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SHORT COLUMN TESTS FOR NICKEL HEAP LEACHING: CRITICAL REVIEW OF TEST DESIGN, HYDRAULIC ARTIFACTS, AND SCALE-UP RELIABILITY

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Abstract

Short-column tests are routinely used to bridge laboratory bottle-roll experiments and industrial heap leaching, particularly for nickel laterite ores; however, their predictive value is often overstated because simplified hydraulic conditions do not replicate the transport and flow phenomena that govern heap performance at scale. This review critically examines the assumptions underlying short-column testing, focusing on the coupling among reaction kinetics, mass-transfer limitations, and fluid distribution, and identifies systematic sources of bias, including preferential flow, wall-confinement effects, non-representative irrigation regimes, and artificially saturated conditions that distort leaching kinetics and produce non-representative recovery trends. A comparative analysis of reported protocols reveals substantial inconsistencies in column geometry, particle-size distribution, agglomeration practices, and control of solution chemistry, limiting reproducibility and cross-study comparisons. The common interpretation of short-column data as intrinsically kinetic leads to overestimating recoveries when extrapolated to heap scale. A scale-aware conceptual framework is proposed to link intrinsic reaction kinetics to transport constraints and structural evolution in real heaps, showing that short-column tests are suitable for comparative and mechanistic evaluation but cannot be used as standalone predictors of industrial performance.

Keywords: Nickel laterite; Heap leaching; Short column tests; Hydrodynamics; Scale-up; Mass transfer limitations

Highlights

- Short column tests often overestimate nickel recovery due to non-representative hydraulic conditions.
- Preferential flow, wall effects, and artificial saturation distort leaching kinetics and mass transfer.
- Lack of standardized test design limits comparability and industrial relevance.
- Reliable scale-up requires integration of kinetics, hydrodynamics, and structural evolution of heaps.

1. Introduction

Short column tests (SCT) are used in nickel heap leaching because they provide faster, cheaper results with less complexity than large columns and pilot heaps (Petersen & van Staden, 2025; van Staden & Petersen, 2021; León et al., 2025). They are common for quickly screening ore variability, agglomeration, irrigation, and reagent use under controlled lab conditions, especially in early project stages when multiple scenarios are needed within tight timelines and budgets (Jia et al., 2024).

Within the testwork hierarchy, SCT occupies an intermediate position between well-mixed screening tests (e.g., bottle roll) and large-scale column or pilot heap experiments. While screening tests primarily capture intrinsic chemical reactivity, SCT introduces percolation through a packed bed, enabling a partial assessment of coupled transport–reaction effects. This intermediate role has led to its widespread adoption as a decision-support tool for ranking ores, defining operating windows, and guiding the design of subsequent column and pilot campaigns (Pereira, 2026a, 2026b; Binnemans & Jones, 2023, 2025; Karmali et al., 2022; Kumar et al., 2024).

Despite its widespread use, SCT overlooks key scale-dependent processes that affect heap leaching. Industrial heaps, lasting 100–300 days or more, involve hydrodynamics, mass transfer, ore bed evolution, and phenomena such as precipitation, pore clogging, and compaction. These depend on heap height, stress, irrigation heterogeneity, and environment, which are missing or controlled in short columns (Robertson & Petersen, 2024; Pourverdi et al., 2025; Saldana et al., 2021; Winarko et al., 2022; Trinanda et al., 2026).

This review states that SCT primarily measures early-stage kinetics under simplified conditions, rather than intrinsic reaction kinetics or long-term behavior. As a result, SCT data tend to overestimate hydraulic stability and metal recovery, missing failure mechanisms like fines migration, precipitation, and compaction. This causes errors in the design and scale-up of heap leaching.

This review examines short column tests in nickel laterite heap leaching, focusing on hydraulic artifacts, intrinsic versus effective kinetics, and implications for scale-up. It aims to redefine SCT's role in a scale-aware strategy, leveraging its strengths while acknowledging limitations.

2. Methodology

This study is a critical review with a systematized literature search, rather than a fully systematic review. The methodological approach is informed by the principles of PRISMA 2020, but it does not aim to strictly comply with all requirements of a formal systematic review. Instead, PRISMA guidelines were adapted to improve transparency in study identification, screening, and selection, while preserving the flexibility required for critical interpretation.

A structured literature search was conducted using Scopus, Web of Science, ScienceDirect, and Google Scholar, covering publications from 2000 to 2026, with emphasis on studies published after 2015. The search strategy included combinations of the following keywords: “heap leaching”, “nickel laterite”, “column leaching”, “short column test”, “hydrodynamics”, “mass transfer”, and “scale-up”. Additional relevant studies were identified through backward and forward citation tracking.

The initial search yielded 233 records. After removal of 78 duplicates, 155 studies were screened based on title and abstract. Screening was conducted by a single reviewer using predefined inclusion and exclusion criteria, with iterative reassessment applied in borderline cases to ensure consistency. From the screened records, 60 studies were excluded due to insufficient experimental detail or lack of relevance, resulting in a final dataset of 95 studies for detailed analysis.

A structured data extraction approach was applied, focusing on parameters directly relevant to hydrometallurgical interpretation and scale-up. Extracted variables included column geometry, particle size distribution (PSD), irrigation conditions, chemical system, and reported outputs such as metal extraction, kinetic trends, permeability evolution, and flow behavior. No formal risk-of-bias scoring or quantitative meta-analysis was performed, as the objective of the study is interpretive rather than statistical.

Studies were included only if they reported quantitative data, clearly defined operating conditions, or physically interpretable models. Inclusion criteria required:

(a) defined column geometry;
(b) particle size distribution (PSD);
(c) irrigation rate or liquid-to-solid ratio;
(d) specification of the chemical system; and
(e) reporting of extraction behavior, kinetics, permeability, or flow response.

Studies were excluded if they lacked time-resolved data, omitted key experimental conditions, focused exclusively on equilibrium chemistry, or relied solely on empirical correlations without physical interpretation.

To improve interpretive transparency, the literature was classified into three categories:

(i) studies directly involving nickel laterite heap leaching;
(ii) (ii) studies on other heap leaching systems (e.g., Cu, U, REE), used by hydrodynamic analogy; and

(iii) (iii) fundamental studies on transport in porous media with mechanistic relevance but no direct ore specificity.

In addition, the final dataset was organized into five technical domains: (1) kinetics and reaction mechanisms, (2) hydrodynamics and transport, (3) column design and experimental artifacts, (4) scale-up methodology, and (5) nickel laterite-specific behavior. These domains were analyzed within an integrated framework that treats chemical kinetics, mass transfer, and hydrodynamics as coupled processes rather than independent variables.

A PRISMA-based workflow adapted for hydrometallurgical studies is presented in Figure 1, illustrating the progression from identification to classification. Beyond standard screening, domain-specific filters were applied to prioritize studies with clear experimental definition and relevance to scale-dependent behavior

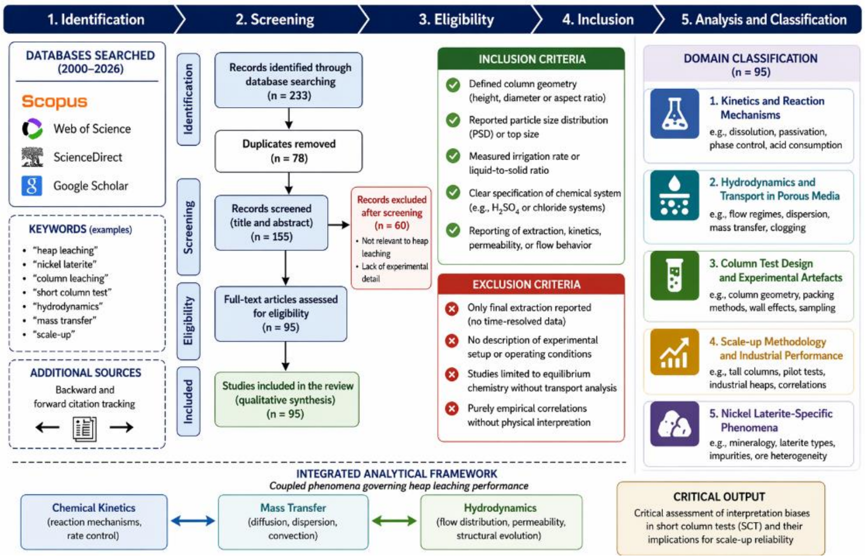

Figure 1. PRISMA-based workflow adapted for hydrometallurgical critical reviews, including domain-specific filtering criteria for heap leaching studies. Adapted from Page et al. (2021), León et al. (2025), and Petersen and van Staden (2025).

This approach differs from traditional reviews by prioritizing physical interpretability and scale relevance over data volume. The selected literature was critically examined to identify recurring sources of bias in short column test (SCT) interpretation, including overfitting of kinetic models, insufficient hydraulic characterization, and lack of long-term experimental data. The resulting framework provides a structured basis for evaluating SCT reliability and defining its role within a scale-aware testing strategy..

3. Definition and Practical Implementation of Short Column Tests

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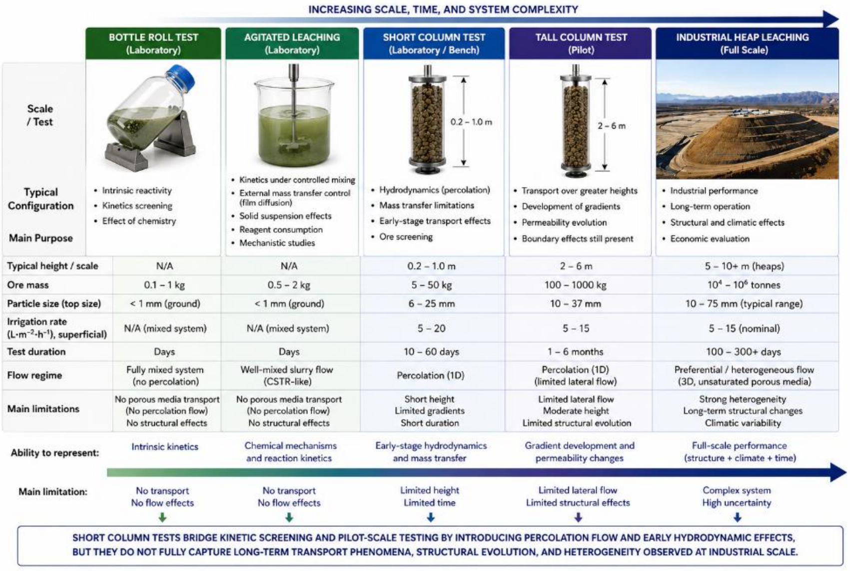
Short column tests (SCT) are laboratory-scale percolation experiments that simulate heap leaching under controlled conditions with reduced column height and time. An SCT involves a packed bed of crushed or agglomerated ore through which a leaching solution percolates downward, usually at ambient temperature and pressure. Despite their common use, there is no standard definition, and significant variability exists in geometry, conditions, and instrumentation (Oraby et al., 2020; Chun-Ming et al., 2022; Cariaga et al., 2015; Güzel, 2024; Arellano et al., 2022; Estay & Díaz-Quezada, 2020; Abeywickrama et al., 2023; Acquah et al., 2025).

Typical SCT setups use column heights of 0.2–1.0 m and diameters of 50–150 mm, with ore masses of 5–50 kg. Irrigation typically occurs at fluxes of 5–20 $L \cdot m^{-2} \cdot h^{-1}$ using drip, intermittent, or spray systems, with liquid-to-solid ratios of 0.5–2.0 $m^3 \cdot t^{-1}$. These differ from industrial heaps, which can be over 5–10 m high, with heterogeneous irrigation and leaching over 100–300 days (Petersen & van Staden, 2025; van Staden & Petersen, 2021).

Figure 2 shows increasing physical complexity across test scales. SCT introduces flow through a porous medium but doesn't replicate the coupled hydro–geo–chemical behavior seen in tall columns and heaps. Moving from lab to field involves geometric scaling and new controlling mechanisms.



INCREASING SCALE, TIME, AND SYSTEM COMPLEXITY

Scale / Test	BOTTLE ROLL TEST (Laboratory)	AGITATED LEACHING (Laboratory)	SHORT COLUMN TEST (Laboratory / Bench)	TALL COLUMN TEST (Pilot)	INDUSTRIAL HEAP LEACHING (Full Scale)
Typical Configuration Main Purpose	• Intrinsic reactivity • Kinetics screening • Effect of chemistry	• Kinetics under controlled mixing • External mass transfer control (film diffusion) • Solid suspension effects • Reagent consumption • Mechanistic studies	• Hydrodynamics (percolation) • Mass transfer limitations • Early-stage transport effects • Ore screening	• Transport over greater heights • Development of gradients • Permeability evolution • Boundary effects still present	• Industrial performance • Long-term operation • Structural and climatic effects • Economic evaluation
Typical height / scale	N/A	N/A	0.2 – 1.0 m	2 – 6 m	5 – 10+ m (heaps)
Ore mass	0.1 – 1 kg	0.5 – 2 kg	5 – 50 kg	100 – 1000 kg	10^4 – 10^6 tonnes
Particle size (top size)	< 1 mm (ground)	< 1 mm (ground)	6 – 25 mm	10 – 37 mm	10 – 75 mm (typical range)
Irrigation rate ($L \cdot m^{-2} \cdot h^{-1}$), superficial)	N/A (mixed system)	N/A (mixed system)	5 – 20	5 – 15	5 – 15 (nominal)
Test duration	Days	Days	10 – 60 days	1 – 6 months	100 – 300+ days
Flow regime	Fully mixed system (no percolation)	Well-mixed slurry flow (CSTR-like)	Percolation (1D)	Percolation (1D) (limited lateral flow)	Preferential / heterogeneous flow (3D, unsaturated porous media)
Main limitations	No porous media transport (No percolation flow) No structural effects	No porous media transport (No percolation flow) No structural effects	Short height Limited gradients Short duration	Limited lateral flow Moderate height Limited structural evolution	Strong heterogeneity Long-term structural changes Climatic variability
Ability to represent:	Intrinsic kinetics	Chemical mechanisms and reaction kinetics	Early-stage hydrodynamics and mass transfer	Gradient development and permeability changes	Full-scale performance (structure + climate + time)
Main limitation:	No transport No flow effects	No transport No flow effects	Limited height Limited time	Limited lateral flow Limited structural effects	Complex system High uncertainty

SHORT COLUMN TESTS BRIDGE KINETIC SCREENING AND PILOT-SCALE TESTING BY INTRODUCING PERCOLATION FLOW AND EARLY HYDRODYNAMIC EFFECTS, BUT THEY DO NOT FULLY CAPTURE LONG-TERM TRANSPORT PHENOMENA, STRUCTURAL EVOLUTION, AND HETEROGENEITY OBSERVED AT INDUSTRIAL SCALE.

Figure 2. Comparison of leaching test scales from bottle roll to industrial heap. Adapted from Petersen and van Staden (2025), León et al. (2025), and Estay and Díaz-Quezada (2020).

A direct comparison between SCT and industrial heap-leaching conditions highlights the origin of scale-dependent deviations. Although SCT may replicate nominal parameters such as irrigation rate or particle size, the governing variables—bed height, mechanical stress, residence time, and flow heterogeneity—differ significantly. Table 1 summarizes these contrasts and their implications for transport and reaction behavior (Petersen & van Staden, 2025; León et al., 2025; Chun-Ming et al., 2022)..

Table 1.Typical operational ranges for short column tests compared to industrial heap leaching conditions. Adapted from Petersen and van Staden (2025), León et al. (2025), and Chun-Ming et al. (2022).

Parameter	Short Column Tests (SCT)	Industrial Heap Leaching	Technical Implication
Column / Heap height	0.2 – 1.0 m	5 – 10+ m	Limited gradient development in SCT; underestimation of transport limitations
Diameter	50 – 150 mm	N/A (heap scale)	Wall effects in SCT may distort flow distribution
Ore mass	5 – 50 kg	10^4 – 10^6 tonnes	No representation of large-scale heterogeneity in SCT
Particle size (top size)	6 – 25 mm (typical)	10 – 50 mm	Different packing and permeability behavior
Fines content	Often reduced or controlled	Variable, often higher	SCT may underestimate clogging risk
Irrigation rate	5 – 20 $L\cdot m^{-2}\cdot h^{-1}$	5 – 15 $L\cdot m^{-2}\cdot h^{-1}$ (nominal)	Similar nominal values but different distribution patterns
Irrigation mode	Controlled (drip/spray)	Drip with non-uniform distribution	SCT assumes more uniform wetting
Test duration	10 – 60 days	100 – 300 days	SCT captures only early-stage behavior
Liquid-to-solid ratio (L/S)	0.5 – 2.0 $m^3\cdot t^{-1}$	1.0 – 5.0 $m^3\cdot t^{-1}$	Lower cumulative interaction in SCT
Mechanical stress	Negligible	Significant (self-weight compaction)	No compaction effects in SCT
Temperature conditions	Controlled (ambient)	Variable (climate-driven)	No thermal gradients in SCT
Chemical gradients	Limited	Strong (depth-dependent)	Underrepresentation of precipitation and re-equilibration
Permeability evolution	Short-term	Long-term (dynamic)	SCT misses progressive clogging mechanisms
Flow regime	Mostly uniform (idealized)	Heterogeneous (channeling)	SCT underestimates preferential flow

Overall, SCT reproduces early-stage behavior under simplified boundary conditions but does not represent long-term processes such as permeability evolution, precipitation, and structural changes. As such, it should be interpreted as a controlled experimental system rather than a scaled-down heap.

From a practical standpoint, SCT can be divided into two main categories: screening tests and instrumented tests.

3.1. Screening Short Column Tests

Screening SCT represents the simplest implementation and is widely used in early-stage testwork. These tests typically last 5–20 days and focus on rapid assessment of metal extraction and reagent consumption, with minimal instrumentation.

They are commonly used to:

- rank ore samples or blends;
- compare agglomeration or curing conditions;
- evaluate sensitivity to acid concentration or irrigation rate.

The absence of hydrodynamic monitoring (e.g., pressure drop or flow distribution) limits interpretation. Flow instabilities such as channeling or localized saturation cannot be detected, meaning that high extraction values may reflect favorable but non-representative flow conditions rather than intrinsic ore behavior (Estay & Díaz-Quezada, 2020; Saldana et al., 2021

3.2. Instrumented Short Column Tests

Instrumented SCT incorporates additional measurements to capture interactions among flow, transport, and reaction. Typical instrumentation includes pressure drop (ΔP), flow rate evolution, moisture distribution, water balance, and tracer tests.

These tests typically last 20–60 days and provide insight into flow non-uniformity, early-stage clogging, and permeability evolution that are not detectable in screening tests (Odidi et al., 2023a, 2023b; Robertson et al., 2021; Wang et al., 2023).

However, even in instrumented configurations, the reduced column height limits the development of vertical gradients in chemistry and flow. This restricts the representation of scale-dependent phenomena such as reprecipitation fronts, capillary effects over large distances, and stress-induced pore structure evolution

3.3. Critical Limitation: Lack of Standardization

A major limitation of SCT is the absence of standardized design and reporting protocols. Significant variability exists in column geometry, particle-size distribution, agglomeration procedures, irrigation methods, solution chemistry, and test duration (Oraby et al., 2020; Cariaga et al., 2015; Güzel, 2024).

This variability prevents direct comparison between studies and often leads to inconsistent conclusions regarding leaching performance and scale-up potential. In many cases, similar extraction results are obtained under fundamentally different hydrodynamic conditions, masking the controlling mechanisms.

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From a critical perspective, SCT should be viewed as a family of experimental approaches with varying degrees of physical representativeness. Without proper contextualization, results may be misinterpreted as intrinsic material properties rather than system-dependent responses.

These limitations become more evident when examining what SCT actually measures—and, more importantly, what it fails to capture—particularly regarding long-term heap behavior.

4. What Short Column Tests Measure—and What They Do Not Measure

Short column tests (SCT) capture early-stage leaching behavior under controlled percolation conditions. Their primary value lies in reproducing the initial extraction regime (typically 5–20 days), during which reactive surfaces remain accessible, and transport limitations are still moderate (Agatzini-Leonardou et al., 2021; Ugwu, 2023; Shayakhmetova et al., 2025). This transient regime differs from industrial heap behavior, which evolves over 100–300 days under coupled hydro–geo–chemical processes (Ansah et al., 2025; Thomas et al., 2024; Bahfie et al., 2023).

Within this early stage, SCT can reproduce dissolution trends of nickel and cobalt and capture short-range interactions between intrinsic reactivity and mass transfer. Reagent consumption is also partially represented, particularly for fast-reacting phases such as magnesium silicates and amorphous iron-bearing materials, typically within the range of 0.2–0.8 t acid per tonne of ore (Hosseini Nasab et al., 2020a; Borda & Torres, 2023).

SCT may provide limited insight into early hydraulic response. Variations in percolation rate can indicate initial permeability changes associated with fines migration or rapid precipitation (Chun-Ming et al., 2022; Odidi et al., 2023a). Sensitivity to irrigation rate and agglomeration quality can also be evaluated within typical flux ranges (5–20 $L \cdot m^{-2} \cdot h^{-1}$) (Jélvez et al., 2025; Urtubia & Suárez, 2020; Guzman et al., 2024).

To clarify the scope of SCT, it is necessary to distinguish between phenomena that are reliably captured and those that are only partially represented or not adequately developed under typical test conditions. Table 2 summarizes these differences by linking observable outputs to underlying physical processes.

Table 2 indicates that agreement between SCT results and industrial performance is generally stronger for early-stage phenomena dominated by reaction kinetics and short-range

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transport. In contrast, long-term controlling processes—such as permeability evolution, precipitation, and flow heterogeneity—are typically only partially represented or remain undeveloped within the typical duration and geometry of SCT.

Table 2. Capabilities and limitations of short column tests in representing heap leaching behavior. Adapted from Petersen and van Staden (2025), León et al. (2025), and Faraji et al. (2022).

Aspect	What SCT Captures Reliably	What SCT Does Not Capture Well	Technical Consequence
Metal extraction	Early-stage Ni and Co dissolution (5–20 days)	Long-term recovery evolution (100–300 days)	Overestimation of final recovery
Reaction kinetics	Effective kinetics under short transport paths	Intrinsic kinetics under evolving transport limitations	Misinterpretation of controlling mechanisms
Reagent consumption	Fast consumption (neutralization, Mg, Fe dissolution)	Delayed consumption (precipitation, secondary reactions)	Underestimation of total reagent demand
Hydrodynamics	Initial percolation behavior and flow response	Preferential flow and large-scale channeling	Underestimation of flow heterogeneity
Permeability	Early-stage permeability trends	Long-term permeability collapse due to clogging	Overestimation of hydraulic stability
Mechanical effects	Negligible (stable bed structure)	Compaction under heap load (5–10 m equivalent)	No representation of structural evolution
Chemical gradients	Weak or limited gradients	Strong vertical gradients and reprecipitation fronts	Underrepresentation of secondary reactions
Precipitation phenomena	Early-stage or rapid precipitation	Delayed precipitation (silica gel, Fe hydroxides, jarosite)	Underestimation of clogging risk
Environmental effects	Controlled laboratory conditions	Climate-driven effects (evaporation, rainfall, temperature)	No representation of field variability
Flow regime	Near-uniform or simplified flow	Heterogeneous, multi-dimensional flow (3D)	Misrepresentation of transport behavior
Time scale	Short-term behavior (<60 days)	Long-term system evolution (>100 days)	Bias toward early-stage processes

This imbalance reflects the dominance of short transport paths and relatively stable hydraulic conditions in laboratory columns. Under these conditions, high extraction values may be observed; however, these results should be interpreted cautiously, as delayed mechanisms that often reduce industrial performance may not yet be fully expressed.

A key limitation arises from the absence of mechanical compaction. Industrial heaps experience vertical stresses equivalent to several meters of ore, leading to a progressive reduction in permeability. In contrast, SCT columns (<1 m) remain mechanically stable and therefore do not reproduce stress-driven structural evolution (Pourverdi et al., 2025; Smith & Sinha, 2022).

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Figure 3 illustrates the fundamental differences between SCT conditions and industrial heap behavior. While SCT often assumes relatively uniform flow and stable structure, real heaps evolve dynamically, with preferential flow, compaction, and time-dependent precipitation influencing transport and reaction.

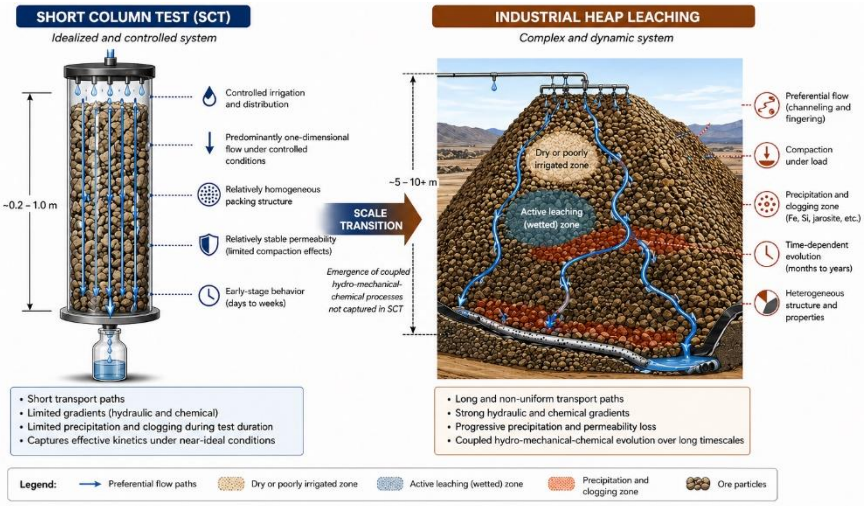

Figure 3. Conceptual comparison between short column tests and industrial heap leaching systems. Conceptual representation based on Robertson and Petersen (2024), Pourverdi et al. (2025), and Wang et al. (2023)

As shown in Figure 3, these differences can lead to systematic deviations when SCT results are interpreted as directly representative of industrial systems. In particular, flow heterogeneity is often less developed in SCT, whereas industrial heaps commonly exhibit preferential flow paths due to segregation, variability in agglomeration, and particle-size distribution (Ju et al., 2021; Wang et al., 2023).

Delayed precipitation phenomena constitute another important limitation. Secondary phases such as silica gel, iron hydroxides, and jarosite typically develop over extended timescales (>30–60 days) under evolving chemical gradients. Because SCT duration is limited, these processes may be only partially captured, leading to underrepresentation of long-term permeability loss (Ansah et al., 2025; Gao et al., 2021).

Environmental effects further differentiate SCT from industrial systems. Evaporation, rainfall, and temperature gradients significantly influence moisture distribution and solute transport in heaps, but are not reproduced under controlled laboratory conditions (Saldana et al., 2021; Trinanda et al., 2026). In addition, the transition from reaction-controlled to transport-limited regimes may not be fully developed within typical SCT durations.

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From a mechanistic standpoint, SCT reflects effective system behavior under constrained boundary conditions rather than fully representative heap performance. Observed extraction therefore results from the interaction among intrinsic kinetics, short-range mass transfer, and relatively stable hydraulic conditions (Chaitanya & Gupta, 2023; Majdalani & Guinot, 2023).

As a result, SCT data may exhibit systematic bias if interpreted without consideration of scale-dependent effects. These biases may include:

- apparent overestimation of metal recovery under favorable flow conditions;
- partial representation of total reagent consumption;
- delayed or absent manifestation of permeability collapse;
- limited detection of flow instability and heterogeneity.

The magnitude of these effects depends strongly on test design, instrumentation level, and ore characteristics.

In practice, SCT is best interpreted as a **diagnostic and comparative tool**, particularly for ranking ores, evaluating early-stage process variables, and estimating initial reagent demand. Its use as a predictive tool for final recovery, long-term permeability evolution, or heap stability requires careful validation through larger-scale testing or integrated multiscale approaches (Faris et al., 2022; Panyushkina & Muravyov, 2025).

The extent to which these limitations manifest depends strongly on ore characteristics, particularly mineralogical composition and particle size distribution, which are addressed in the following section.

5. Ore Characterization and the “Mixing Problem.”

The interpretation of short column test (SCT) results depends directly on the quality of ore characterization. Without a rigorous description of mineralogy and particle size distribution, outputs such as extraction curves and reagent consumption lose physical meaning and cannot be reliably extrapolated. Many inconsistencies reported in column leaching studies arise from poorly characterized feed materials rather than from test design itself (Kolmachikhina et al., 2021; Qi et al., 2026; Petrakis et al., 2021).

Nickel laterite processing is inherently complex due to mineralogical variability and multi-phase reactions, which strongly influence leaching behavior (Mamyrbayeva et al., 2023).

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Nickel laterite ores exhibit strong variability between limonitic, saprolitic, and blended systems, with distinct reaction pathways and failure mechanisms. Limonitic ores, rich in iron oxides, typically show high acid consumption (>300–500 kg H_2SO_4/t ore) and a strong tendency toward precipitation and pore clogging. Saprolitic ores, dominated by magnesium silicates, present lower precipitation risk but are more sensitive to permeability loss due to fines migration and clay swelling. In blended systems, these effects interact non-linearly, making system behavior difficult to predict (Mweene et al., 2024; Tauakelov et al., 2025; Acquah et al., 2025).

This variability leads to the so-called *mixing problem*: the inability to predict heap performance from tests performed on simplified or non-representative samples. In practice, SCT is often conducted on homogenized laboratory materials that do not capture spatial variability, segregation, or layering typical of industrial heaps. As a result, measured behavior reflects an artificial average rather than realistic system response.

Figure 4 shows how mineralogy and particle size cause structural heterogeneity in the ore bed. Clay-rich zones, fines buildup, and flow paths create non-uniform leaching conditions, which homogenized lab samples can't capture. This explains why SCT results from well-prepared materials often do not reflect industrial heap behavior.

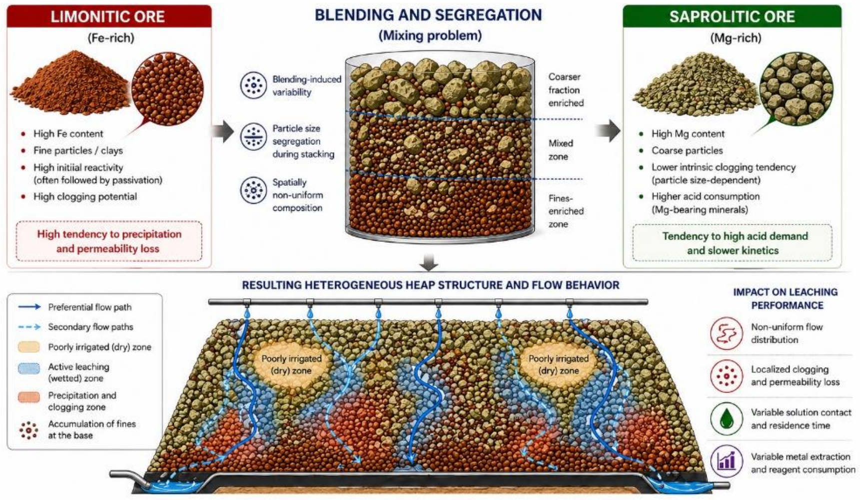

Figure 4: Conceptual representation of the “mixing problem” in nickel laterite heap leaching. Adapted from Mweene et al. (2024), Tauakelov et al. (2025), and Wang et al. (2023).

Figure 4 illustrates how mineralogical variability and particle size distribution generate structural heterogeneity within the ore bed. Clay-rich zones, fines accumulation, and preferential flow paths produce non-uniform leaching conditions that cannot be reproduced in

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homogenized laboratory samples. This explains why SCT results obtained under controlled conditions often fail to represent industrial heap behavior.

Reliable SCT interpretation, therefore, requires a minimum set of characterization parameters:

- Fine content (<75 µm / <38 µm): values >15–20 wt% reduce permeability and increase clogging risk, particularly in limonitic ores.
- Clay content and plasticity: swelling clays (e.g., smectite) reduce pore connectivity under wet conditions and limit flow (Ramirez-Torres et al., 2025).
- Quantitative mineralogy (QXRD, MLA): identifies reactive phases (e.g., goethite, serpentine, smectite) and controls both extraction and reagent consumption.
- Particle size distribution (PSD): full PSD curves are required; broad distributions promote segregation and non-uniform flow.
- Moisture content and bulk density: initial conditions (5–15 wt% moisture; ~1.2–1.8 t·m^{-3} density) define packing structure, permeability, and initial saturation.

Accurate interpretation of short column test results depends strongly on the prior characterization of the ore. Parameters such as particle size distribution, mineralogy, and fines content directly control both chemical reactivity and hydraulic behavior. Without this information, SCT results may appear consistent but lack physical meaning. Table 3 summarizes the key ore characterization parameters required for reliable test interpretation and their impact on leaching performance.

Table 3. Key ore characterization parameters required for short column test interpretation and their impact on heap leaching performance. Adapted from Kolmachikhina et al. (2021), Petrakis et al. (2021), Mweene et al. (2024), and Tauakelov et al. (2025)

Parameter	Typical Range / Method	Impact on SCT Behavior	Scale-Up Relevance
Particle size distribution (PSD)	Full PSD curve; top size 6–50 mm	Controls permeability and surface area	Governs flow distribution and heap stability
Fines content (<75 µm / <38 µm)	5–30% (variable)	Promotes clogging and permeability loss	Major driver of channeling and compaction
Clay content / plasticity	Qualitative + Atterberg limits	Affects agglomeration and moisture retention	Controls heap stability and flow heterogeneity
Mineralogy (QXRD, MLA)	Quantitative phase composition	Defines reactivity and acid consumption	Determines long-term leaching behavior
Ni-bearing phases	Limonite vs saprolite vs mixed	Controls extraction kinetics	Influences recovery and reagent demand
Mg-bearing minerals	Serpentine, olivine content	High acid consumption in early stage	Drives OPEX and solution chemistry

Fe phases	Goethite, hematite, amorphous Fe	Precipitation and clogging potential	Affects permeability evolution
Moisture content	5–20 wt% (typical)	Influences agglomeration and flow	Controls irrigation efficiency
Bulk density	1.2–2.0 $t \cdot m^{-3}$	Affects packing and porosity	Influences compaction at heap scale
Porosity / void fraction	30–50% (typical)	Controls flow and residence time	Determines transport behavior
Agglomerate size distribution	5–25 mm (after curing)	Controls permeability and flow uniformity	Critical for heap performance
Segregation tendency	Qualitative (handling-dependent)	Leads to flow heterogeneity	Drives preferential flow at scale

Table 3 shows that parameters such as fines content, mineralogy, and PSD control both chemical reactivity and hydraulic behavior. In particular, fines and clay content are strongly associated with permeability loss and flow heterogeneity, while mineralogical composition governs extraction kinetics and reagent consumption.

From a scale-up perspective, these variables define dominant operational risks. Limonitic ores are typically controlled by precipitation and permeability loss, whereas saprolitic ores are more influenced by acid consumption and flow distribution. Without this level of characterization, SCT results may reflect experimental conditions rather than intrinsic ore behavior.

When characterization is incomplete, SCT outputs are frequently reduced to isolated extraction values without physical context. In such cases, identical recoveries may correspond to fundamentally different systems, making comparison across studies unreliable.

From a critical perspective, SCT conducted without mineralogical and granulometric characterization should be treated with caution. In extreme cases, it reduces to a numerical output without mechanistic interpretation, where extraction is reported but controlling processes remain undefined (Pereira, 2014; Pereira et al., 2016).

This limitation becomes more severe at an industrial scale, where heterogeneity and segregation dominate system behavior. Ore characterization is therefore not a complementary step, but a prerequisite for meaningful SCT interpretation.

The influence of these variables becomes more pronounced during bed preparation, particularly during agglomeration and curing, which directly control permeability and structural stability. These aspects are discussed in the following section.

6. Bed Preparation: Agglomeration and Curing

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Bed preparation governs the initial hydraulic and structural behavior in short-column tests (SCT). Among all variables, agglomeration and curing determine whether the system behaves as a permeable bed or rapidly evolves toward clogging and flow instability. Despite their critical role, these parameters are often underreported or inconsistently controlled (Urtubia & Suárez, 2020; Guzman et al., 2024; Moncada et al., 2025) .

Agglomeration typically involves mixing crushed ore with water and/or acidic solution, followed by tumbling to form granules. In nickel laterites, acid curing is commonly applied to initiate partial dissolution and enhance particle binding. Moisture content usually ranges from 8 to 16 wt%, while acid addition varies between 20 and 80 kg H_2SO_4/t ore, depending on mineralogy (Hosseini Nasab et al., 2020a; Guzman et al., 2024).

Agglomeration and curing define the initial pore structure, particle stability, and resistance to fines migration, thereby controlling permeability and flow distribution. Small variations in these parameters can significantly alter hydraulic behavior, particularly in fine-rich lateritic systems.

Agglomeration and curing shape the initial structure and hydraulic behavior of leaching beds by affecting particle stability, pore connectivity, and resistance to fines migration, which influence permeability and flow. Small changes in moisture, acid, or curing time can alter bed performance, especially in fine-rich lateritic ores. Figure 5 shows how agglomeration quality impacts flow regimes and permeability.

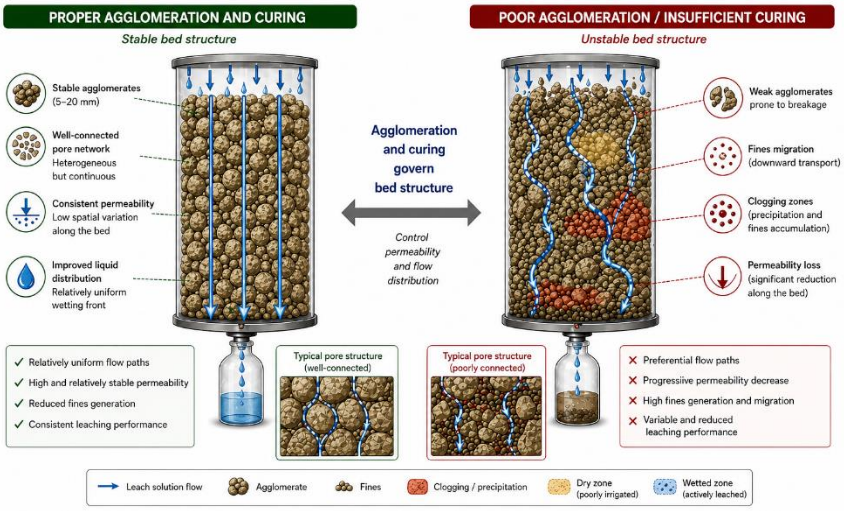

Figure 4. Effect of agglomeration and curing on bed structure and permeability in short column tests. Adapted from Urtubia and Suárez (2020), Guzman et al. (2024), and Gao et al. (2021).

Figure 5 illustrates that well-formed agglomerates promote uniform flow and stable permeability, whereas insufficient curing leads to fines release, localized clogging, and heterogeneous flow distribution.

Curing time (typically 12–72 h) allows partial chemical reactions that increase agglomerate strength. Insufficient curing results in weak agglomerates that disintegrate under irrigation, while excessive curing may promote premature precipitation and unnecessary acid consumption.

6.1. Agglomerate Quality and Structural Stability

Agglomerate integrity controls permeability evolution during leaching. Granules must withstand hydraulic shear, chemical weakening due to dissolution, and internal stresses during wetting–drying cycles.

Key quality indicators include compressive strength (5–25 kPa), abrasion resistance, and size stability. Imaging studies show that pore structure and fines distribution govern fluid pathways (Chen et al., 2025; Ghadiri, 2020). Mechanical activation prior to agglomeration may enhance bonding but can also increase fines generation if not properly controlled (Acquah et al., 2026a, 2026b)

6.2. Segregation and Fines Migration

Segregation is a major driver of non-uniform flow. During bed formation, fine particles migrate downward, forming low-permeability zones. This effect is amplified in systems with broad particle size distributions or poor agglomeration.

Consequences include:

- formation of clay-rich layers;
- permeability gradients;
- localized saturation and flow bypassing.

Even in SCT, partial segregation may occur. At industrial scale, the effect is significantly more pronounced due to stacking dynamics and mechanical disturbance. Poor control of segregation in laboratory preparation leads to non-representative hydraulic behavior.

6.3. Initial Permeability as a Controlling Parameter

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Initial permeability is a key predictor of leaching performance and is typically measured before irrigation. Reported values for agglomerated laterites range from 10^{-11} to 10^{-9} m² (Chun-Ming et al., 2022; Guzman et al., 2024).

Low permeability leads to rapid clogging, limited solution–ore contact, and increased preferential flow. Conversely, high permeability does not guarantee performance, as excessive void space or poor packing may promote channeling and reduce effective contact.

Agglomeration and curing are vital in heap leaching, especially for fine lateritic ores. They form stable agglomerates that influence permeability, flow, and segregation resistance. Changes in moisture, acid, and curing affect bed structure and hydraulics. Table 4 summarizes these parameters and their impacts.

Table 4. Key agglomeration and curing parameters and their impact on permeability and structural stability. Adapted from Guzman et al. (2024), Urtubia and Suárez (2020), and Petersen and van Staden (2025)

Parameter	Typical Range / Condition	Effect on Agglomerate Structure	Impact on Permeability	Impact on Scale-Up Stability
Moisture content (agglomeration)	8–16 wt%	Promotes particle binding and granule formation	Optimal range increases permeability; too low → weak agglomerates; too high → collapse	Controls mechanical integrity and resistance to segregation
Acid addition (curing)	20–80 kg H_2SO_4/t ore	Enhances chemical bonding and partial dissolution	Improves initial permeability but may promote later precipitation	Affects long-term stability and clogging risk
Binder addition (if used)	0–5 wt% (cement, polymers)	Increases mechanical strength of agglomerates	Stabilizes permeability under flow	Reduces breakdown under heap load
Agglomerate size	5–25 mm	Defines pore structure and void connectivity	Larger size → higher permeability; too large → segregation risk	Controls flow distribution and channeling
Mixing intensity	Low to high (process-dependent)	Determines homogeneity of agglomerates	Poor mixing → heterogeneous permeability	Drives segregation and flow instability
Curing time	12–72 h	Allows chemical and mechanical stabilization	Insufficient curing → permeability loss during leaching	Critical for long-term structural stability
Curing temperature	Ambient (20–40°C typical)	Affects reaction kinetics during curing	Higher temperature may accelerate bonding	Limited effect unless extreme conditions

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Initial bed permeability	$10^{-9} – 10^{-7}$ m² (typical)	Reflects combined agglomeration quality	Direct indicator of flow capacity	Key parameter for heap design
Agglomerate strength	Qualitative / compression tests	Resistance to breakage under load	Weak agglomerates → fines generation → clogging	Controls durability over time
Segregation tendency	Qualitative (handling-dependent)	Separation of coarse and fine fractions	Leads to localized permeability variation	Major cause of preferential flow

Table 4 shows that agglomeration is not merely a preparation step but a primary control on hydraulic performance. Moisture content and acid addition define the initial structure, while curing time governs mechanical stability under flow. Deviations from optimal conditions lead to fines generation, permeability loss, and flow instability.

From a scale-up perspective, long-term stability parameters are more critical than initial performance. For instance, high acid addition can boost early permeability but raises precipitation and clogging risks over time. Likewise, inadequate curing may seem fine in SCT but causes degradation under heap load.

These interactions reinforce the idea that agglomeration must be optimized not only for short-term permeability but also for sustained structural integrity. Failure to account for these effects is a major contributor to discrepancies between laboratory tests and industrial heap performance.

6.4. Critical Perspective: Agglomeration as a Source of Bias

Agglomeration in SCT creates a biased bed that is more homogeneous and stable than industrial heaps. Lab conditions ensure uniform mixing and moisture, but industrial systems vary in agglomerate quality, curing, and stacking.

As a result, SCT tends to overestimate:

- permeability stability;
- flow uniformity;
- early-stage extraction.

This distortion arises because measured performance reflects laboratory preparation quality rather than intrinsic ore behavior under realistic conditions.

Agglomeration and curing must therefore be treated as controlled experimental variables rather than routine preparation steps. Without explicit reporting and validation, SCT results lose predictive value and cannot be reliably used for scale-up

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7. Experimental Design of Short Column Tests

Short-column tests (SCTs) design influences chemical reactions, fluid flow, and mass transfer during leaching. Small changes in geometry, irrigation, or chemical conditions can greatly impact results, leading to inconsistency in literature often due to experimental design rather than ore behavior.

Column geometry defines the fundamental boundary conditions for flow and transport. Two parameters are critical: column diameter and bed height. The ratio between column diameter (D) and particle size (d_p) governs wall effects. When $D/d_p < 20–30$, flow becomes strongly wall-dominated, reducing tortuosity and leading to overestimation of permeability and extraction (Chun-Ming et al., 2022; Wang et al., 2020; Ju et al., 2021).

Bed height introduces a second limitation. Typical SCT heights (0.2–1.0 m) are insufficient to develop vertical gradients that control industrial heap behavior. As a result, chemical stratification, precipitation fronts, and slow reaction mechanisms are suppressed or delayed, despite their importance in heaps exceeding 5–10 m (Cariaga, 2015; Petersen & van Staden, 2025).

Column geometry influences hydraulic behavior and reaction gradients in short column tests. Parameters like diameter and height affect flow, residence time, and secondary reactions. Narrow columns amplify wall effects, and short columns limit chemical gradient formation, crucial in industry. Figure 6 shows how geometry impacts flow and transport behavior..

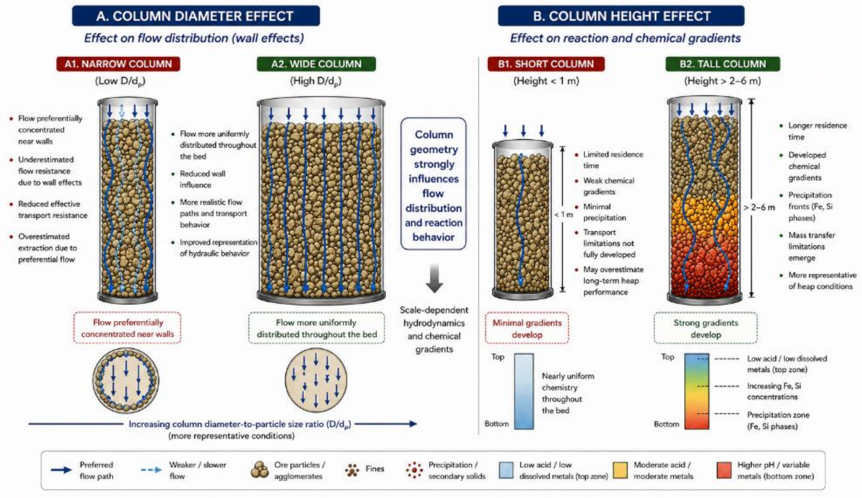

Figure 5. Effect of column geometry on flow distribution and reaction gradients. Narrow columns promote wall-dominated flow and reduced transport resistance, while short columns limit the development of chemical gradients. Adapted from Chun-Ming et al. (2022), Wang et al. (2020), and Ju et al. (2021).

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Figure 6 illustrates that narrow columns amplify wall effects, while short columns limit the development of chemical gradients. Together, these factors reduce the physical representativeness of SCT and increase scale-up uncertainty.

Irrigation controls the distribution, saturation, and residence time of liquid within the bed. Typical SCT fluxes range from 5–20 $L \cdot m^{-2} \cdot h^{-1}$, but irrigation mode strongly influences system behavior. Continuous flow stabilizes percolation but suppresses wetting–drying cycles, while intermittent irrigation enhances oxygen transfer, cracking, and flow redistribution. Spray systems improve wetting uniformity, although they differ from industrial drip irrigation (Huang et al., 2026).

Recirculation of pregnant leach solution (PLS) further alters system behavior. It increases ionic strength and accelerates extraction, but may reduce apparent reagent consumption and mask precipitation effects. In contrast, a fresh solution better represents early heap conditions but does not capture the accumulation of dissolved species (Jélvez et al., 2025; Wang et al., 2021, 2022). These differences highlight the sensitivity of SCT results to irrigation strategy.

Chemical conditions define the driving forces for dissolution and secondary phase formation. Sulfuric acid systems are most common, although chloride systems are also used. Sulfuric acid promotes iron dissolution and subsequent precipitation (e.g., iron hydroxides, jarosite, silica gel), whereas chloride systems modify iron speciation, reducing precipitation but introducing operational challenges such as corrosion and volatilization. Typical acid concentrations range from 5 to 50 $g \cdot L^{-1}$ (Hosseini Nasab et al., 2020a, 2020b; Cui et al., 2020).

In addition, geomicrobiological interactions and mineral transformations may further modify leaching pathways under industrial conditions (Pakostova et al., 2024).

Reliable interpretation requires a comprehensive characterization of the pregnant leach solution, including Ni and Co extraction, impurity levels (Fe, Al, Mg, Si), pH, redox potential (Eh), and total dissolved solids. Incomplete reporting limits the industrial relevance of SCT data (Mends et al., 2024; Rao et al., 2020).

Chemical and operational conditions in SCT greatly influence dissolution and secondary phase formation. Variables such as acid concentration, pH, redox potential, and solution composition affect metal extraction, precipitation, permeability, and compatibility. These change over time and interact with mineralogical and hydraulic factors, requiring structured interpretation. Table 5 summarizes typical SCT conditions and their effects on dissolution, precipitation, and scale-up.

Table 5. Typical chemical and operational conditions in short column tests and their impact on dissolution, precipitation, and scale-up reliability. Adapted from Hosseini Nasab et al. (2020a), Cui et al. (2020), and Mends et al. (2024).

Parameter	Typical Range / Condition	Effect on Dissolution	Effect on Precipitation / Secondary Reactions	Impact on Scale-Up Reliability
Acid concentration (H_2SO_4)	5–50 $g\cdot L^{-1}$	Increases Ni/Co dissolution rate	High levels promote Fe precipitation and silica dissolution	Overestimation of extraction if long-term effects ignored
Chloride concentration (HCl systems)	10–100 $g\cdot L^{-1}$	Enhances metal solubility and kinetics	Lower Fe precipitation but possible volatilization losses	Requires full Cl^- balance; risk of underestimation
pH	0.5–2.5 (typical)	Low pH favors dissolution	pH increase promotes Fe/Al precipitation	pH drift not fully captured in short tests
Redox potential (Eh)	400–700 mV	Controls Fe^{2+}/Fe^{3+} equilibrium	High Eh favors Fe precipitation (hydroxides, jarosite)	Misrepresentation of long-term redox evolution
Temperature	Ambient (20–40°C)	Moderate increase in kinetics	Higher temperature may accelerate precipitation	Industrial thermal gradients not represented
Irrigation rate	5–20 $L\cdot m^{-2}\cdot h^{-1}$	Controls liquid–solid contact and residence time	High rates may reduce local supersaturation	Differences in distribution vs industrial heaps
Liquid-to-solid ratio (L/S)	0.5–2.0 $m^3\cdot t^{-1}$	Determines cumulative dissolution extent	Low L/S may limit precipitation development	Underestimation of long-term reactions
Recirculation vs fresh feed	Both used	Recirculation increases metal concentration	Promotes accumulation of dissolved species and secondary reactions	Alters chemical equilibrium vs industrial systems
Fe concentration in PLS	0.5–10 $g\cdot L^{-1}$	Competes with Ni/Co dissolution	Drives precipitation ($Fe(OH)_3$, jarosite)	Affects downstream processing and clogging risk
Mg concentration in PLS	5–30 $g\cdot L^{-1}$	Indicates consumption of acid by gangue	Limited precipitation but increases ionic strength	Impacts reagent demand and solution handling
Si concentration (dissolved)	0.1–2 $g\cdot L^{-1}$	Limited effect on dissolution	Forms silica gel → clogging risk	Often underestimated in SCT
Test duration	10–60 days	Captures early dissolution only	Insufficient for delayed precipitation	Major source of scale-up error

Table 5 shows that chemical and operational variables simultaneously influence dissolution and precipitation. While parameters such as acid concentration and pH are often

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optimized for early extraction, they also control secondary reactions that govern permeability and long-term stability.

A key limitation is that precipitation mechanisms—particularly those involving iron and silica—develop over extended timescales and in response to evolving chemical gradients. Due to the limited test duration, SCT captures these processes only partially, resulting in systematic underestimation of permeability loss and reagent consumption.

From a scale-up perspective, chemical conditions cannot be evaluated independently of transport and structural effects. Variables such as recirculation, liquid-to-solid ratio, and ionic strength alter equilibrium conditions and may obscure long-term behavior. Consequently, SCT results must be interpreted within a time-dependent framework that accounts for system evolution (Maghsoudy et al., 2022).

More broadly, SCT design can introduce artifacts that are often misinterpreted as intrinsic or behavioral. Narrow columns enhance apparent extraction through wall-driven flow, short beds suppress precipitation, uniform irrigation underestimates channeling, and recirculation alters chemical equilibria. These effects systematically bias results toward optimistic performance.

SCT should therefore be treated as an approximation rather than a direct representation of heap leaching. Accurate interpretation requires recognition of design-induced artifacts and, where possible, sensitivity analysis of key variables such as geometry, irrigation strategy, and chemical conditions.

Ultimately, the reliability of SCT results depends on experimental design quality and the completeness of monitoring. The following section examines the distinction between robust and fragile datasets and its implications for data interpretation.

8. Minimum Instrumentation Requirements: Distinguishing Robust from Fragile Tests

Instrumentation determines whether a short column test (SCT) provides mechanistic insight or only descriptive results. Because leaching involves coupled hydraulic, transport, and chemical processes, the absence of key measurements prevents identification of controlling mechanisms. Under such conditions, smooth extraction curves may mask internal artifacts such as channeling or permeability loss (Odidi et al., 2023a, 2023b, 2024; Krishnamoorthy, 2023).

Instrumentation level in short column tests crucially affects data quality and interpretability. Basic setups can show general trends but often miss internal hydraulic and transport phenomena that influence system behavior. Insufficient instrumentation may yield seemingly consistent data that hides critical artifacts. Figure 7 compares minimally and fully instrumented SCTs, illustrating measurement impact on diagnostics.

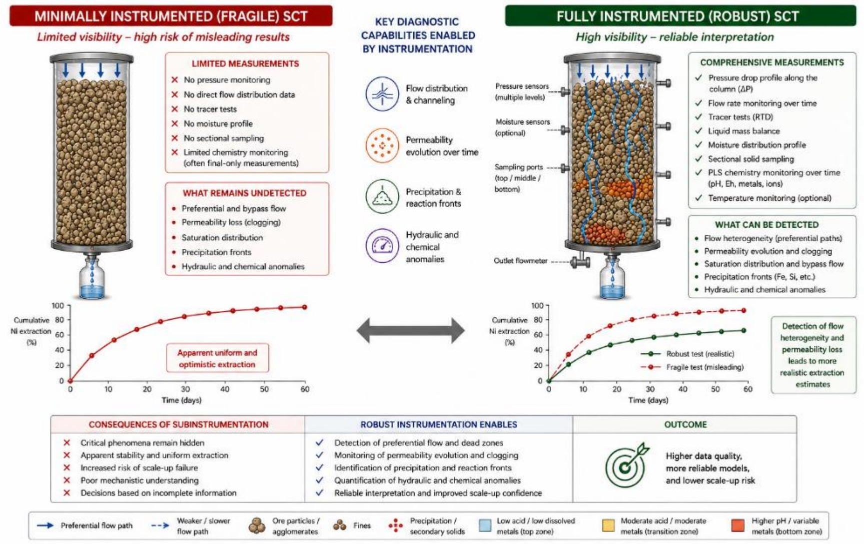

Figure 6. Comparison between minimally instrumented (fragile) and fully instrumented (robust) short column tests. Adapted from Odidi et al. (2023a, 2023b), Robertson et al. (2021), and Wang et al. (2023).

Figure 7 shows that the distinction between fragile and robust SCT datasets is defined by the ability to observe internal system behavior rather than relying solely on outlet measurements. Minimally instrumented tests may produce smooth and consistent extraction curves, but lack the resolution required to detect preferential flow, permeability evolution, and reaction gradients. In contrast, fully instrumented systems provide direct evidence of hydraulic behavior, often yielding lower yet more realistic extraction estimates (Krishnamoorthy, 2023).

From a scale-up perspective, this distinction is critical. Sub-instrumented tests systematically overestimate performance and increase the risk of failure at an industrial scale, whereas robust instrumentation enables physically grounded interpretation and more reliable process modeling (Kalungi et al., 2024).

Among the required measurements, pressure drop (ΔP) is one of the most informative variables for tracking the evolution of permeability. Monitoring ΔP along the column height is preferred, although even a global measurement provides valuable insight. Stable ΔP indicates consistent permeability, while gradual increases suggest clogging due to fines migration or precipitation. Sudden variations typically reflect structural rearrangement or localized blockage. Without ΔP data, it is not possible to distinguish between uniform flow and channeling-driven extraction (Binnemans & Jones, 2023, 2025).

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Percolation flow rate must also be measured as a function of time. Reporting cumulative volume alone obscures transient hydraulic behavior. A declining flow rate indicates permeability loss, whereas an increase suggests channel formation or bypass flow. Oscillatory patterns are typically associated with unstable flow regimes. Although nominal irrigation rates in SCT range from 5 to 20 L·m^{-2}·h^{-1}, local variations may be significant under non-uniform flow conditions (Wang et al., 2023; Robertson et al., 2021).

Hydraulic closure, obtained through a complete water balance, is essential. This includes measuring inlet and outlet flows, estimating evaporation, and quantifying liquid retention within the bed. Mass balance discrepancies exceeding 5–10% indicate bypass flow, dead zones, or measurement errors. Without hydraulic closure, interpretation of extraction data becomes unreliable (Ibrahim, 2026).

Reliable interpretation of short column tests depends on proper experimental design and instrumentation, which help detect artifacts like channeling, clogging, and flow instability. Without adequate measurements, these issues remain hidden, making data appear consistent but masking inconsistencies. Table 6 outlines the minimum instrumentation needed for SCT and its diagnostic role.

Table 6. Minimum instrumentation requirements for short column tests and their diagnostic value for detecting hydraulic and transport artifacts. Adapted from Odidi et al. (2023a, 2023b), Robertson et al. (2021), and Wang et al. (2023).

Measurement / Instrumentation	Typical Method / Tool	What It Detects	If Not Measured	Impact on Data Reliability
Pressure drop (ΔP) along bed	Pressure sensors / manometers	Permeability evolution, clogging onset	Clogging remains invisible	High risk of misinterpreting stable flow
Total pressure drop	Inlet–outlet pressure measurement	Global hydraulic resistance	No detection of gradual permeability loss	Overestimation of system stability
Percolation flow rate vs time	Flowmeter / volumetric collection	Flow stability, channeling, saturation changes	Flow heterogeneity undetected	Misinterpretation of extraction kinetics
Water balance (in/out/retention)	Mass balance / collection tanks	Retention, evaporation, bypass flow	Unknown fluid distribution	Incorrect residence time estimation
Tracer tests (RTD)	Chemical tracer / conductivity	Channeling, dead zones, flow paths	No identification of preferential flow	Major uncertainty in transport behavior
Moisture profile (bed)	Sampling / sensors (optional)	Saturation distribution	Dry/wet zones not identified	Misrepresentation of flow regime

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Sectional solid sampling (top/mid/bottom)	Post-test sampling + analysis	Precipitation zones, reaction gradients	No spatial resolution of reactions	Loss of mechanistic interpretation
PLS composition vs time	Chemical analysis (ICP, titration)	Dissolution and precipitation trends	Only final extraction known	Incomplete reaction pathway understanding
pH and Eh monitoring	Electrodes / probes	Chemical driving forces, redox conditions	No control of reaction environment	Misinterpretation of kinetics
Temperature monitoring	Thermocouples	Reaction rate effects	Thermal influence ignored	Minor to moderate impact depending on system

Table 6 demonstrates that instrumentation is fundamental to SCT interpretation. Measurements such as pressure drop, flow-rate evolution, and tracer response provide direct evidence of hydraulic behavior, enabling the detection of artifacts that cannot be inferred from extraction data alone.

A critical limitation of poorly instrumented tests is that major failure mechanisms—particularly channeling and clogging—cannot be identified from metal recovery curves. Systems may appear stable while undergoing progressive loss of permeability or internal flow redistribution. Similarly, without tracer tests, preferential flow paths remain undetected, despite being a primary cause of scale-up failure (Mbedzi, 2020).

Tracer experiments provide direct insight into flow distribution and are among the most effective methods for diagnosing channeling. These tests typically involve pulse injection of a conservative tracer, followed by monitoring of breakthrough curves. Sharp peaks indicate short-circuiting, whereas broader distributions reflect more uniform flow. Delayed responses are associated with stagnant zones or high liquid retention. Residence time distribution (RTD) analysis derived from these data is particularly valuable for linking hydraulic behavior to extraction trends (Odidi et al., 2023b; Wang et al., 2023).

Post-test solid sampling complements hydraulic diagnostics by revealing spatial heterogeneity within the bed. Sectioning the column into top, middle, and bottom zones allows identification of reaction gradients and precipitation fronts. Typical patterns include higher extraction near the top, intermediate precipitation zones, and fines accumulation at the base. Without this spatial resolution, SCT results are reduced to bulk averages, obscuring key mechanisms (Santos et al., 2021).

From a critical perspective, instrumentation acts as a quality filter rather than an optional enhancement. Tests lacking pressure monitoring, flow measurement, or hydraulic

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closure cannot support mechanistic interpretation, even when extraction data appear consistent. Robust SCT integrates pressure data, flow monitoring, water balance, tracer analysis, and post-test characterization, enabling interpretation of coupled transport and reaction processes. In contrast, fragile SCT relies solely on extraction and reagent consumption and is suitable only for preliminary screening.

In practice, many published studies fall into the latter category, leading to systematic overinterpretation. Common errors include misinterpreting channeling as high permeability, assuming uniform leaching under localized flow conditions, and attributing early extraction exclusively to intrinsic kinetics. These biases consistently result in overestimating performance and underestimating operational risk.

The implications of these limitations become clearer when examining the typical failure modes observed in short column tests, which are addressed in the following section.

9. Typical Failure Modes and How Short Column Tests Mislead

Short column tests (SCT) may be prone to misinterpretation because similar experimental signals can arise from fundamentally different mechanisms. Without adequate instrumentation and contextual analysis, these mechanisms may be misidentified, potentially leading to incorrect conclusions regarding kinetics, permeability, and process performance (Ju et al., 2022; Maghsoudy et al., 2022; Ansah et al., 2025).

Interpreting SCT results is inherently complex because outputs such as extraction curves, flow stability, or pressure response do not uniquely identify the underlying processes, particularly in systems where transport, reaction, and structural evolution are strongly coupled. Under such conditions, simplified interpretation may introduce systematic errors in kinetic analysis and scale-up assessment.

Figure 8 presents a conceptual framework linking observed SCT signals to their possible origins and associated misinterpretations.

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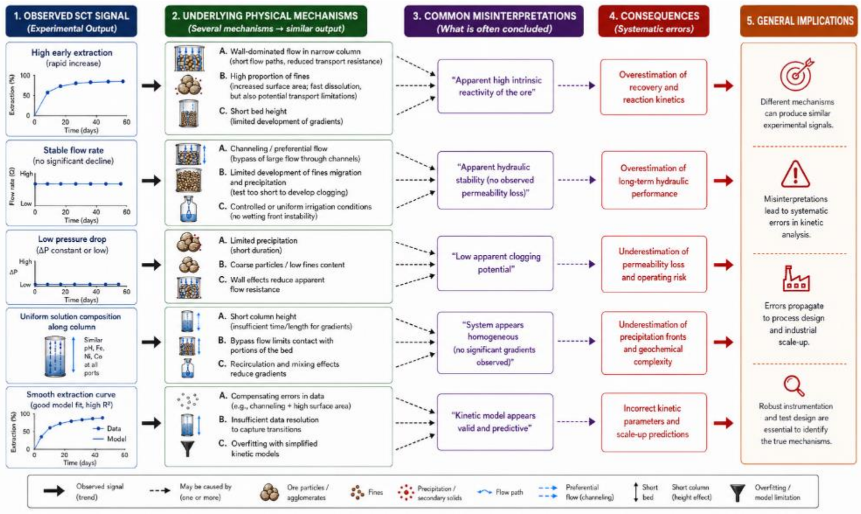

Figure 7. Relationship between observed SCT signals, underlying physical mechanisms, and common misinterpretations. Conceptual representation based on Estay and Díaz-Quezada (2020), Saldana et al. (2021), and Ansah et al. (2025).

As illustrated in Figure 8, similar outputs—such as extraction trends, flow-rate variations, or pressure responses—may result from different combinations of transport, reaction, and structural effects. Consequently, single-variable interpretation is often insufficient, and reliance on global metrics such as cumulative extraction may obscure the controlling mechanisms.

To improve interpretive reliability, failure modes should be analyzed by their diagnostic signatures rather than by data extraction alone. Table 7 summarizes common SCT failure modes, linking observable signals to underlying causes and typical interpretations

Table 7. Typical failure modes in short column tests, corresponding diagnostic signals, and underlying causes. Adapted from Estay and Díaz-Quezada (2020), Saldana et al. (2021), and Ansah et al. (2025).

Failure Mode	Observable Signal	Underlying Cause	Typical Misinterpretation	Impact on Scale-Up
Progressive clogging	Gradual decrease in flow rate (Q ↓), increase in ΔP	Fines migration, silica gel formation, Fe precipitation	Interpreted as stable kinetics slowing down	Underestimation of permeability loss
Channeling / preferential flow	High flow rate with low extraction	Non-uniform packing, segregation, poor irrigation distribution	Interpreted as low ore reactivity	Underestimation of recoverable metal
Artificially high extraction	Rapid early extraction (<10–20 days)	Short transport paths, wall effects, fine particles	Interpreted as high intrinsic kinetics	Overestimation of final recovery

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Low apparent reagent consumption	Low acid consumption relative to expectations	Short duration, limited secondary reactions	Interpreted as low gangue reactivity	Underestimation of OPEX
Apparent hydraulic stability	Constant flow rate over time	Absence of compaction and delayed precipitation	Interpreted as stable permeability	Overestimation of long-term performance
Flow bypass / dead zones	Irregular flow or stagnant regions (if detected)	Segregation, poor agglomeration, and non-uniform wetting	Often undetected in non-instrumented tests	Major uncertainty in scale-up
Delayed permeability collapse (not observed)	No change in ΔP during test	Test duration too short	Interpreted as absence of clogging risk	Failure at industrial scale
Inconsistent extraction trends	Fluctuating recovery vs time	Transient flow paths, unstable wetting front	Treated as experimental noise	Misinterpretation of kinetics
Overfitting of kinetic models	High R^2 (>0.95) but poor predictive power	Use of simplified models on non-representative data	Interpreted as valid predictive model	Incorrect design assumptions
Underdeveloped chemical gradients	Uniform PLS composition along test	Short column height	Interpreted as homogeneous system behavior	Underestimation of precipitation zones

Table 7 indicates that many observed behaviors in SCT can be associated with identifiable mechanisms when appropriate measurements are available. However, when key variables are not monitored, these same behaviors may lead to consistent but potentially misleading interpretations.

Among the most recurrent mechanisms, progressive clogging is typically associated with a gradual decrease in flow rate and an increase in pressure drop, reflecting fines migration, silica gel formation, or iron precipitation. In short-duration tests, this effect may appear limited, whereas in industrial heaps it often becomes more pronounced over time (Ansah et al., 2025).

Conversely, high flow rates combined with relatively low extraction may indicate channeling, in which the leaching solution bypasses reactive zones through preferential pathways. This behavior is commonly associated with non-uniform packing, particle segregation, or uneven irrigation distribution. In the absence of tracer or pressure data, it may be interpreted as low ore reactivity rather than a hydraulic artifact (Ju et al., 2022; Wang et al., 2023).

Rapid early extraction is another characteristic feature frequently observed in SCT. High recovery within the first 10–20 days is generally associated with short transport paths, enhanced mass transfer, and readily accessible reactive surfaces. While useful for comparative assessment, these results should be interpreted cautiously when extrapolating to long-term performance, as they may not reflect sustained reaction conditions.

Similarly, low apparent reagent consumption may be observed due to limited test duration and incomplete development of secondary reactions. Processes such as iron precipitation and silica gel formation typically evolve over longer timescales and may therefore be only partially represented, potentially affecting estimates of total reagent demand and operational costs.

Apparent hydraulic stability is also context-dependent. Constant flow rates observed in SCT may reflect stable conditions within the test duration and geometry; however, they may also be associated with the absence of compaction and delayed precipitation mechanisms that are more relevant at the heap scale (Smith & Sinha, 2022; Pourverdi et al., 2025).

More broadly, SCT does not fully reproduce the structural and geotechnical evolution observed in industrial heaps. Processes such as compaction, particle rearrangement, and stress-induced permeability gradients develop over larger spatial and temporal scales, continuously modifying flow pathways and reaction environments. Their limited representation in SCT contributes to differences between laboratory observations and industrial behavior.

Taken together, these effects may introduce systematic bias if SCT results are interpreted without considering scale-dependent constraints. Depending on test design, instrumentation level, and ore characteristics, SCT data may:

- suggest higher apparent metal recovery under favorable flow conditions;
- indicate stable permeability within the test duration;
- partially represent reagent consumption;
- provide limited detection of clogging and channeling mechanisms.

The magnitude and direction of these effects are not universal and depend strongly on experimental conditions and material properties.

Reliable interpretation, therefore, requires a multi-parameter approach, integrating extraction data with flow-rate evolution, pressure measurements, solution chemistry, and, where possible, spatial characterization of the bed. Without this integration, interpretation may remain descriptive and potentially misleading.

A central source of error is the implicit assumption that SCT-derived kinetic parameters represent intrinsic reaction rates. In practice, these parameters reflect the system's effective behavior under specific hydraulic and experimental conditions. Distinguishing between effective and intrinsic kinetics is therefore essential and is addressed in the following section.

10. Kinetic Interpretation: Effective vs Intrinsic

Leaching kinetics derived from short column tests (SCT) are more appropriately interpreted as apparent or system-dependent rates, rather than strictly intrinsic reaction constants. These observed kinetics reflect the combined influence of reaction, transport, and hydrodynamic conditions within the experimental system (Faraji et al., 2022; Zhang et al., 2023).

In SCT, the measured extraction curve arises from the interaction among surface reaction kinetics, intra-particle diffusion, external mass transfer, and flow distribution. Because these processes are coupled, the resulting kinetic response is dependent on experimental conditions and may not directly represent intrinsic material properties (Chaitanya & Gupta, 2023; Majdalani & Guinot, 2023).

The reduced column height and limited test duration generally favor conditions of low transport resistance, high accessibility of reactive surfaces, and limited development of secondary phases. Under these conditions, extraction curves typically exhibit rapid initial rates followed by progressive slowing. This behavior is often interpreted as a transition from reaction-controlled to diffusion-controlled regimes; however, in short columns (<1 m), this pattern may also reflect experimental constraints rather than a clear mechanistic shift.

Various kinetic models, including the Shrinking Core Model, pseudo-first-order expressions, and empirical power-law formulations, can provide good fits to SCT data ($R^2 > 0.95$). While such fits are useful for comparative purposes, a high correlation does not necessarily imply physical validity, particularly when model assumptions are not independently verified or when parameters are extrapolated beyond the experimental domain (Cui et al., 2020; Shayakhmetova et al., 2025).

Kinetic modeling is therefore valuable as an interpretive tool, but its reliability depends on how model assumptions are treated. Because SCT data are typically smooth and monotonic, multiple models may fit the same dataset with similar statistical quality, even though they represent different mechanisms. This introduces a risk of overinterpretation if model selection is based solely on goodness-of-fit criteria.

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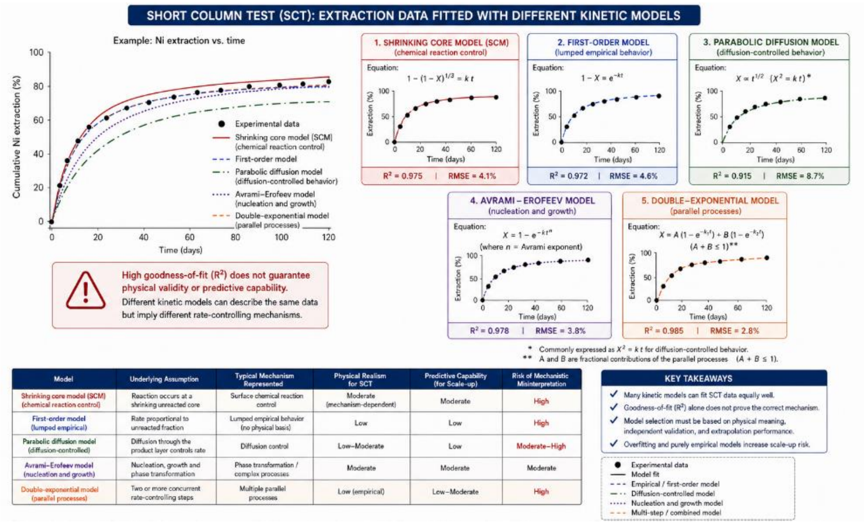
Figure 9 illustrates typical SCT extraction data fitted using different kinetic models, highlighting the limitations of relying exclusively on statistical correlation.



High goodness-of-fit (R^2) does not guarantee physical validity or predictive capability.
Different kinetic models can describe the same data but imply different rate-controlling mechanisms.

* Commonly expressed as $X^2 = kt$ for diffusion-controlled behavior.
** A and B are fractional contributions of the parallel processes $(A + B \leq 1)$.

Model	Underlying Assumption	Typical Mechanism Represented	Physical Realism for SCT	Predictive Capability (for Scale-up)	Risk of Mechanistic Misinterpretation
Shrinking core model (SCM) (chemical reaction control)	Reaction occurs at a shrinking unreacted core	Surface chemical reaction control	Moderate (mechanism-dependent)	Moderate	High
First-order model (lumped empirical)	Rate proportional to unreacted fraction	Lumped empirical behavior (no physical basis)	Low	Low	High
Parabolic diffusion model (diffusion-controlled)	Diffusion through the product layer controls rate	Diffusion control	Low–Moderate	Low	Moderate–High
Avrami–Erofeev model (nucleation and growth)	Nucleation, growth and phase transformation	Phase transformation / complex processes	Moderate	Moderate	Moderate
Double-exponential model (parallel processes)	Two or more concurrent rate-controlling steps	Multiple parallel processes	Low (empirical)	Low–Moderate	High

KEY TAKEAWAYS

- ✓ Many kinetic models can fit SCT data equally well.
- ✓ Goodness-of-fit (R^2) alone does not prove the correct mechanism.
- ✓ Model selection must be based on physical meaning, independent validation, and extrapolation performance.
- ✓ Overfitting and purely empirical models increase scale-up risk.

● Experimental data
— Model fit
- - - Empirical / first-order model
— · · Diffusion-controlled model
····· Nucleation and growth model
- - - Multi-step / combined model

Figure 8. Typical fitting of SCT extraction data using different kinetic models. High correlation does not necessarily imply physical validity or predictive capability. Conceptual representation based on Faraji et al. (2022), Shayakhmetova et al. (2025), and Zhang et al. (2023).

As shown in Figure 9, models based on surface reaction control, diffusion limitations, or empirical formulations may all reproduce experimental data with similar accuracy. In such cases, the apparent agreement reflects the mathematical flexibility of the models rather than confirmation of the underlying mechanism.

This issue may be further amplified when early-stage data are extrapolated to longer times. In many cases, kinetic parameters derived from short-duration tests are extended beyond their valid range without accounting for the progressive emergence of transport limitations, structural changes, or secondary reactions. As a result, fitted parameters may be interpreted as intrinsic constants, even though the experimental system conditions them.

The implications of this limitation become more evident during scale-up. Short-term SCT data (typically 10–30 days) are sometimes used to infer behavior over industrial timescales of 100–300 days. Such extrapolation implicitly assumes that controlling mechanisms, transport conditions, and bed structure remain stable over time—a condition that is rarely maintained in practice.

At larger scales, long-term behavior is influenced by the evolution of permeability, the development of preferential flow paths, precipitation and pore blockage, and progressive compaction. These processes tend to modify transport conditions and, consequently, the apparent kinetics. Because their development is limited in SCT, their influence on reaction rates may be underrepresented.

This limitation often manifests as a discrepancy between predicted and observed performance at industrial scale, referred to here as the "long-term extrapolation gap." This gap reflects the difference between early-stage system response and time-evolving behavior under field conditions.

From a mechanistic perspective, SCT-derived kinetic parameters are best interpreted as effective system-level descriptors, rather than transferable material constants. The observed rates depend on geometry, flow regime, chemical environment, and structural evolution of the bed.

Improving the reliability of kinetic interpretation, therefore, requires a clear distinction between different levels of description:

- Empirical fitting, useful for comparative analysis of datasets;
- Apparent kinetics, reflecting system-dependent behavior under specific conditions;
- Intrinsic kinetics, associated with fundamental reaction mechanisms and requiring independent validation;
- Mechanistic models, which integrate reaction and transport processes and require multi-scale verification.

In this context, model selection should be supported by independent evidence, such as transport analysis, tracer experiments, or validation using larger-scale columns. Without such support, kinetic parameters should be interpreted cautiously and within the limits of the experimental domain.

Overall, SCT is most appropriately used for comparative evaluation and mechanistic insight at early stages, rather than for direct prediction of long-term industrial performance.

The interpretation of kinetics is closely linked to reagent consumption, which may be subject to similar limitations and is discussed in the following section.

11. Reagent Consumption: How to Report Correctly

Reagent consumption in heap leaching is a key parameter influencing operating costs, solution chemistry, and downstream processing. In short column tests (SCT), it is often reported as a single cumulative value; however, this approach may obscure the temporal

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evolution of consumption mechanisms and the controlling processes that govern them (Borda & Torres, 2023; Hosseini Nasab et al., 2020a; Ibrahim, 2026).

A more informative interpretation requires evaluating reagent consumption as a function of time rather than as a final value. Time-resolved profiles provide insight into the sequence of reactions and allow differentiation between early-stage and delayed consumption regimes. In SCT, cumulative consumption curves often stabilize within 10–30 days, with values on the order of 200–400 kg H_2SO_4/t ore for limonitic laterites. However, this apparent stabilization should be interpreted with caution, as longer-term processes may not have fully developed within the test's limited duration.

The challenge in interpreting SCT data lies in linking laboratory observations to scale-up reliability. While previous sections highlight limitations in hydraulics, chemistry, and kinetics, the central issue is integrating them into a coherent decision framework. SCT data are sometimes used directly in process design without sufficient validation or mechanistic interpretation, which may introduce uncertainty in predicted reagent demand and system behavior.

Figure 10 presents a conceptual framework for the interpretation of reagent consumption in SCT, distinguishing between direct extrapolation and mechanism-based approaches

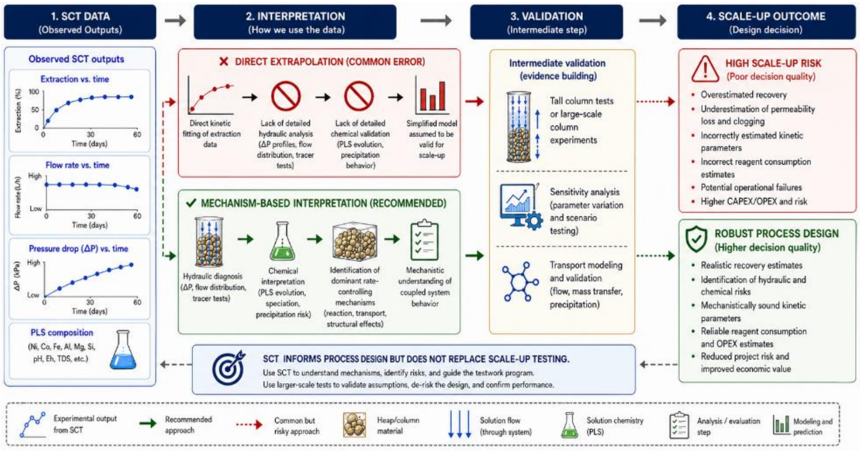

Figure 9. Evolution of reagent consumption in short column tests compared to expected industrial behavior. Early-stage reactions dominate SCT observations, while longer-term contributions may be underrepresented. Conceptual representation based on Borda and Torres (2023) and Ibrahim (2026)

As illustrated in Figure 10, the value of SCT lies primarily in informing early-stage behavior rather than replacing scale-up testing. Direct extrapolation of SCT-derived consumption values—particularly when based solely on cumulative data—may lead to

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optimistic estimates of reagent demand and insufficient consideration of long-term mechanisms.

In contrast, a mechanism-based interpretation integrates hydraulic diagnostics, solution chemistry, and transport behavior to identify the processes controlling reagent consumption. Within this framework, SCT functions as a diagnostic tool, supporting identification of early-stage reactions and potential system sensitivities, rather than serving as a standalone predictive model.

Bridging the gap between laboratory and industrial scales generally requires intermediate validation steps. Taller column tests, extended-duration experiments, and sensitivity analyses are typically necessary to capture transport limitations, precipitation effects, and structural evolution that are only partially represented in short columns. These approaches provide a more reliable basis for estimating reagent demand under industrial conditions.

From a process design perspective, the distinction between direct extrapolation and structured validation is critical. Use of SCT data without validation may lead to underestimation of reagent consumption, mischaracterization of kinetic parameters, and suboptimal process design. Conversely, integrating SCT into a structured, multi-scale framework can reduce uncertainty and improve robustness in heap-leaching design.

Reagent consumption evolves over multiple timescales, with early reactions dominating SCT observations, while delayed processes become increasingly important at larger scales. Early consumption is typically associated with rapid neutralization and dissolution of reactive phases, while later stages involve slower dissolution, precipitation, and transport-limited reactions. Recognizing this progression is essential for interpreting test results and estimating total reagent demand.

Table 8 summarizes the main mechanisms of reagent consumption, their characteristic timescales, and their degree of representation in SCT.

Table 8. Classification of reagent consumption mechanisms in heap leaching, including characteristic timescales and controlling processes. Adapted from Hosseini Nasab et al. (2020a), Borda and Torres (2023)

Mechanism	Typical Timescale	Main Reactions / Processes	Controlling Factors	Representation in SCT	Impact on Scale-Up
Rapid neutralization	Minutes to hours	Acid consumption by carbonates and reactive gangue	Mineralogy (carbonates, Mg phases),	Well captured	Minor uncertainty if

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			acid concentration		properly measured
Fast dissolution (Mg, Fe phases)	Hours to days	Dissolution of serpentine, olivine, amorphous Fe phases	Surface area, acid strength, temperature	Well captured (early stage)	Moderate contribution to total acid demand
Primary metal dissolution (Ni, Co)	Days to weeks	Leaching of Ni-bearing phases (limonite/saprolite)	Mineralogy, particle size, solution chemistry	Captured in early stage	Often overestimated due to short transport paths
Slow gangue dissolution	Weeks to months	Continued dissolution of silicates and less reactive phases	Diffusion, particle size, acid availability	Partially captured	Underestimated in SCT
Precipitation reactions (Fe, Al)	Days to months	Formation of $Fe(OH)_3$, jarosite, Al hydroxides	pH, Eh, Fe concentration, temperature	Weakly captured	Major driver of permeability loss
Silica gel formation	Weeks to months	Polymerization of dissolved silica	pH, Si concentration, residence time	Poorly captured	Critical for long-term clogging
Secondary reactions / re-equilibration	Weeks to months	Re-dissolution and reprecipitation cycles	Flow conditions, ionic strength, residence time	Not captured	Alters long-term chemical balance
Recirculation-driven accumulation	Days to months	Build-up of dissolved species (Fe, Mg, Cl^-, etc.)	Recirculation rate, solution management	Artificially enhanced or distorted	Affects equilibrium and downstream processing
Transport-limited consumption	Weeks to months	Reaction limited by diffusion and flow constraints	Permeability, flow distribution, saturation	Not represented	Major source of scale-up deviation

Table 8 shows that reagent consumption results from a sequence of processes operating over different timescales and controlled by distinct physicochemical factors. Short column tests tend to capture rapid neutralization and early-stage dissolution effectively, while slower mechanisms—particularly those associated with precipitation and transport limitations—may be only partially represented.

As a result, reagent consumption derived from SCT may be biased toward early-stage reactions if interpreted without consideration of time-dependent effects. This effect is more pronounced in systems in which silica gel formation, iron precipitation, and diffusion-

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controlled dissolution contribute significantly to the total consumption. In such cases, delayed processes may play a substantial role in both reagent demand and the evolution of permeability.

From a scale-up perspective, the coupling between chemical reactions and transport becomes increasingly important. Mechanisms that appear secondary in short-duration tests may become dominant under industrial conditions, where extended residence times and evolving chemical gradients influence system behavior. Reagent consumption should therefore be interpreted as a dynamic process rather than a fixed parameter.

Because SCT operates under limited duration and constrained chemical gradients, delayed consumption mechanisms may be underrepresented. At an industrial scale, these processes can contribute significantly—often on the order of 20–50% of total reagent consumption, depending on mineralogy and operating conditions—highlighting the importance of cautious extrapolation.

In chloride-based systems, reagent consumption should be evaluated using a complete mass balance that accounts for chloride inputs, accumulation in the pregnant leach solution (PLS), and losses due to volatilization or operational handling. Unlike sulfate systems, chloride losses may be significant, and simplified estimates may lead to underestimation of both reagent demand and environmental impact (Mends et al., 2024; Cui et al., 2020).

Overall, reagent consumption is best interpreted as a time-dependent, multi-stage process. Reporting only cumulative values may obscure underlying mechanisms and limit comparability between studies. Reliable interpretation requires time-resolved data, the identification of dominant reaction regimes, and an explicit linkage among reagent consumption, mineralogical evolution, and scale-dependent effects.

Errors in reagent estimation propagate directly into process design. Underestimating acid demand may lead to deviations in OPEX projections, inadequate sizing of storage and handling systems, and mispredictions of PLS composition and downstream performance. Deviations on the order of +100 kg H_2SO_4/t ore can have a substantial economic impact, particularly in low-grade nickel laterite operations.

The composition of the pregnant leach solution ultimately defines downstream processing constraints and performance, as discussed in the following section.

12. PLS Quality and Downstream Compatibility

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In heap leaching, short column tests (SCT) must be interpreted not only in terms of metal extraction but also in terms of pregnant leach solution (PLS) quality. Focusing exclusively on nickel recovery while neglecting solution chemistry can lead to fundamentally flawed process decisions (Rao et al., 2020; Mbedzi, 2020) .

PLS composition directly governs the feasibility, efficiency, and cost of downstream operations such as solvent extraction (SX), mixed hydroxide precipitation (MHP), and mixed sulfide precipitation (MSP). Therefore, SCT should be considered a combined assessment of extraction and solution processability.

12.1. Key Impurities and Their Impact

PLS composition in nickel laterite systems is typically dominated by Fe, Al, Mg, and Si, each of which affects downstream processing differently (Rao et al., 2020; Mends et al., 2024; Picazo-Rodriguez et al., 2023).

- Iron (Fe^{2+}/Fe^{3+}): increases reagent consumption and promotes scaling through precipitation (e.g., jarosite, Fe hydroxides).
- Aluminum (Al^{3+}): competes during extraction and increases neutralization demand.
- Magnesium (Mg^{2+}): drives acid consumption and reduces precipitation selectivity.
- Silicon (Si): poses major operational risks due to silica gel formation, affecting filtration and handling.

Typical SCT-derived PLS compositions fall within the following ranges: Ni: 1–10 $g \cdot L^{-1}$; Fe: 0.5–10 $g \cdot L^{-1}$; Mg: 5–30 $g \cdot L^{-1}$; Al: 0.5–5 $g \cdot L^{-1}$; Si: 0.1–2 $g \cdot L^{-1}$ (Mends et al., 2024; Picazo-Rodriguez et al., 2023; Tayip et al., 2026; Xiao, 2023).

Pregnant leach solutions (PLS) in nickel laterite processing affect downstream separation because of their composition. As shown in Table 9, industrial PLS streams contain high levels of dissolved gangue elements, impacting extraction, reagent use, and product quality, unlike idealized systems.

Table 9. Typical PLS composition ranges in nickel laterite leaching and their impact on downstream processing routes. Adapted from Rao et al. (2020), Mends et al. (2024), and Picazo-Rodriguez et al. (2023).

Component	Typical concentration in PLS	Source in laterite system	Impact on SX (Solvent Extraction)	Impact on MHP (Mixed Hydroxide Precipitate)	Impact on MSP (Mixed Sulfide Precipitate)
Ni^{2+}	1 – 6 g/L	Target metal	Defines loading capacity and	Primary product ($Ni(OH)_2$)	Primary product (NiS)

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			extraction efficiency		
Co^{2+}	0.05 – 0.5 g/L	Associated metal	Co-extraction with Ni requires selective stripping	Co-precipitates with Ni	Co-precipitates (valuable co-product)
Fe^{3+} / Fe^{2+}	5 – 50 g/L	Major gangue dissolution	Severe interference; requires pre-removal	Consumes lime; increases sludge volume	Must be removed prior to sulfide precipitation
Al^{3+}	1 – 10 g/L	Clay minerals	Competes with Ni in extraction systems	Increases reagent consumption	Precipitation contamination risk
Mg^{2+}	5 – 30 g/L	Silicate dissolution	Low SX affinity but increases ionic strength	Major lime consumption driver	Minimal direct effect, but dilutes product
Mn^{2+}	0.5 – 5 g/L	Oxide phases	Can co-extract depending on the extractant	Co-precipitates partially	May contaminate MSP
Ca^{2+}	0.5 – 5 g/L	Gangue dissolution/neutralization	Scaling and phase disengagement issues	Forms gypsum; increases solids handling	Limited direct impact
Si (as SiO_2 / colloidal)	0.05 – 1 g/L	Silicate dissolution	Causes crud formation and emulsion instability	Gel formation; filtration issues	Minimal direct effect
Cr^{3+}	0.01 – 0.5 g/L	Spinel dissolution	Potential impurity in the organic phase	Contamination of the hydroxide product	Impurity in sulfide product
Zn^{2+} / Cu^{2+}	0.01 – 0.5 g/L	Minor sulfides	Co-extraction risk	Minor contamination	May co-precipitate
SO_4^{2-}	20 – 100 g/L	Leaching acid	Governs phase equilibria	Controls precipitation chemistry	Essential for sulfide system chemistry
Free acid (H_2SO_4)	5 – 50 g/L	Residual acid	Affects the extraction equilibrium	Neutralization demand	Controls sulfide precipitation kinetics
Cl^- (if present)	0 – 10 g/L	Process water/ore	Corrosion and SX instability	Minor effect	Can affect sulfide precipitation

Table 9 shows that process complexity is primarily driven by Fe, Mg, and Al. Iron must be removed prior to most downstream routes; magnesium controls reagent consumption; and silica causes operational instability, particularly in SX, through crud formation and phase disengagement.

These interactions demonstrate that downstream performance depends on overall chemical complexity rather than nickel concentration alone (Binnemans & Jones, 2023, 2025).

12.2. Extraction–Treatability Trade-Off

A central challenge in heap leaching is the trade-off between metal recovery and PLS quality. Increasing acid concentration or leaching duration enhances nickel extraction but simultaneously promotes gangue dissolution.

For example, increasing acid concentration from 10 to 30 $g \cdot L^{-1}$ may improve Ni recovery by 10–20%, while significantly increasing Fe and Al dissolution. Similarly, prolonged leaching promotes silica dissolution and gel formation, negatively affecting filtration and flow behavior.

Optimal operation is therefore defined not by maximum extraction, but by a balance between recovery and solution quality.

12.3. Compatibility with Downstream Routes

Each downstream route imposes distinct compositional constraints:

- **SX:** requires strict impurity control (Fe and Al typically <1–2 $g \cdot L^{-1}$); high Mg reduces efficiency and increases reagent demand.
- **MHP:** tolerates higher impurity levels but results in lower product purity and higher reagent consumption.
- **MSP:** is highly sensitive to redox conditions and impurity content, particularly iron (Mends et al., 2024; Picazo-Rodriguez et al., 2023).

Short column tests are considered leaching indicators, but as shown in Figure 11, they operate under controlled conditions that miss the complexity of industrial heap systems. Lab columns suppress flow heterogeneity, mechanical consolidation, and pore changes, all of which are key to industrial performance.

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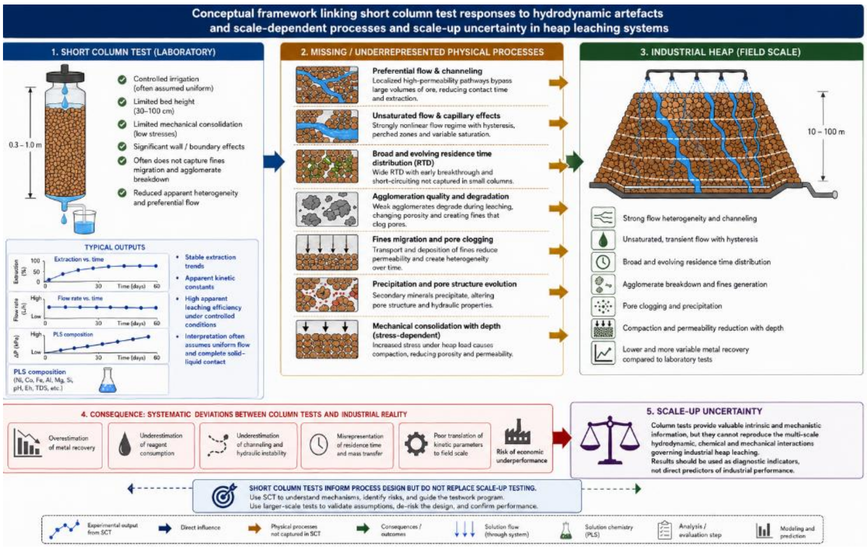
Conceptual framework linking short column test responses to hydrodynamic artefacts and scale-dependent processes and scale-up uncertainty in heap leaching systems

1. SHORT COLUMN TEST (LABORATORY)

- Controlled irrigation (often assumed uniform)
- Limited bed height (30–100 cm)
- Limited mechanical consolidation (low stresses)
- Significant wall / boundary effects
- Often does not capture fines migration and agglomerate breakdown
- Reduced apparent heterogeneity and preferential flow

TYPICAL OUTPUTS

- Stable extraction trends
- Apparent kinetic constants
- High apparent leaching efficiency under controlled conditions
- Interpretation often assumes uniform flow and complete solid–liquid contact

PLS composition (Ni, Co, Fe, Al, Mg, Si, pH, Eh, TDS, etc.)

2. MISSING / UNDERREPRESENTED PHYSICAL PROCESSES

Preferential flow & channeling Localized high-permeability pathways bypass large volumes of ore, reducing contact time and extraction.

Unsaturated flow & capillary effects Strongly nonlinear flow regime with hysteresis, perched zones and variable saturation.

Broad and evolving residence time distribution (RTD) Wide RTD with early breakthrough and short-circuiting not captured in small columns.

Agglomeration quality and degradation Weak agglomerates degrade during leaching, changing porosity and creating fines that clog pores.

Fines migration and pore clogging Transport and deposition of fines reduce permeability and create heterogeneity over time.

Precipitation and pore structure evolution Secondary minerals precipitate, altering pore structure and hydraulic properties.

Mechanical consolidation with depth (stress-dependent) Increased stress under heap load causes compaction, reducing porosity and permeability.

3. INDUSTRIAL HEAP (FIELD SCALE)

- Strong flow heterogeneity and channeling
- Unsaturated, transient flow with hysteresis
- Broad and evolving residence time distribution
- Agglomerate breakdown and fines generation
- Pore clogging and precipitation
- Compaction and permeability reduction with depth
- Lower and more variable metal recovery compared to laboratory tests

4. CONSEQUENCE: SYSTEMATIC DEVIATIONS BETWEEN COLUMN TESTS AND INDUSTRIAL REALITY

- Overestimation of metal recovery
- Underestimation of reagent consumption
- Underestimation of channeling and hydraulic instability
- Misrepresentation of residence time and mass transfer
- Poor translation of kinetic parameters to field scale
- Risk of economic underperformance

5. SCALE-UP UNCERTAINTY

Column tests provide valuable intrinsic and mechanistic information, but they cannot reproduce the multi-scale hydrodynamic, chemical and mechanical interactions governing industrial heap leaching. Results should be used as diagnostic indicators, not direct predictors of industrial performance.

SHORT COLUMN TESTS INFORM PROCESS DESIGN BUT DO NOT REPLACE SCALE-UP TESTING. Use SCT to understand mechanisms, identify risks, and guide the testwork program. Use larger-scale tests to validate assumptions, de-risk the design, and confirm performance.

Figure 11: Influence of PLS composition on downstream processing routes in nickel laterite operations. Adapted from Rao et al. (2020) and Mends et al. (2024).

Figure 11 highlights the mismatch between laboratory SCT conditions and industrial systems. While laboratory tests exhibit uniform flow and stable kinetics, industrial heaps develop preferential flow, channeling, and evolving pore structures that strongly influence residence time, reagent consumption, and impurity distribution (Odidi et al., 2023a; Robertson et al., 2023; Wang et al., 2022).

This discrepancy reflects a structural limitation: SCT systematically underestimates hydraulic instability and overestimates extraction performance. As a result, column test outputs should be interpreted as diagnostic indicators rather than predictive tools (Estay & Díaz-Quezada, 2020).

12.4. Critical Perspective: Extraction Alone Is Misleading

Reporting nickel extraction without PLS composition is insufficient and potentially misleading. High extraction values may coincide with elevated impurity levels, unstable chemistry, and poor downstream compatibility.

This creates a common misinterpretation: SCT results appear successful based on recovery, while the resulting PLS is unsuitable for industrial processing.

12.5. Recommended Reporting Framework

To ensure meaningful interpretation, SCT studies should report:

- complete PLS composition (Ni, Co, Fe, Al, Mg, Si);
- pH and Eh evolution;

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- total dissolved solids (TDS);
- explicit linkage between extraction and impurity behavior.

Without this information, SCT data cannot be reliably integrated into process design.

12.6. Implications for Process Design

Neglecting PLS quality leads to systematic errors in process design, including:

- underestimation of CAPEX due to additional purification requirements;
- increased OPEX from reagent consumption and waste handling;
- reduced product quality and market value.

In practice, high-impurity PLS often requires additional neutralization, filtration, and reprocessing steps, significantly affecting project viability.

13. Scale-Up Reliability, Reproducibility, and Research Directions in Short Column Tests

The shift from short-column tests (SCT) to industrial heap leaching involves fundamental changes in governing regimes, hydrodynamics, and timescales. These differences make direct extrapolation unreliable, especially when SCT results are interpreted as predictive rather than diagnostic (Estay & Díaz-Quezada, 2020; Petersen & van Staden, 2025).

SCT provides comparative insight into early-stage factors such as ore ranking, agglomeration, curing, and initial permeability, but does not capture long-term system evolution. Industrial heaps transition from reaction-controlled to transport-limited regimes, while SCT primarily reflects early-stage kinetics under simplified and more uniform hydraulic conditions (Odidi et al., 2023b, 2024; Wang et al., 2022, 2023). Consequently, SCT tends to overestimate metal recovery while underestimating reagent consumption, leaching time, and operational risks (Pereira, 2026a; van Staden & Petersen, 2021).

This scale-dependent divergence is summarized in Figure 12, which highlights the non-linear transition between laboratory-scale behavior and industrial heap performance, driven by transport limitations, structural evolution, and heterogeneous flow conditions.

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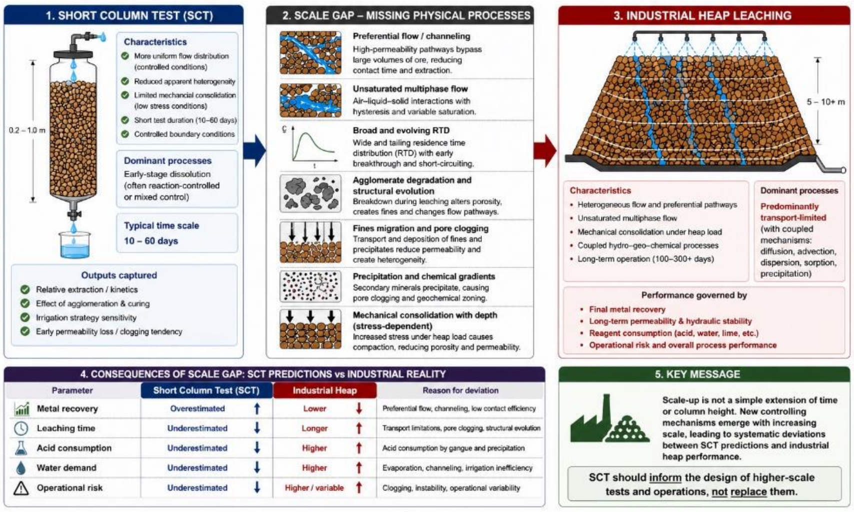

1. SHORT COLUMN TEST (SCT)

Characteristics
- ✓ More uniform flow distribution (controlled conditions)
- ✓ Reduced apparent heterogeneity
- ✓ Limited mechancial consolidation (low stress conditions)
- ✓ Short test duration (10–60 days)
- ✓ Controlled boundary conditions

Dominant processes
Early-stage dissolution (often reaction-controlled or mixed control)

Typical time scale
10 – 60 days

Outputs captured
- ✓ Relative extraction / kinetics
- ✓ Effect of agglomeration & curing
- ✓ Irrigation strategy sensitivity
- ✓ Early permeability loss / clogging tendency

2. SCALE GAP – MISSING PHYSICAL PROCESSES

Preferential flow / channeling
High-permeability pathways bypass large volumes of ore, reducing contact time and extraction.

Unsaturated multiphase flow
Air–liquid–solid interactions with hysteresis and variable saturation.

Broad and evolving RTD
Wide and tailing residence time distribution (RTD) with early breakthrough and short-circuiting.

Agglomerate degradation and structural evolution
Breakdown during leaching alters porosity, creates fines and changes flow pathways.

Fines migration and pore clogging
Transport and deposition of fines and precipitates reduce permeability and create heterogeneity.

Precipitation and chemical gradients
Secondary minerals precipitate, causing pore clogging and geochemical zoning.

Mechanical consolidation with depth (stress-dependent)
Increased stress under heap load causes compaction, reducing porosity and permeability.

3. INDUSTRIAL HEAP LEACHING

Characteristics
- Heterogeneous flow and preferential pathways
- Unsaturated multiphase flow
- Mechanical consolidation under heap load
- Coupled hydro–geo–chemical processes
- Long-term operation (100–300+ days)

Dominant processes
Predominantly transport-limited (with coupled mechanisms: diffusion, advection, dispersion, sorption, precipitation)

Performance governed by
- Final metal recovery
- Long-term permeability & hydraulic stability
- Reagent consumption (acid, water, lime, etc.)
- Operational risk and overall process performance

4. CONSEQUENCES OF SCALE GAP: SCT PREDICTIONS vs INDUSTRIAL REALITY

Parameter	Short Column Test (SCT)	Industrial Heap	Reason for deviation
Metal recovery	Overestimated ↑	Lower ↓	Preferential flow, channeling, low contact efficiency
Leaching time	Underestimated ↓	Longer ↑	Transport limitations, pore clogging, structural evolution
Acid consumption	Underestimated ↓	Higher ↑	Acid consumption by gangue and precipitation
Water demand	Underestimated ↓	Higher ↑	Evaporation, channeling, irrigation inefficiency
Operational risk	Underestimated ↓	Higher / variable ↑	Clogging, instability, operational variability

5. KEY MESSAGE

Scale-up is not a simple extension of time or column height. New controlling mechanisms emerge with increasing scale, leading to systematic deviations between SCT predictions and industrial heap performance.

SCT should inform the design of higher-scale tests and operations, not replace them.

Figure 10. Conceptual framework for scale-up from SCT to industrial heap leaching, highlighting non-linear effects and transport limitations. Adapted from van Staden and Petersen (2021), Robertson and Petersen (2024), and Bravo-Gutiérrez et al. (2026)

Figure 12 shows that discrepancies between laboratory and industrial performance arise from the absence of key processes in SCT, including preferential flow, structural evolution, and transport limitations. These phenomena emerge at larger scales and fundamentally alter system behavior (Robertson et al., 2023, 2021; Bravo-Gutiérrez et al., 2026).

Two non-linear scale gaps define this limitation:

- **Length scale:** SCT operates at 0.2–1.0 m, whereas industrial heaps reach 5–10 m or more, affecting flow distribution, residence time, and gradient development (van Staden & Petersen, 2021).
- **Time scale:** SCT duration (10–60 days) is insufficient to capture processes dominant at industrial timescales (100–300 days), such as precipitation, pore clogging, and structural evolution (Petersen & van Staden, 2025; Majdalani & Guinot, 2023).

These effects cannot be reproduced simply by increasing column height or duration, as they arise from coupled hydro–geo–chemical interactions (Bravo-Gutiérrez et al., 2026).

13.1. Hierarchical Testing Framework

Reliable scale-up requires a hierarchical approach in which each experimental level addresses specific mechanisms:

- **Bottle roll tests:** intrinsic reactivity under well-mixed conditions
- **Short column tests (SCT):** early-stage reaction–flow interaction
- **Tall columns (≥2–6 m):** development of transport limitations and gradients
- **Pilot heaps:** full-scale validation under realistic conditions

Within this framework, SCT serves as a diagnostic step guiding subsequent testing rather than a predictive tool.

13.2. Reproducibility and Reporting Standards

A major limitation of SCT is inconsistent experimental design and incomplete reporting. Many studies present extraction curves without sufficient context, preventing mechanistic interpretation and comparison across datasets.

Reliable interpretation requires complete reporting of::

- ore characterization (PSD, mineralogy, fines content);
- bed properties (density, packing, moisture);
- experimental conditions (geometry, agglomeration, curing, irrigation);
- hydraulic diagnostics (pressure drop, flow rate, liquid balance);
- solution chemistry and post-test solid analysis (Odidi et al., 2024; Wang et al., 2022, 2023).

Interpreting short column test (SCT) results requires consistent, complete reporting of experimental conditions. Many studies report extraction data without sufficient context, limiting comparability and mechanistic understanding. To address this, the reporting framework is organized around experimental design parameters (Table 10).

Table 10. Minimum reporting parameters for SCT: experimental design, ore characteristics, and operating conditions. Adapted from Page et al. (2021), Petersen and van Staden (2025), and Pereira et al. (2019).

Category	Parameter	Typical range/format	Purpose	Impact if not reported
Ore characterization	Particle size distribution (PSD)	Full curve (µm–mm)	Defines permeability and flow regime	Cannot assess transport limitations
	Fines content	% <75 µm / <38 µm	Indicates clogging potential	Underestimation of permeability loss
	Mineralogical composition	QXRD / MLA	Identifies reactive phases	Misinterpretation of kinetics
	Clay content	wt%	Controls agglomeration behavior	Hydraulic instability not predicted
Bed properties	Bulk density	$t\cdot m^{-3}$	Defines packing and porosity	Incorrect flow modeling
	Initial moisture	wt%	Affects capillary flow	Misrepresentation of unsaturated flow
	Packing method	qualitative	Controls structure	Non-reproducible results
Column geometry	Height	m (0.2–1.0)	Defines scale and gradients	No scale comparison possible

	Diameter	m	Affects wall effects	Flow distortion not assessed
	Aspect ratio (H/D)	dimensionless	Governs flow regime	Non-comparable experiments
	Ore mass	kg	Defines loading conditions	Inconsistent scaling
Agglomeration & curing	Moisture during agglomeration	8–16 wt%	Controls agglomerate strength	Poor permeability prediction
	Acid addition	kg/t ore	Affects reaction extent	Incorrect reagent estimation
	Binder type/content	qualitative / wt%	Improves stability	Agglomerate degradation ignored
	Curing time	12–72 h	Stabilizes structure	Unstable test conditions
Irrigation conditions	Irrigation rate	5–20 $L\cdot m^{-2}\cdot h^{-1}$	Controls residence time	Misinterpretation of kinetics
	Mode	continuous / intermittent	Affects flow distribution	Non-representative operation
	Cycle duration	h	Defines wetting patterns	Missing hysteresis effects
	Solution type	fresh / recirculated	Affects chemistry	Incorrect PLS interpretation

Table 10 defines the physical and operational conditions governing flow and reaction. Without this information, SCT results remain descriptive and cannot be reliably compared or scaled.

While experimental design sets the test conditions, interpreting results requires direct measurements of system response. Key outputs are summarized in Table 11.

Table 11. Minimum reporting parameters for SCT: monitoring, chemical outputs, and post-test diagnostics. Adapted from Page et al. (2021), Petersen and van Staden (2025), and Pereira et al. (2019)

Category	Parameter	Typical range/format	Purpose	Impact if not reported
Hydraulic monitoring	Pressure drop (ΔP)	Pa or kPa vs time	Detects clogging/compaction	No permeability evolution data
	Flow rate	L/h vs time	Tracks hydraulic behavior	Cannot identify instability
	Water balance	inlet/outlet/retention	Defines saturation	No RTD interpretation
Solution chemistry (PLS)	Ni, Co concentration	g/L	Target extraction	No recovery validation
	Impurities (Fe, Al, Mg, Si)	g/L	Defines downstream impact	Underestimation of OPEX
	pH / Eh	dimensionless / mV	Controls reaction conditions	Kinetic misinterpretation
	TDS / sulfate	g/L	Ionic strength	Affects precipitation behavior

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Post-test solids	Sectional sampling	top/middle/bottom	Identifies gradients	No scale-up relevance
	Residual metal	wt%	Defines extraction completeness	Overestimated recovery
	Mineralogical changes	qualitative/quantitative	Identifies precipitation	Mechanism unknown
	Precipitate identification	phases	Detects pore blocking	Transport effects ignored

Table 11 highlights that hydraulic monitoring, solution chemistry, and spatial diagnostics are essential for identifying controlling mechanisms. Without these measurements, SCT cannot support mechanistic interpretation or scale-up.

Common reporting gaps include missing PSD data, absence of hydraulic diagnostics, incomplete PLS characterization, and lack of agglomeration details. From a critical standpoint, SCT lacking these elements should not be used for process design or scale-up.

13.3. Methodological Limitations and Diagnostic Gaps

Despite widespread use, SCT remains limited by:

- lack of standardized protocols;
- restricted diagnostic capability;
- weak integration with predictive modeling.

A key limitation is the inability to resolve internal flow heterogeneity. Preferential flow, dead zones, and evolving permeability often remain undetected without advanced diagnostics, leading to systematic misinterpretation.

Emerging techniques—including tracer-based residence time distribution (RTD), X-ray computed tomography, distributed sensing, and real-time monitoring—enable direct observation of these phenomena and represent a critical advancement in SCT reliability.

13.4. Toward Integrated Experimental–Modeling Frameworks

A major research gap lies in linking SCT results to larger-scale systems. Reliable scale-up requires frameworks that integrate:

- multi-scale experimentation;
- advanced diagnostics;
- multi-physics modeling (flow–reaction–mechanics coupling).

Enhancing SCT reliability requires a shift toward integrated frameworks combining experimentation, diagnostics, and predictive modeling (Figure 13). This integration is essential to bridge the gap between laboratory observations and industrial heap performance in systems governed by coupled hydro–geo–chemical processes..

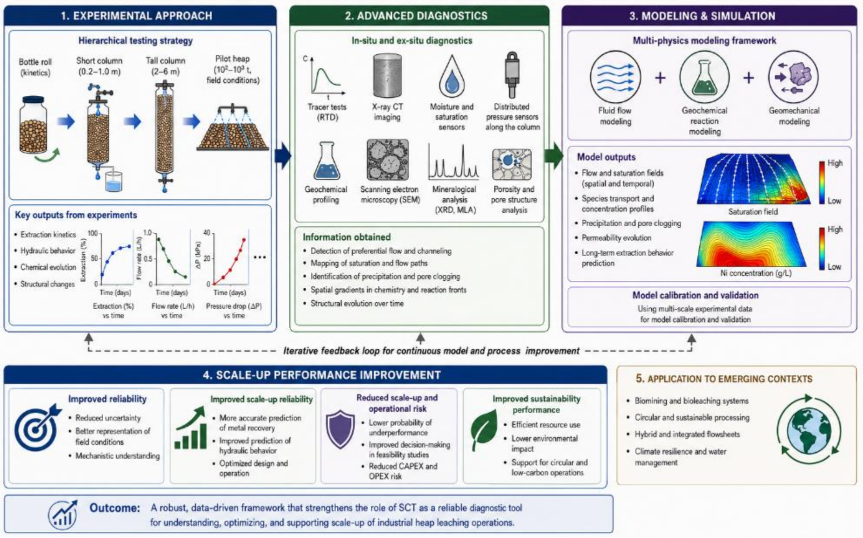

Figure 11. Integrated framework combining experiments, diagnostics, and multi-physics modeling to improve SCT reliability and scale-up prediction. Adapted from Odidi et al. (2024), Bravo-Gutiérrez et al. (2026), and Jia et al. (2024).

Figure 13 shows that reliable scale-up cannot be achieved through experimental data alone. Instead, it requires a continuous feedback loop between observation, diagnosis, and modeling. Experimental data provide inputs for models, while model predictions guide test design.

Within this framework, SCT evolves from an empirical test into a component of a data-driven, mechanistic workflow.

13.5 Implications for Emerging Processing Systems

These limitations become more pronounced in emerging contexts such as biomining, circular resource recovery, and hybrid flowsheets. These systems introduce additional complexity—including biological activity, gas–liquid interactions, and environmental constraints—that further challenge simplified laboratory interpretations (Pereira, 2026c).

13.6 Critical Perspective

From a critical standpoint, SCT should be regarded primarily as a diagnostic tool. Its strength lies in providing mechanistic insight under controlled conditions, but it does not capture the full complexity of industrial heap leaching systems.

Improving scale-up reliability requires:

- standardized experimental protocols;
- complete and consistent reporting;

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- advanced diagnostics;
- multi-scale validation;
- integrated modeling frameworks.

Without this integration, SCT remains a qualitative screening tool with limited predictive value. Achieving reliable scale-up requires treating SCT as part of a multi-scale, data-driven framework rather than as an isolated experimental method.

To translate the critical findings of this review into practical guidance, a structured protocol for the design, interpretation, and scale-up use of short column tests is proposed. Table 12 summarizes recommended practices, distinguishing between appropriate and inappropriate uses, minimum experimental requirements, and key considerations for reliable interpretation.

Table 12. Recommended protocol for short column tests (SCT), including appropriate use, minimum design requirements, diagnostic measurements, and scale-up considerations

Category	Recommendation	Technical Rationale	Implication for Scale-Up
Primary role of SCT	Use primarily for comparative and diagnostic purposes	SCT captures early-stage behavior under controlled conditions	Supports ore ranking and sensitivity analysis, but not direct prediction
Inappropriate use	Avoid direct extrapolation of recovery, kinetics, or reagent consumption	Scale-dependent processes (transport, precipitation, compaction) are only partially represented	Reduces risk of overestimating performance
Column geometry (D/d_p)	Maintain $D/d_p > 20–30$	Minimizes wall effects and artificial flow paths	Improves representativeness of flow behavior
Column height	Prefer ≥ 1 m, when feasible	Enhances development of gradients and transport limitations	Improves approximation of vertical heterogeneity
Test duration	Extend beyond 30–60 days, when possible	Allows partial development of delayed processes	Reduces bias toward early-stage reactions
Ore characterization	Report PSD, mineralogy, fines content, moisture	Controls both kinetics and hydrodynamics	Essential for interpreting variability and scale-up risk
Agglomeration and curing	Fully document moisture, acid addition, curing time	Defines bed structure and permeability evolution	Critical for predicting stability and flow behavior
Irrigation conditions	Specify rate, mode (drip/spray), recirculation	Strongly influences saturation and transport	Affects comparability with industrial conditions
Minimum instrumentation	Include flow rate, pressure drop (ΔP), water balance	Enables detection of clogging, channeling, and instability	Distinguishes robust vs fragile datasets

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Advanced diagnostics (recommended)	Apply tracer tests (RTD), sectional sampling, PLS profiling	Provides insight into flow distribution and reaction zones	Improves mechanistic interpretation
Kinetic interpretation	Treat kinetics as apparent/system-dependent	Coupled reaction–transport effects dominate	Avoids misinterpretation of intrinsic rates
Modeling approach	Use models for comparison, not direct prediction, unless validated	Multiple models may fit the same data	Prevents overfitting and incorrect extrapolation
Reagent consumption	Report as time-dependent profiles, not only cumulative values	Consumption evolves across multiple mechanisms	Improves estimation of total reagent demand
PLS characterization	Measure Ni, Co, Fe, Mg, Al, Si, pH, Eh vs time	Defines downstream processing constraints	Essential for SX/MHP/MSP design
Failure mode identification	Interpret results using multi-parameter diagnostics	Similar signals may arise from different mechanisms	Reduces risk of misinterpretation
Validation strategy	Integrate SCT with tall columns or pilot testing	Captures scale-dependent processes	Required for reliable scale-up
Data interpretation	Apply mechanism-based analysis rather than curve fitting alone	Improves physical understanding	Enhances predictive reliability
Scale-up use	Use SCT to inform, not replace, higher-scale testing	SCT provides partial system representation	Supports structured decision-making
Uncertainty management	Explicitly acknowledge limitations and assumptions	Reduces overconfidence in results	Improves robustness of engineering design

Table 12 consolidates the role of short column tests within a scale-aware framework. Rather than serving as predictive tools, SCTs are most effective when used as part of a structured, multi-scale testing strategy that integrates experimental design, diagnostic measurements, and validation steps. This approach reduces uncertainty and improves the reliability of heap leaching design and performance prediction.

This study presents a critical synthesis of the literature; however, several limitations should be acknowledged.

First, the available literature is highly heterogeneous in terms of experimental design, reporting standards, and ore types.

Second, part of the analysis relies on analog systems (Cu, U, REE), which provide mechanistic insight but may not fully represent nickel laterite behavior.

Third, no formal meta-analysis or quantitative statistical aggregation was performed, as the objective was interpretive rather than statistical.

Finally, variability in experimental protocols limits direct comparability across studies and introduces uncertainty in generalized conclusions.

16. Conclusion

Short column tests (SCTs) are widely used in nickel heap leaching as a rapid, cost-effective tool for early-stage evaluation. Their primary value lies in providing controlled, comparative insights, particularly for ranking ores, assessing agglomeration strategies, and identifying early hydraulic responses. However, as demonstrated throughout this review, SCT does not reproduce the full complexity of industrial heap leaching systems and must therefore be interpreted within a clearly defined framework of limitations.

The central conclusion is that SCT measures effective short-term system behavior rather than intrinsic reaction kinetics or long-term process performance. The observed results reflect the combined effects of chemical reactions, mass transfer, and artificially stable hydrodynamic conditions within a short column. As a consequence, SCT consistently overestimates metal recovery and apparent hydraulic stability, while underestimating reagent consumption, precipitation phenomena, and operational risks.

These discrepancies arise from fundamental limitations inherent to the method, including scale-dependent differences in flow and transport, the absence of mechanical compaction and structural evolution, limited development of chemical gradients and secondary reactions, and insufficient instrumentation or incomplete data reporting. These effects are often compounded by the lack of standardized experimental protocols and simplified interpretation practices, such as using kinetic models without physical validation or extrapolating short-term data to industrial timescales.

Misusing SCT in heap leaching design risks propagating errors through feasibility studies, affecting recovery, reagent use, and economics. When applied correctly, SCT guides large-scale experiments and highlights key variables for later stages.

A scale-aware testwork strategy is therefore essential. Within such a framework, screening tests provide insight into intrinsic reactivity, SCT captures early coupled behavior between reaction and flow, taller column tests allow development of transport limitations and chemical gradients, and pilot heaps provide full-scale validation under realistic conditions. In this context, SCT should inform the design of larger-scale experiments rather than replace them.

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Improving SCT reliability requires advancements in experimental practices and interpretation. Standardized test protocols and reports are necessary for comparability. Improved diagnostic tools are needed to monitor flow and transport and support mechanistic interpretation. Simultaneously, developing quantitative correlations across scales and integrating geo-hydro-chemical models are vital to connect laboratory results to industrial performance.

In conclusion, SCT remains a valuable but inherently limited method. Its strength lies in controlled comparison and mechanistic insight, not in direct prediction of industrial outcomes. Recognizing this distinction is essential to avoid systematic errors and to improve the design, operation, and economic performance of nickel heap leaching processes.

Declarations

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Conflicts of Interest

The author declares no conflicts of interest related to this study.

Data Availability

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

Author Contributions

The author confirms sole responsibility for all aspects of this work, including conceptualization, methodology, analysis, writing, and revision of the manuscript.

Ethical Approval

This article does not contain any studies with human participants or animals performed by the author.

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