients reinforce reagent consumption by promoting precipitation of secondary phases, which further consume acid and reduce effective leaching efficiency. This behavior reflects strong coupling between chemical reactions and transport processes, particularly under conditions of reduced flow velocity and increased residence time.

The temporal evolution of reagent consumption mechanisms can be illustrated conceptually, as shown in Figure 7.

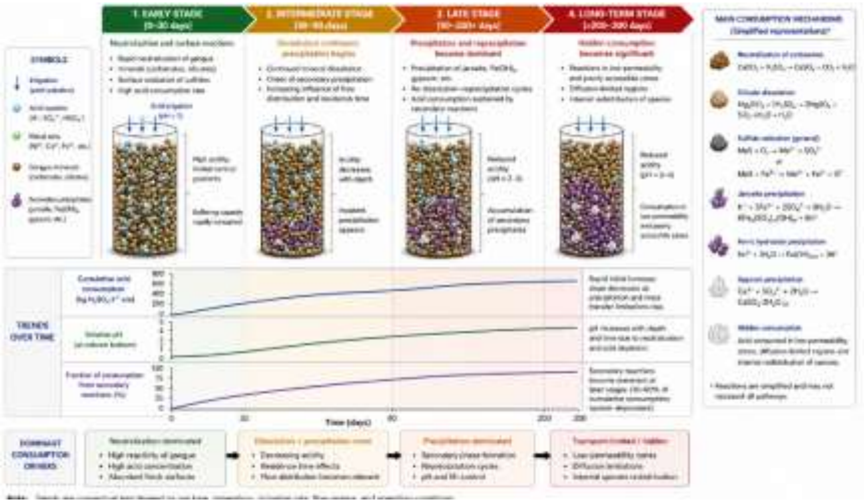


Figure 7. Evolution of reagent consumption mechanisms in tall column leaching. Early-stage consumption is dominated by neutralization and dissolution, followed by a progressive and non-linear transition to precipitation-controlled consumption at later stages.

Figure 7 shows the progressive and non-linear transition from neutralization-dominated to precipitation-controlled consumption as reaction and transport processes evolve over time.

8.3. Hidden Consumption and Mass Balance

A key advantage of tall columns is the ability to perform cumulative mass balances over extended periods, enabling identification of hidden consumption mechanisms. These include reagents consumed in precipitation that do not contribute to metal recovery, reactions occurring in low-permeability zones with long residence times, and the redistribution of dissolved species within the porous medium.

These effects often lead to discrepancies between apparent consumption (based on solution analysis) and true consumption derived from mass balance calculations, particularly in systems with strong hydro-geochemical coupling (Acquah et al., 2025; Ribeiro et al., 2021).

8.4. Implications for Scale-Up

Reagent consumption is a critical economic parameter in heap leaching, often accounting for a significant share of operating costs (typically 20–50% of OPEX, depending on ore type and operating conditions). Underestimating acid demand can lead to incorrect system design, underestimated operating costs, and misinterpretation of process viability.

Although tall columns yield better predictions than short columns, limitations remain. Reduced heterogeneity, lower stress conditions, and shorter effective residence times delay the onset of precipitation and structural effects, leading to an underestimation of long-term reagent demand.

This behavior reflects incomplete chemical and transport similarity between column and industrial systems. Consequently, reagent consumption in tall columns reflects coupled chemical and transport processes and cannot be directly extrapolated to industrial heaps without accounting for scale-dependent effects.

Reagent consumption is closely linked to flow distribution and structural evolution, particularly in systems where precipitation and fines migration alter permeability. The next section examines structural heterogeneity and channeling, focusing on how deviations from uniform flow impact leaching performance.

9. STRUCTURAL HETEROGENEITY AND CHANNELING LIMITATIONS

Structural heterogeneity is a defining feature of industrial heap leaching systems, arising from coupled physical and chemical processes that evolve over time. Variations in particle size distribution, agglomeration quality, moisture content, and mineral composition generate spatial variability in permeability (k), porosity (ε), and residence time distributions. In contrast, tall columns are prepared under controlled conditions, resulting in relatively homogeneous beds with limited lateral variability. This fundamental difference constrains their ability to reproduce realistic flow connectivity, preferential pathways, and contact efficiency (Ghadiri, 2020; Vriens et al., 2020).

Heterogeneity spans multiple spatial scales. At the particle scale (10^{-3}–10^{-2} m), irregular shapes and pore structures influence local diffusion and surface access. At the bed scale (10^{-1}–10^{1} m), segregation, compaction, and agglomeration produce permeability variations. At the heap scale (>10 m), operational factors such as stacking, irrigation, and environmental conditions introduce additional variability. These effects create scale-dependent flow connectivity and transport, resulting in complex flow networks in which solution follows high-permeability pathways (Wang et al., 2020; Ju et al., 2021).

9.1. Channeling and Flow Bypass

Channeling is the formation of preferential flow paths driven by permeability contrasts and hydraulic instability. Experimental and modeling studies indicate that up to 60–80% of total flow may be confined to 10–30% of the cross-sectional area, indicating strong flow localization (Ju et al., 2021).

This leads to flow bypass, in which solution exits the system with limited fluid–solid interaction and a reduced effective reaction volume. The consequences include lower metal recovery, higher reagent consumption per unit of metal, and non-uniform chemical environments. Although channeling can develop in tall columns, its intensity is constrained by the relatively uniform initial structure and limited lateral extent. As a result, column tests systematically underestimate the extent and impact of preferential flow observed in industrial heaps (Larrabure et al., 2024).

9.2. Sources and Evolution of Heterogeneity

Heterogeneity in industrial heaps arises from multiple interacting processes, including particle-size segregation during stacking, non-uniform agglomeration and curing, localized compaction, fines migration, and precipitation-induced clogging. These processes are dynamic and mutually reinforcing. For example, the accumulation of fines reduces local permeability, diverting flow to adjacent regions with higher velocities and shorter residence times. This feedback amplifies spatial variability and promotes the development of preferential flow networks over time.

Tall columns partially reproduce fines migration and precipitation effects but lack the spatial scale required for heterogeneity to fully develop. Consequently, flow paths remain shorter and more weakly connected, resulting in higher apparent contact efficiency and smoother system behavior compared to industrial conditions (Larrabure et al., 2025; Ghadiri, 2020).

The main sources of structural heterogeneity, their effects on flow behavior, and their representation in column-scale experiments are summarized in Table 6.

Table 6. Sources, effects, and scale limitations of structural heterogeneity in heap leaching systems. Adapted from Wang et al. (2020), Ju et al. (2021), and Larrabure et al. (2024, 2025).

Category	Mechanism	Effect on Flow	Impact on Performance	Scale Impact	Representation in Tall Columns
Particle scale	Irregular particles, pore structure	Local diffusion limitation	Variable reaction rates	Minor at heap scale	Partially captured
Bed scale	Segregation, agglomeration variability	Permeability heterogeneity	Flow redistribution	Strong influence	Underestimated
Heap scale	Stacking, irrigation, weather	Channeling and bypass	Reduced recovery	Dominant control	Not captured
Fines migration	Particle movement	Local clogging, flow diversion	Increased variability	Amplifies heterogeneity	Limited reproduction
Precipitation	Secondary phase formation	Permeability reduction	Higher reagent consumption	Strong feedback	Underestimated
Channeling	Preferential flow paths	Flow localization	Reduced contact efficiency	Governs system behavior	Strongly underestimated

Table 6 shows that structural heterogeneity develops across multiple spatial scales and is only partially reproduced in column experiments. Large-scale variability and flow connectivity, which govern channeling and bypass, are largely absent, resulting in systematic differences in flow behavior and contact efficiency.

9.3. Diagnostic Techniques

Several experimental techniques are used to assess heterogeneity and channeling. Tracer tests provide residence time distributions (RTD) and indirect quantification of flow variability. Distributed sensors, such as pressure and moisture probes, offer spatial information on hydraulic conditions. Imaging methods, including X-ray computed tomography and neutron imaging, enable direct visualization of internal structure and fluid distribution.

These techniques demonstrate that even in controlled column systems, flow is rarely uniform. However, the degree of heterogeneity and connectivity remains significantly lower than in full-scale heaps, reinforcing the scale limitation of column-based observations (Wang et al., 2020; Larrabure et al., 2024).

The difference in flow distribution and connectivity between column-scale and industrial systems can be illustrated conceptually, as shown in Figure 8.

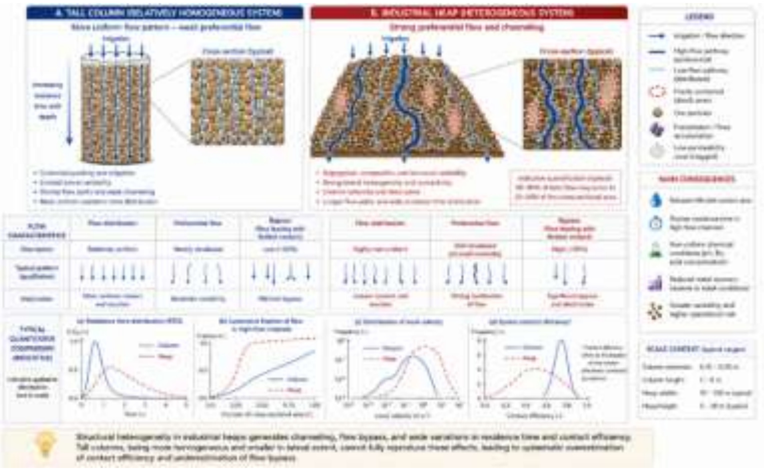


Figure 8. Conceptual comparison of flow distribution in homogeneous columns and heterogeneous heaps. Industrial heaps develop complex, spatially connected channel networks that reduce effective contact area and increase flow bypass, whereas tall columns exhibit more uniform and weakly connected flow patterns.

Figure 8 shows that industrial heaps develop complex, spatially variable flow networks, whereas columns exhibit comparatively uniform, weakly connected flow patterns, limiting their ability to reproduce real-world system behavior.

9.4. Impact on Leaching Performance

Structural heterogeneity and channeling have direct consequences for leaching performance. Preferential flow reduces effective residence time and reaction volume, leading to non-uniform reaction progress and spatial variability in reagent distribution. These effects reduce effective recovery and increase variability in system performance.

In industrial heaps, such phenomena often dominate system behavior. In contrast, tall columns tend to produce smoother extraction curves and more stable hydraulic responses, which can be misinterpreted as indicators of favorable performance.

9.5. Critical Interpretation

The limited ability of tall columns to reproduce structural heterogeneity introduces systematic bias in both flow characterization and kinetic interpretation. As a consequence, contact efficiency tends to be overestimated, while reagent losses associated with bypass flow and long-term system instability are insufficiently captured.

These discrepancies arise from intrinsic scale-induced constraints rather than experimental deficiencies. Although increasing column height enhances vertical gradients, it does not produce the lateral variability needed to reproduce realistic flow connectivity and heterogeneity. As a result, structural complexity remains attenuated, reflecting incomplete similitude between column-scale systems and industrial heaps.

The limitations identified here are closely tied to experimental design and data resolution. The following section, therefore, examines instrumentation, monitoring strategies, and data gaps, with emphasis on how current practices influence the reliability and interpretability of column-based observations.

10. EXPERIMENTAL DESIGN, INSTRUMENTATION, AND DATA GAPS

The analysis in this review shows that tall column tests yield valuable mechanistic insights into leaching behavior but cannot be used as direct predictors of industrial performance. Their primary limitation stems from scale-dependent constraints that affect flow distribution, transport processes, structural evolution, and hydro-geochemical coupling.

While tall columns improve smaller-scale tests by adding vertical gradients and longer timescales, they do not replicate the multiscale heterogeneity, stress conditions, and flow connectivity that influence industrial heap performance. This reflects incomplete similitude between column and industrial systems, especially in transport, structure, and hydraulic connectivity. Consequently, biases usually occur, overestimating recovery and underestimating reagent use and flow variability (Robertson & Petersen, 2024; Larrabure et al., 2024; Zheng, 2026).

Consequently, experimental observations must be interpreted within a framework that clearly distinguishes between diagnostic value and predictive capability.

10.1. Diagnostic vs Predictive Use of Tall Column Tests

Tall column tests are most effective as diagnostic tools, enabling the identification of dominant mechanisms such as transport limitations, precipitation effects, and permeability evolution. However, diagnostic capability does not imply predictive validity. These tests are well-suited for identifying rate-controlling mechanisms, evaluating trends in reagent consumption, and assessing hydro-mechanical and hydro-geochemical coupling within the system.

In contrast, their predictive use—particularly for estimating final recovery, long-term kinetics, or flow stability—is inherently limited. Such predictions require interpretation beyond column-scale data, as key processes are strongly influenced by scale-dependent effects that cannot be reproduced experimentally (Krishnamoorthy et al., 2022; Bravo-Gutiérrez et al., 2026). The distinction between diagnostic and predictive applications of tall column tests, together with their limitations, is summarized in Table 7

Table 7. Diagnostic capabilities and predictive limitations of tall column leaching tests. Adapted and synthesized from Faraji et al. (2020), Ju et al. (2021), Saldaña et al. (2022), Robertson and Petersen (2024), Larrabure et al. (2024), Bravo-Gutiérrez et al. (2026), and Zheng (2026)

Aspect	Diagnostic Capability	Predictive Limitation	Scale Implication
Kinetics	Identifies rate-controlling mechanisms	Overestimates early-stage rates	Not transferable across scales
Flow behavior	Detects onset of channeling	Underestimates large-scale heterogeneity	Limited connectivity representation
Permeability	Captures trends in evolution	Underestimates long-term reduction	Incomplete structural development
Reagent consumption	Captures temporal evolution	Underestimates cumulative demand	Hidden consumption not resolved
Precipitation	Identifies dominant reactions	Underestimates spatial variability	Limited accumulation
Structural effects	Detects fines migration and clogging	Limited representation of heterogeneity	Not scalable
Scale-up	Supports comparative analysis	Cannot directly predict performance	Requires external validation

Table 7 shows that tall columns are effective for identifying mechanisms but have limited predictive capability due to scale-dependent constraints. Their use should therefore be restricted to mechanistic interpretation and comparative evaluation rather than direct performance prediction.

10.2. Framework for Scale-Aware Interpretation

A scale-aware interpretation framework is required to integrate column data into process design. This framework reflects the transition from intrinsic to effective kinetics, the evolution of flow regimes, and the development of structural heterogeneity.

Three governing principles define scale-dependent behavior:

- **Kinetics are system-dependent**
- Apparent reaction rates reflect coupled transport–reaction processes and cannot be treated as intrinsic properties (Faraji et al., 2020; Saldaña et al., 2022).
- **Flow distribution controls performance**
- Preferential flow and channeling reduce effective contact area and dominate large-scale behavior (Ju et al., 2021; Larrabure et al., 2024).
- **Structural evolution modifies transport**
- Compaction, precipitation, and fines migration progressively alter permeability and diffusion pathways (Ghadiri, 2020; Wang et al., 2020).

Together, these principles define a nonlinear, coupled system governed by transport limitations and structural evolution, limiting the extrapolation of column-scale observations.

A recommended instrumentation scheme for tall column tests is shown in Figure 9, highlighting the need for spatially distributed measurements to resolve hydraulic and chemical gradients.

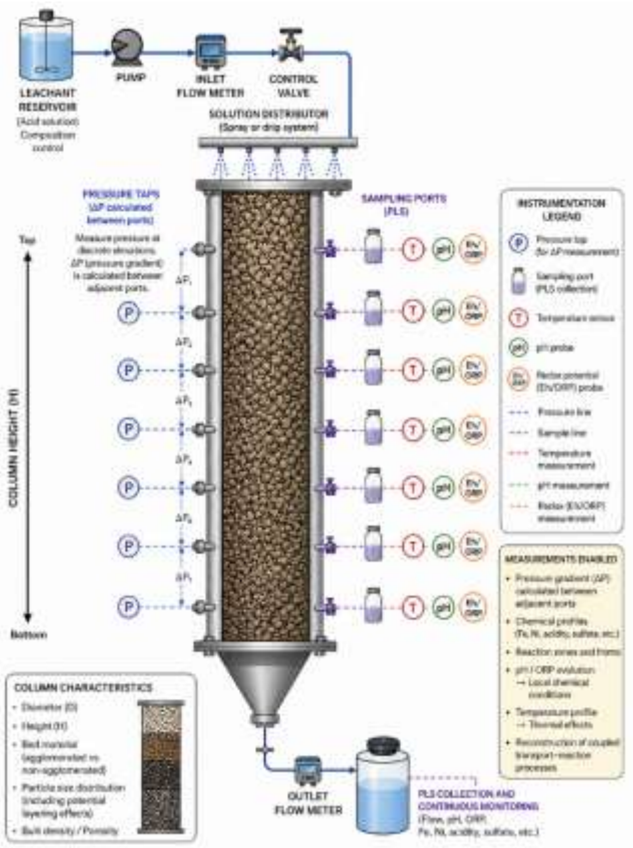


Figure 9. Recommended instrumentation scheme for tall column leaching tests. Sensors distributed along the column height enable measurement of pressure, flow, and chemical gradients, allowing reconstruction of coupled transport–reaction behavior. Adapted from Zheng (2026), Chen et al. (2025), and Krishnamoorthy et al. (2022).

Figure 9 shows that reliable interpretation requires distributed instrumentation rather than inlet–outlet measurements alone. Pressure sensors, flow monitoring, and segmented sampling are essential for distinguishing among transport limitation, reaction control, and structural effects such as clogging and channeling.

10.3. Implications for Process Design

For engineering applications, the limitations of tall column tests have direct and practical implications for process design. Design assumptions should remain conservative, explicitly accounting for reduced contact efficiency and the amplification of transport limitations at larger scales. In parallel, reagent consumption estimates must be adjusted upward to reflect delayed reaction pathways and hidden consumption mechanisms that are not fully captured in short-duration or confined systems.

Equally critical is the validation of flow behavior under conditions representative of industrial operation, particularly with respect to channeling, bypassing, and non-uniform solution distribution. These phenomena, often suppressed or poorly represented at column scale, become dominant factors controlling performance in full-scale heaps.

Addressing these challenges requires an integrated framework that combines pilot-scale testing, transport–reaction modeling, and industrial operational data. Such an approach reduces uncertainty in scale-up and improves the reliability of design predictions, as emphasized by Robertson and Petersen (2024) and Bravo-Gutiérrez et al. (2026).

10.4. Critical Outlook

The continued use of tall column tests as standalone predictive tools reflects a persistent methodological gap in current practice. Although widely applied, these tests are often interpreted without sufficient consideration of scale-dependent effects, resulting in systematic overestimation of process performance.

Addressing this limitation requires the development of standardized testing protocols and the integration of experimental data with transport–reaction modeling frameworks. In parallel, improved characterization of flow distribution, heterogeneity, and structural evolution within the column is essential, particularly through quantitative assessment of flow connectivity and permeability changes. Bridging laboratory observations with industrial-scale behavior further demands closer coupling between experimental results and operational data.

Advances in these areas are critical to reducing uncertainty in scale-up and to establishing more reliable links between column-scale testing and heap-scale performance (Hou et al., 2026; Zheng, 2026)

11. SCALE-UP FRAMEWORK AND INDUSTRIAL IMPLICATIONS

Scaling up heap leaching involves translating column-scale observations into industrial design inputs. This process is uncertain because tall-column tests only reproduce part of the coupled transport, reaction, and structural processes that govern heap behavior. The main challenge is not just data extrapolation but correctly interpreting which outputs reflect transferable system tendencies and which are scale-dependent.

Incomplete similarity between column and industrial systems, particularly in flow connectivity, structural heterogeneity, and stress conditions, introduces systematic bias. In practical terms, this bias manifests as overestimation of metal recovery and underestimation of reagent consumption and hydraulic variability when column data are used without correction. These deviations are not experimental artifacts, but rather intrinsic consequences of scale.

Tall column tests effectively capture qualitative system behavior, describing extraction trends like rapid initial recovery slowing over time, reagent consumption, hydraulic instability signs (flow decline, pressure changes, preferential flow). They aid ore comparison, condition ranking, and initial feasibility, but are trend indicators, not precise predictions.

Several key parameters can't be directly scaled up. Final recovery is often overestimated due to less heterogeneity and shorter flow paths in column systems. Apparent kinetic rates depend on coupled transport–reaction processes and vary with scale, making them non-transferable. Long-term hydraulic stability is poorly represented because industrial heaps experience stronger compaction, channeling, and structural changes. External factors like climate, stacking method, and operational variability, which are significant at industrial scale, are not captured in controlled column experiments. These limitations mean column-derived parameters must be corrected, validated, or supplemented with additional data before using them in design.

The extent to which parameters can be transferred from column tests to industrial systems is summarized in Table 8, which highlights the distinction between qualitative trends and quantitative values. The table shows that while trends such as extraction profiles are robust, most performance-governing parameters are scale-dependent and must be treated accordingly.

Table 8. Transferability of key parameters from column tests to industrial heap leaching systems. Adapted and synthesized from van Staden and Petersen (2021), Robertson and Petersen (2024), and Segura (2026).

Parameter	Column Representation	Industrial Behavior	Transferability	Design Implication
Extraction trend	Well captured	Similar shape	High (qualitative)	Useful for ore ranking
Final recovery	Overestimated	Lower due to heterogeneity	Low (requires correction)	Apply conservative factors
Kinetic rates	Apparent (effective)	Transport-limited	Low (non-transferable)	Not directly usable
Flow distribution	Relatively uniform	Strongly heterogeneous	Low (non-representative)	Validate with pilot data
Permeability evolution	Trend captured	Stronger decline	Moderate (magnitude uncertain)	Apply safety factors
Reagent consumption	Underestimated at late stage	Higher cumulative	Moderate–low (requires correction)	Increase design margins
Channeling	Weakly developed	Strongly dominant	Low (non-representative)	Critical design risk
Structural heterogeneity	Limited	Multiscale and dynamic	Very low (not reproducible)	Not captured

A consistent scale-up strategy integrates experimental data across multiple levels of complexity, starting with mineralogical characterization and bottle roll tests for kinetics and recovery. Short and tall column tests reveal hydraulic behavior, reagent use, coupled transport–reaction effects, and longer timescales. Pilot heaps validate conditions at larger scales, and reactive transport modeling synthesizes the data for long-term, scale-dependent behavior. Each stage increases realism and reduces uncertainty, but none is sufficient alone.

This multistage approach in Figure 10 shows an integrated scale-up framework linking lab kinetics to industrial heap performance. It highlights that scale-up is not linear but involves progressively integrating data, models, and engineering judgment. As complexity grows, transport limitations, flow redistribution, and structural changes become more important.

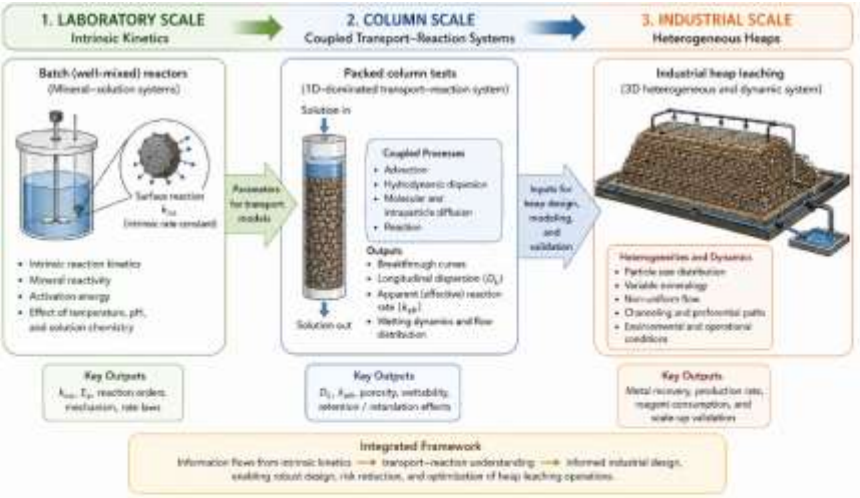


Figure 10. Integrated scale-up framework for heap leaching. The process evolves from intrinsic kinetics (laboratory scale) to coupled transport–reaction systems (column scale) and finally to heterogeneous industrial heaps, with each stage providing complementary information for design.

Within this context, reactive transport modeling plays a central role. By combining multiphase flow descriptions, advection–dispersion transport, and geochemical reaction networks, such models provide a means of bridging the gap between controlled experiments and industrial systems. Recent developments have further enhanced predictive capability through hybrid approaches that integrate mechanistic models with data-driven methods, allowing better representation of non-linear phenomena such as channeling and permeability evolution. Nevertheless, model reliability remains strongly dependent on data quality and spatial resolution. Without adequate experimental constraints, models may reproduce observed trends while failing to capture the underlying physical mechanisms.

Scale-up uncertainty affects project design and economics, with errors in parameter estimates, such as acid use and recovery, impacting costs and profitability, especially in lateritic systems where reagent costs are high. Conservative designs mitigate risk but raise CAPEX, while accurate strategies offer technical and economic advantages.

The analysis presented in this review leads to a clear conclusion: tall column tests reduce uncertainty but do not eliminate scale-up risk. Their primary value lies in identifying dominant mechanisms and system trends, rather than providing direct quantitative predictions. Reliable scale-up must therefore be approached as a risk-managed, multiscale process that integrates experimental observations, physically consistent modeling, and critical interpretation of system limitations.

12. APPLICATION TO NICKEL LATERITE SYSTEMS (CROSS-CUTTING PERSPECTIVE)

Nickel laterites are among the most challenging applications for heap leaching due to their complex mineralogy, high gangue reactivity, and strong sensitivity to hydrogeochemical conditions. These characteristics amplify the limitations discussed in previous sections, particularly those related to transport constraints, reagent consumption, and structural evolution. As a result, the interpretation of tall column data in lateritic systems requires careful consideration of scale-dependent effects.

Lateritic ores are broadly classified into limonitic and saprolitic types, which exhibit fundamentally different leaching behavior. Limonitic ores, typically rich in iron-bearing phases such as goethite, tend to show high initial reactivity but extremely high acid consumption, often exceeding 400–700 kg $H_2SO_4 \cdot t^{-1}$. In contrast, saprolitic ores, dominated by magnesium silicates, exhibit lower acid consumption (typically 100–300 $kg \cdot t^{-1}$) but slower kinetics due to reduced mineral reactivity and stronger transport limitations.

12.1. Hydro-Geochemical Sensitivity

Leaching in lateritic systems is sensitive to pH, redox, and temperature. Effective dissolution needs strongly acidic conditions ($pH < 1.5$), while redox potential controls Fe^{2+}/Fe^{3+} balance and precipitation. Temperature changes (ambient to ~60°C) affect reaction kinetics and transport.

Small variations in these parameters can lead to significant changes in system behavior. Iron precipitation as jarosite or goethite reduces solution acidity and promotes additional reagent consumption. Silica dissolution and subsequent polymerization may lead to gel formation, reducing permeability and flow continuity. Magnesium dissolution increases ionic strength, affecting diffusion and mass transfer. These processes are spatially distributed and evolve over time, reinforcing the importance of hydro-geochemical coupling.

12.2. Transport Limitations and Structural Evolution

Transport limitations are particularly severe in lateritic ores due to their high fines content, presence of clay minerals, and propensity for secondary phase formation. These factors reduce permeability, increase tortuosity, and promote localized flow restriction.

Tall-column tests show permeability decreases of 10-100 times over 100–200 days, especially in limonitic systems. These reductions are less severe than in industrial heaps, where heterogeneity and compaction amplify effects. This causes a decoupling between reactivity and extraction, with mass transfer often governing overall kinetics, even under good chemical conditions.

12.3. Reagent Consumption and Economic Impact

Acid consumption represents one of the main constraints in laterite processing, often accounting for 30–60% of total operating cost. In limonitic systems, high consumption is driven by dissolution of iron-bearing phases, neutralization reactions, and precipitation of secondary minerals. Saprolitic ores, although less chemically reactive, can still undergo significant consumption due to extended residence times and transport limitations.

Tall column tests provide valuable insight into the temporal evolution of reagent demand, particularly the transition from rapid neutralization to precipitation-driven consumption. However, long-term consumption is often underestimated due to limited test duration and reduced structural heterogeneity. This underestimation can lead to optimistic projections of operating costs and project feasibility.

The main differences in leaching behavior, transport limitations, and economic implications between limonitic and saprolitic ores are summarized in Table 9.

Table 9. Comparison of leaching behavior in limonitic and saprolitic nickel laterite ores and implications for heap leaching design. Adapted from Agatzini-Leonardou et al. (2021), Komnitsas et al. (2023), Petersen and van Staden (2025), and Segura (2026).

Aspect	Limonitic Ores	Saprolitic Ores	Design Implication
Mineralogy	Fe-rich (goethite, hematite)	Mg-silicate-rich	Strong influence on chemistry
Intrinsic reactivity	High	Moderate–low	Faster initial dissolution (limonite)
Acid consumption	Very high (400–700 kg/t)	Moderate (100–300 kg/t)	Major OPEX driver
Kinetics	Fast initial, strong slowdown	Slower but more stable	Different leaching strategies
Transport limitation	Moderate to high	High	Flow control critical
Permeability evolution	Strong decline	Moderate decline	Risk of clogging
Secondary phases	Jarosite, $Fe(OH)_3$	Silica gel, Mg salts	Impacts flow and chemistry
Overall recovery	Moderate–high potential	Moderate	Trade-off with cost

Table 9 shows that limonitic and saprolitic ores present fundamentally different trade-offs between reactivity, transport limitations, and reagent consumption, requiring distinct design and operating strategies.

12.4. Comparison with Alternative Processing Routes

Nickel laterites can also be processed through high-pressure acid leaching (HPAL) or pyrometallurgical routes. HPAL typically achieves high recoveries (>90%) but involves high capital and energy costs. Pyrometallurgical processing is more suitable for saprolitic ores but is also energy-intensive.

Heap leaching offers a lower-cost alternative, albeit with lower recoveries (typically 50–80%) and longer processing times. Its viability depends on achieving a balance between acceptable recovery, controlled reagent consumption, and stable hydraulic behavior. Tall column tests are essential for evaluating this balance, but must be interpreted within the scale limitations discussed earlier.

The contrasting behavior of limonitic and saprolitic ores can be conceptually illustrated, as shown in Figure 11.

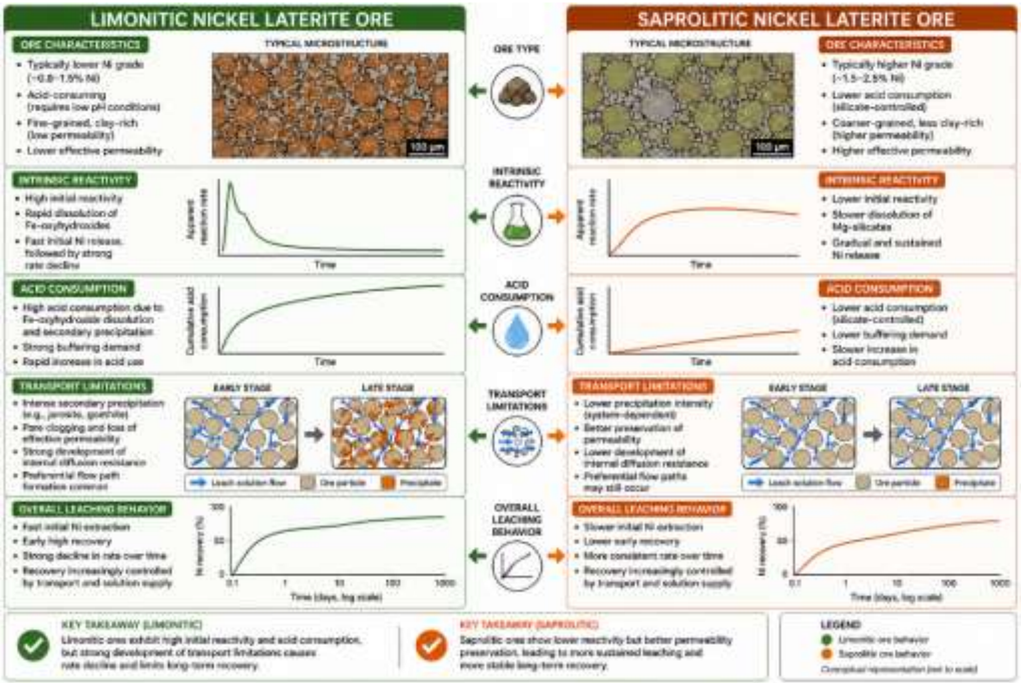


Figure 11. Conceptual comparison of leaching behavior in limonitic and saprolitic nickel laterite ores, highlighting differences in intrinsic reactivity, reagent consumption, and transport limitations. Adapted from Jeong et al. (2025), Pandey et al. (2023), and Petersen and van Staden (2025).

Figure 11 shows that recovery in lateritic systems depends on both reactivity and transport constraints, not just one factor. Limonitic ores have high initial reactivity and rapid acid consumption, leading to rapid early extraction but also to transport limitations due to precipitation and pore blockage. Saprolitic ores have lower reactivity but more stable permeability, leading to slower but more transport-controlled leaching. Consequently, performance depends on timescale: short-term tests favor limonitic, while long-term behavior is governed by transport in both types.

12.5. Critical Interpretation

The application of tall column testing to nickel laterites highlights a key insight: high intrinsic reactivity does not necessarily translate into high recovery at scale. Instead, system performance is often controlled by transport limitations, structural evolution, and time-dependent reagent consumption.

These effects are particularly pronounced in lateritic systems, where strong coupling between chemical reactions and physical transport leads to highly scale-sensitive behavior. As a result, discrepancies between intrinsic and effective kinetics are amplified, making scale-up more uncertain and requiring careful integration of experimental data and modeling.

Beyond technical performance, the selection of processing routes for nickel laterites is increasingly influenced by environmental and sustainability considerations. The next section examines these aspects, integrating technical and environmental perspectives.

13. SUSTAINABILITY AND PROCESS CONTEXT (CONCEPTUAL SUPPORT)

Sustainability considerations are increasingly central to the selection and design of hydrometallurgical processes. Heap leaching, including tall column-based evaluation, is often positioned as a lower-intensity alternative to high-temperature routes. However, its environmental and economic performance depends on the balance between recovery, reagent consumption, water use, and emissions, all of which are influenced by the scale-dependent effects discussed in previous sections (Binnemans & Jones, 2023; Binnemans et al., 2020).

From a life-cycle perspective, heap leaching typically operates at ambient temperature and pressure, with energy demand significantly lower than pyrometallurgical processes. Estimated energy consumption ranges from 10 to 50 $kWh \cdot t^{-1}$ ore, compared to >200–500 $kWh \cdot t^{-1}$ for high-temperature routes such as ferronickel production or HPAL when including steam generation and oxygen supply. This lower energy intensity translates into reduced direct CO_2 emissions, particularly when electricity is sourced from low-carbon grids (Trinanda et al., 2026).

13.1. Resource Efficiency and Reagent Use

Despite its relatively low energy intensity, heap leaching is often highly reagent-intensive, particularly in systems characterized by reactive gangue minerals, such as nickel laterites. Under such conditions, acid consumption can exceed 300–700 kg $H_2SO_4 \cdot t^{-1}$ of ore, representing a major economic and environmental burden.

This impact extends beyond on-site operations, as reagent use is intrinsically linked to upstream sulfuric acid production, transportation logistics, and the downstream management of residual acidity. The cumulative footprint associated with these stages can offset some of the apparent environmental advantages of heap leaching compared with more energy-intensive processes.

From a process design perspective, one of the most critical challenges is reliably estimating reagent demand. Underestimation during laboratory or pilot-scale testing—particularly when based on short-duration experiments—can lead to substantial deviations at industrial scale, directly increasing OPEX and complicating effluent management.

Therefore, the predictive value of reagent consumption data depends less on absolute values obtained under controlled conditions and more on accurately representing consumption trends over time, including the contributions of slow, transport-controlled mechanisms. This perspective is consistent with the broader principles of resource efficiency in hydrometallurgical systems highlighted by Binnemans and Jones (2023).

13.2. Water Use and Effluent Management

Heap leaching systems operate predominantly with recirculated solutions; however, continuous make-up water is required to compensate for evaporation, solution retention within the heap, and operational losses. Reported water consumption typically ranges from 0.2 to 1.0 $m^3 \cdot t^{-1}$ of ore, with variability primarily controlled by climatic conditions, irrigation strategies, and heap design parameters.

From an environmental perspective, water management represents a critical constraint on process sustainability. The handling of pregnant leach solution (PLS), control of seepage and leakage, and treatment of raffinate and bleed streams must be addressed as an integrated system rather than as isolated unit operations. Failures in containment or hydraulic control can result in long-term environmental liabilities, particularly in large-scale heap facilities.

Residual materials and leached heaps can become secondary contamination sources over time, especially in systems with dissolution–precipitation cycles. These cycles remobilize metals due to changing hydrogeochemical conditions, highlighting the link between fluid flow, geochemistry, and structural evolution.

Consequently, effective water and effluent management requires a hydro-geochemically informed design framework that integrates solution chemistry, transport processes, and long-term stability considerations, as emphasized by Liu et al. (2026).

13.3. Process Selection and Trade-Offs

The choice between heap leaching and alternative routes involves trade-offs.

Nickel laterite ore processing methods vary in energy use, reagent consumption, efficiency, and capital needs, reflecting differences in reaction mechanisms, conditions, and scale, as summarized in Table 10.

Table 10. Comparative assessment of major nickel laterite processing routes in terms of energy demand, reagent consumption, recovery, and capital expenditure (CAPEX). Adapted from Petersen and van Staden (2025), Pandey et al. (2023), Surya et al. (2026), Li et al. (2023), and Msumange et al. (2026)

Process	Energy demand	Reagent use	Recovery	CAPEX
Heap leaching	Low	High	Moderate (50–80%)	Low
HPAL	High	Moderate	High (>90%)	Very high
Pyrometallurgy	Very high	Low	Moderate–high	High

Table 10 shows trade-offs among processing routes. Heap leaching uses less energy and costs less, but has high reagent use and moderate recovery due to transport and incomplete leaching. HPAL achieves better recovery through intensive reactions but requires significant energy and capital. Pyrometallurgical options require high energy inputs and infrastructure, limiting their economic viability to certain ore types and scales.

The trade-offs between energy demand, reagent consumption, recovery, and capital cost across different nickel laterite processing routes are synthesized in Figure 12, which provides a conceptual comparison of their environmental and economic performance.

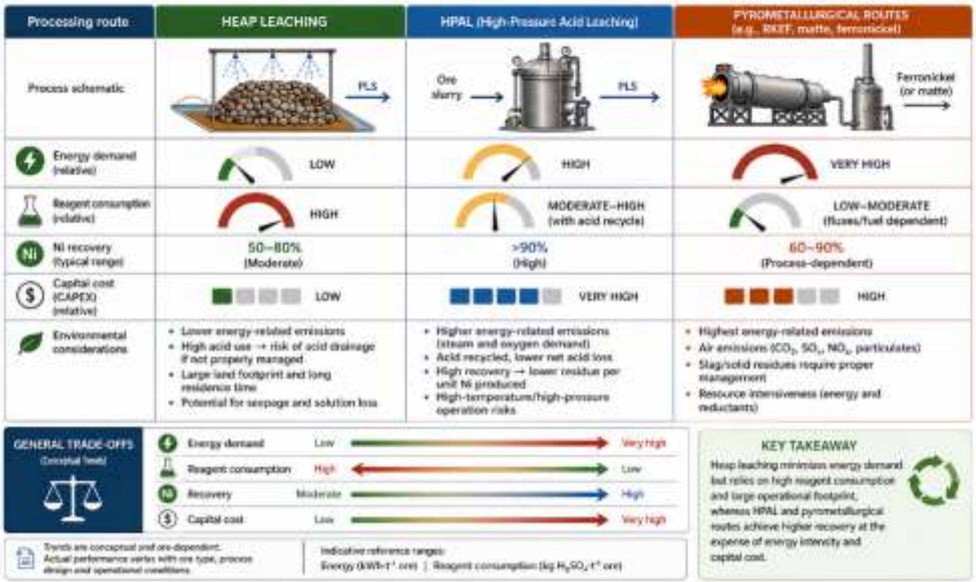


Figure 12. Conceptual comparison of environmental and economic trade-offs in nickel laterite processing routes. Heap leaching has lower energy demand but higher reagent consumption, while HPAL and pyrometallurgy offer higher recovery at increased energy and capital costs. Adapted from Binnemans and Jones (2023) and Trinanda et al. (2026).

Figure 12 shows that no single processing route is inherently optimal, as each involves a distinct balance between energy intensity, reagent demand, recovery, and capital investment. Heap leaching is characterized by low energy requirements but high reagent consumption and extended residence times. In contrast, HPAL and pyrometallurgical routes achieve higher recoveries at the expense of greater energy input and capital intensity.

This comparison highlights that process selection cannot be based on a single metric, but must consider the combined impact of operating costs, environmental footprint, and system performance. In particular, the apparent advantage of heap leaching in terms of energy efficiency is conditional on effective control of reagent consumption and hydraulic stability, both of which are strongly influenced by scale-dependent phenomena.

13.4. Circularity and Process Integration

Recent advances in hydrometallurgy have increasingly focused on circular process design, aiming to reduce resource consumption and minimize waste generation through integrated flowsheets. Central to this approach are strategies such as reagent recovery and reuse, valorization of process residues, and tighter coupling with downstream purification stages, including solvent extraction (SX) and selective precipitation.

Within this context, heap leaching systems offer several opportunities for integration. The implementation of closed-loop solution recycling, selective removal of impurities through controlled precipitation, and direct coupling with solvent extraction circuits can significantly enhance overall process efficiency and reduce environmental impact. However, these strategies are not inherently robust and depend strongly on the stability and predictability of solution chemistry throughout operation.

Solution composition changes continuously due to dissolution–precipitation reactions, transport limits, and heterogeneity, affecting impurity buildup, reagent losses, and separation efficiency. Circularity in heap leaching needs a system-level understanding of hydrogeochemical behavior, not just process design.

This perspective aligns with the principles of integrated and circular hydrometallurgical design discussed by Binnemans et al. (2020), emphasizing that effective process integration must account for dynamic interactions between reaction chemistry, transport processes, and separation performance.

13.5. Critical Perspective

Although heap leaching is frequently regarded as an environmentally favorable processing route, this characterization is inherently conditional and depends on the robustness of process design and operational control. In particular, underestimation of reagent consumption can significantly increase the overall environmental footprint, while inadequate hydraulic management may lead to inefficient resource utilization and poor recovery performance.

The long-term stability of residual materials is critical and underexplored. Post-closure heap behavior depends on ongoing hydro-geochemical processes, which can cause delayed contaminant release. These factors add uncertainty to lifecycle assessments and challenge simplified sustainability claims.

Consequently, sustainability in heap leaching should not be viewed as an intrinsic attribute of the technology, but rather as an outcome of accurate scale-up, effective hydraulic control, and a comprehensive understanding of coupled transport and geochemical processes.

The considerations outlined in this section reflect both recent developments and established principles in leaching science. The following section builds on this foundation by reviewing complementary and seminal studies, providing context for the evolution of current methodologies and conceptual frameworks.

14. COMPLEMENTARY AND FOUNDATIONAL STUDIES

Beyond column and heap-specific investigations, a broader body of work provides essential context for interpreting leaching systems as coupled reactive transport processes. Studies spanning pre-feasibility design, reactor-based hydrometallurgy, and in situ leaching (ISL) offer complementary perspectives on kinetics, transport, and system integration. When considered together, these approaches highlight the fundamental limitations of simplified representations and reinforce the importance of scale-aware interpretation.

Pre-feasibility and process design studies show early assumptions impact project results. Simplified models often assume uniform flow, constant permeability, and steady conditions. While useful initially, they ignore the dynamic changes in porous media, like permeability decrease, flow redistribution, and reaction front evolution. Consequently, these models tend to overestimate recovery and underestimate reagent use, especially at industrial scale (Mokmeli, 2020), consistent with limitations from column testing.

Reactor-based hydrometallurgical systems, including stirred tanks and bioreactors, provide a contrasting framework in which mass transfer and mixing are externally controlled. Under these conditions, diffusion limitations are minimized, and intrinsic reaction kinetics can be more directly quantified. However, the absence of flow heterogeneity and structural evolution makes these systems fundamentally different from heap leaching. Consequently, kinetic parameters derived from well-mixed systems cannot be directly transferred to porous media, where transport resistance and spatial variability dominate system behavior (Fernando et al., 2024; Véliz et al., 2023).

In situ leaching (ISL) is a better analogy for heap systems. While ISL occurs in natural formations rather than engineered heaps, it shares key features such as heterogeneous permeability, preferential flow paths, and the coupling of hydrodynamics and geochemistry. Field data show that flow and reaction fronts in ISL are sensitive to geological variability, leading to uneven recovery and complex evolution of solution chemistry (Li & Yao, 2024; Fang et al., 2025). These behaviors resemble those in industrial heaps, highlighting heterogeneity as a main control factor (Wang et al., 2022).

Field-scale heap leaching studies show limitations of simplified models. Long-term data reveal variability in recovery, reagent use, and hydraulic behavior within a site, driven by heterogeneity, environmental factors, and operational practices, which lab or column experiments can't fully capture (Surimbayev et al., 2026). These findings confirm that system behavior is governed by complex multiscale interactions beyond simplified assumptions.ions.

14.1. Cross-System Comparison

To consolidate these insights, Table 11 compares the dominant controlling mechanisms across different leaching system types.

Table 11. Comparison of leaching system types and dominant controlling mechanisms. Adapted from Fernando et al. (2024), Li and Yao (2024), and Fang et al. (2025).

System Type	Flow Regime	Dominant Control	Transport Limitation	Heterogeneity	Scale Dependence
Batch / stirred reactors	Fully mixed	Intrinsic kinetics	Minimal	None	Low
Packed columns	1D-dominated flow	Coupled transport–reaction	Moderate	Limited	Moderate
Heap leaching	3D heterogeneous flow	Transport + structural evolution	High	Strong	High
In situ leaching (ISL)	Natural porous media flow	Transport + geological variability	Very high	Very strong	Very high

Table 11 shows a clear transition from kinetically controlled systems to transport- and structure-controlled systems as scale and heterogeneity increase. This transition defines the limits of parameter transferability and highlights the need for scale-aware modeling approaches.

14.2. Conceptual Integration

The relationships among these systems are illustrated in Figure 13, which synthesizes the transition from intrinsic kinetics to transport-dominated behavior.

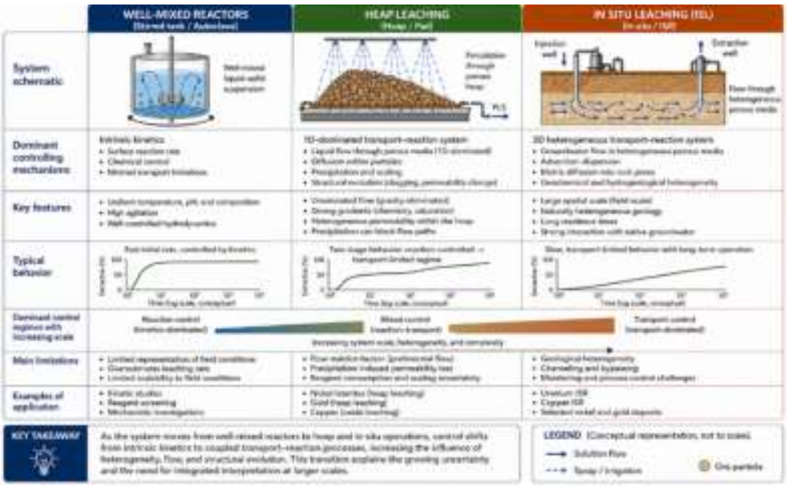


Figure 13. Comparison of leaching system types and dominant controlling mechanisms. Well-mixed reactors are governed primarily by intrinsic kinetics, whereas heap and in situ systems are controlled by coupled transport–reaction processes and structural heterogeneity. Adapted from Krishnamoorthy et al. (2022), Chaitanya and Gupta (2023), Majdalani and Guinot (2023), and Petersen and van Staden (2025).

Figure 13 highlights that increasing system scale is associated with a shift from reaction-controlled to transport-controlled behavior, accompanied by increasing structural complexity and uncertainty.

14.3. Synthesis of Foundational Insights

The combined evidence from complementary systems leads to a unified interpretation of leaching behavior. At a small scale, system performance is largely governed by intrinsic reaction kinetics, with minimal influence from transport limitations. As scale increases, transport processes become progressively dominant, and structural heterogeneity emerges as a key controlling factor.

This transition has several important implications. First, kinetic parameters are inherently context-dependent and cannot be treated as intrinsic properties when applied to porous media systems. Second, flow distribution becomes a primary control on reaction efficiency, particularly in heterogeneous systems where preferential pathways and bypass effects reduce effective contact. Finally, simplified assumptions—such as uniform flow or constant permeability—are insufficient for predictive modeling and must be replaced by integrated approaches that account for system evolution.

14.4. Critical Perspective

The insights derived from complementary and foundational studies reinforce a central conclusion of this review: accurate prediction of heap leaching performance requires a system-level understanding of coupled processes rather than reliance on isolated experimental data.

Tall column tests represent an important intermediate step in this framework, bridging controlled laboratory experiments and complex field systems. However, they do not eliminate the fundamental challenges associated with scale-dependent behavior. Reliable interpretation, therefore, requires integration of column data with complementary experimental systems, field observations, and physically consistent modeling.

The integration of experimental evidence, modeling approaches, and complementary studies provides the foundation for the final conclusions of this review, which consolidate the limitations and practical implications of tall column testing in heap leaching.

15. CONCLUSIONS

Tall column tests occupy a central position in the experimental hierarchy of heap leaching, providing a critical link between laboratory-scale kinetics and field-scale behavior. By introducing gravity-driven flow, vertical chemical gradients, and time-dependent permeability evolution, they capture key processes that are absent in smaller systems. However, this review demonstrates that their predictive capability remains fundamentally constrained by scale-dependent phenomena.

Across hydro-mechanical, hydro-geochemical, and hydraulic domains, a consistent picture emerges. The kinetics observed in tall columns are not intrinsic material properties but rather effective rates governed by the coupling among reaction, mass transfer, and evolving pore structure. Permeability and flow distribution are inherently dynamic, progressively modified by compaction, fines migration, and precipitation. Although chemical gradients develop along the column height, their magnitude and variability remain attenuated compared with those in industrial heaps. These factors collectively produce system-dependent behavior that cannot be directly extrapolated to full-scale operations.

A fundamental limitation is that tall columns cannot reproduce large-scale heterogeneity and channeling. Industrial heaps are characterized by complex flow networks, where preferential pathways can carry a disproportionate fraction of the solution, reducing effective contact and altering reaction conditions. In contrast, the relatively homogeneous structure of column systems leads to systematic overestimation of contact efficiency, recovery, and hydraulic stability.

Reagent consumption further illustrates the importance of scale. While tall columns capture the transition from rapid neutralization to precipitation-driven consumption, they frequently underestimate cumulative reagent demand, particularly in systems with strong hydro-geochemical coupling such as nickel laterites. Given that reagent consumption often dominates operating costs, this limitation has direct economic implications.

The review also highlights critical gaps in current methodologies. Many studies lack spatially resolved measurements, long-term datasets exceeding 300 days, and integration with reactive transport modeling. Without adequate instrumentation and data quality, it becomes difficult to distinguish between competing mechanisms, resulting in ambiguous interpretation. Advances in modeling and data assimilation offer a pathway forward, but their effectiveness depends on robust experimental constraints.

From a scale-up perspective, tall column tests should be interpreted as diagnostic tools rather than predictive models. They provide reliable insight into extraction trends, reagent consumption behavior, and early indicators of hydraulic instability, and are particularly useful for comparative evaluation of ores and operating conditions. However, they cannot reliably predict final recovery, long-term hydraulic behavior, or the full impact of heterogeneity and environmental variability.

A robust scale-up strategy therefore requires integration across multiple levels of complexity, combining staged experimental testing—from bottle roll to column and pilot scale—with detailed mineralogical characterization and physically consistent hydro-geochemical modeling. This multiscale approach reduces uncertainty by progressively incorporating transport limitations, structural evolution, and system heterogeneity, rather than relying on direct extrapolation.

In nickel laterite systems, these challenges are amplified. High gangue reactivity, elevated acid consumption, and strong sensitivity to transport constraints increase the discrepancy between intrinsic and effective kinetics. Accurate prediction of performance in such systems therefore depends critically on understanding the coupling between chemical reactions and physical transport processes.

Finally, sustainability considerations reinforce the importance of accurate scale-up. Although heap leaching offers lower energy intensity compared to alternative routes, its environmental and economic performance depends on controlling reagent consumption, maintaining hydraulic stability, and managing long-term system behavior. Misinterpretation of column data can therefore lead not only to technical inefficiencies but also to increased environmental impact.

The central conclusion of this review is clear: **tall column tests reduce uncertainty but do not eliminate scale-up risk**. Their primary value lies in providing mechanistic insight and identifying system trends. Reliable process design requires a scale-aware framework that integrates experimental data, modeling, and critical interpretation of system limitations.

Declarations

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Conflicts of Interest / Competing Interests

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code Availability

No custom code or software was developed for this study.

Authors' Contributions

Antonio Clareti Pereira conceived the study, performed the analysis, and wrote the manuscript.

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