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DUMP HEAP LEACHING SYSTEMS: ENGINEERING DESIGN, HYDRODYNAMICS, ENVIRONMENTAL CONTROL, AND INDUSTRIAL APPLICATIONS

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Abstract

Dump leaching remains one of the earliest and most cost-effective hydrometallurgical methods for extracting metals from low-grade ores and mine waste; however, its industrial relevance is increasingly limited by fundamental issues in fluid dynamics, metallurgical efficiency, and environmental impact. This review critically assesses the engineering design, fluid-flow behavior, and leaching chemistry that shape dump leaching systems, with an emphasis on how heterogeneity, preferential flow, and poor solution distribution affect recovery efficiency. While traditional operations report metal recoveries generally below those achieved in modern heap leaching systems, recent innovations—including the integration of bioleaching, geotechnical monitoring, and reprocessing of old dumps—have partly mitigated these limitations. The analysis points out that the main obstacle is not just leaching kinetics but the interaction between hydraulic movement and reactive interfaces within large, unstructured ore masses. Additionally, environmental concerns like acid drainage and groundwater pollution remain key barriers to sustainable use. The review suggests that dump leaching should not be a stand-alone technology but rather serve as a transitional or supplementary method, combined with controlled heap leaching and advanced monitoring, to enhance recovery and environmental safety.

Keywords: Dump leaching; Heap leaching; Percolation leaching; Hydrometallurgy; Low-grade ores; Mine waste processing

Highlights

- Dump leaching is fundamentally limited by poor hydraulic control and preferential flow effects.
- The coupling between hydrodynamics and ore heterogeneity governs metallurgical performance.
- Recovery rates remain significantly lower than modern heap leaching systems.
- Future relevance lies in integration with bioleaching, monitoring technologies, and dump reprocessing strategies.

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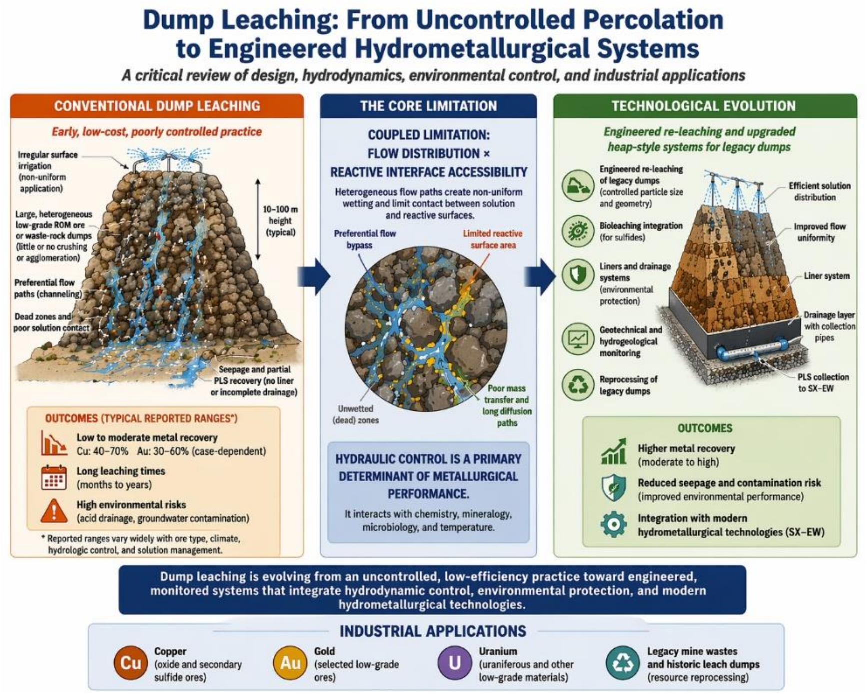
Graphical abstract



Dump Leaching: From Uncontrolled Percolation to Engineered Hydrometallurgical Systems

A critical review of design, hydrodynamics, environmental control, and industrial applications

CONVENTIONAL DUMP LEACHING

Early, low-cost, poorly controlled practice

OUTCOMES (TYPICAL REPORTED RANGES*)

- **Low to moderate metal recovery** Cu: 40–70% Au: 30–60% (case-dependent)
- **Long leaching times** (months to years)
- **High environmental risks** (acid drainage, groundwater contamination)

* Reported ranges vary widely with ore type, climate, hydrologic control, and solution management.

THE CORE LIMITATION

COUPLED LIMITATION: FLOW DISTRIBUTION × REACTIVE INTERFACE ACCESSIBILITY

Heterogeneous flow paths create non-uniform wetting and limit contact between solution and reactive surfaces.

HYDRAULIC CONTROL IS A PRIMARY DETERMINANT OF METALLURGICAL PERFORMANCE.

It interacts with chemistry, mineralogy, microbiology, and temperature.

TECHNOLOGICAL EVOLUTION

Engineered re-leaching and upgraded heap-style systems for legacy dumps

- **Engineered re-leaching of legacy dumps** (controlled particle size and geometry)
- **Bioleaching integration** (for sulfides)
- **Liners and drainage systems** (environmental protection)
- **Geotechnical and hydrogeological monitoring**
- **Reprocessing of legacy dumps**

OUTCOMES

- **Higher metal recovery** (moderate to high)
- **Reduced seepage and contamination risk** (improved environmental performance)
- **Integration with modern hydrometallurgical technologies (SX–EW)**

Dump leaching is evolving from an uncontrolled, low-efficiency practice toward engineered, monitored systems that integrate hydrodynamic control, environmental protection, and modern hydrometallurgical technologies.

INDUSTRIAL APPLICATIONS

- Cu **Copper** (oxide and secondary sulfide ores)
- Au **Gold** (selected low-grade ores)
- U **Uranium** (uraniferous and other low-grade materials)
- ♻ **Legacy mine wastes and historic leach dumps** (resource reprocessing)

1. Introduction

The depletion of high-grade deposits and increasing ore complexity have led the mining industry to adopt processing for large volumes of low-grade materials. Recovering metals from waste rock, tailings, and discarded resources has become an economic and strategic priority, especially for resource efficiency and the circular economy (Wang, 2023; Kiprono et al., 2023).

Dump leaching, an early hydrometallurgical method for low-grade ores, was developed in the 19th century mainly for copper. It relied on natural acidic percolation through rock, with limited understanding of flow or reactions (Bhatti & Tuovinen, 2023). Its continued use in the 20th century was due to low costs and simplicity rather than efficiency (Lizama, 2021).

Dump leaching's limitations include coarse particles, heterogeneity, and limited control, leading to uneven solution flow and restricted mineral contact, thereby hindering metal recovery (Litvinov et al., 2023). Although leaching reactions are thermodynamically favorable, their effectiveness depends on access to reactive surfaces and lixiviant penetration.

It is therefore important to emphasize that dump leaching performance cannot be interpreted solely in terms of chemical kinetics. Instead, the process is governed by the coupling of hydrodynamic behavior, mass-transport limitations, and reaction mechanisms, with transport restrictions often dominating at the field scale. However, this dominance does not eliminate the role of mineralogical variability, surface passivation, or local kinetic constraints, which may become significant depending on ore type and operational conditions.

Dump leaching remains relevant, especially for reprocessing legacy dumps and marginal resources with low capital costs (Krook et al., 2020; Funari et al., 2023). Growing interest in critical metals has renewed focus on unconventional feedstocks, though success depends on mineralogical and hydraulic conditions (Zhan et al., 2025).

Advances in hydrometallurgical engineering, such as improved solution management, bioleaching, and geotechnical monitoring, can improve performance under certain conditions. However, these may add complexity, costs, and risks and are not always universally applicable. The distinction between dump leaching and controlled systems such as heap leaching can blur, especially during reprocessing with partial re-engineering.

This review aims to critically examine dump leaching from an engineering perspective, focusing on the interaction between system geometry, hydrodynamic behavior, reactive transport, and metallurgical performance. Rather than providing a purely descriptive overview, the analysis seeks to identify the fundamental constraints governing process efficiency and to position dump leaching within the broader spectrum of hydrometallurgical technologies, including heap, vat/box, tank, and in-situ leaching.

Note that the comparative ranges and performance indicators are context-dependent and indicative, reflecting variability in ore types, climate, scale, and process control reported in the literature. The goal is to support understanding of trade-offs between recovery, time, cost, and environmental impact across different leaching strategies.

By framing dump leaching as a transport- and structure-constrained process within a continuum of increasing engineering control, this work seeks to contribute to a more rigorous and realistic assessment of its current and future role in mineral processing.

2. Methodology

This study is a critical narrative review with a structured literature search, aiming to integrate engineering, hydrodynamic, environmental, and techno-economic aspects of dump leaching systems.

A structured search strategy was conducted using multiple scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Wiley Online Library, complemented by gray literature sources such as conference proceedings and technical reports.

The search covered publications from 2020 to 2026 and resulted in an initial dataset of 1,247 records.

Principles inspired by PRISMA 2020 (Page et al., 2021) guided the selection process for identification, screening, eligibility, and inclusion stages, not as a full systematic review. The goal was to build a strong, representative dataset for critical engineering, not to conduct an exhaustive or meta-analytic synthesis.

After removing 312 duplicate records using reference management software, 935 records were screened based on title and abstract using predefined inclusion and exclusion criteria. During this stage, 670 records were excluded due to irrelevance to dump leaching, non-hydrometallurgical focus, or non-English language.

A total of 263 reports were subsequently assessed for eligibility through full-text analysis. Of these, 165 studies were excluded for the following reasons: lack of focus on dump leaching, absence of quantitative or qualitative process data, insufficient methodological detail, duplicate or overlapping datasets, or classification as review articles without primary data.

The final dataset comprised 98 studies, which were selected for qualitative synthesis and critical interpretation.

Inclusion criteria required that studies report at least one operational or quantitative parameter relevant to process analysis, such as metal recovery (%), leaching time, particle size distribution, acid consumption, irrigation rate, or permeability indicators. Studies lacking measurable process data were excluded. Priority was given to experimental studies, pilot-scale investigations, and validated modeling approaches (Wang, 2023; Saldaña et al., 2022).

Data extraction focused on key variables like hydrodynamics, reactive transport, and metallurgical response. When available, economic parameters—such as relative CAPEX (dump = 1, heap = 2–4, tank = 5–10) and OPEX drivers (acid, water, energy)—were included for cross-technology comparison (Schlesinger et al., 2021; Binnemans & Jones, 2023). These should be seen as trend indicators rather than universal design standards, due to varied operating conditions.

The selection workflow in Figure 1 shows the stages: identification, screening, eligibility, and inclusion. This workflow serves as an organizational tool rather than evidence of a fully systematic review.

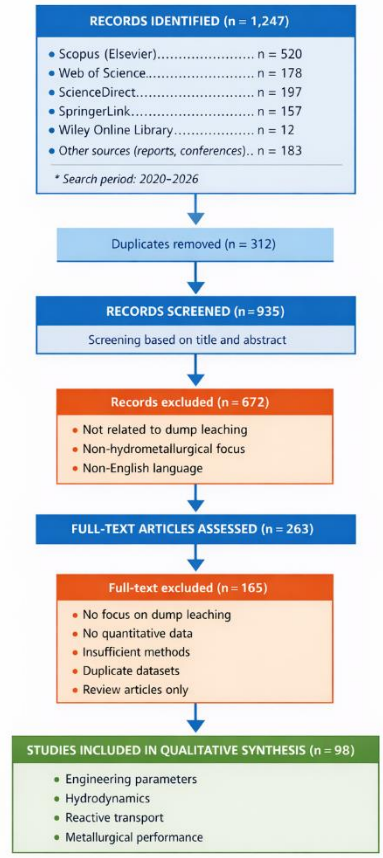


Figure 1. PRISMA flow diagram for literature selection and screening process applied in this review**:** Flow diagram showing identification, screening, eligibility, and inclusion stages, with quantitative record counts at each step. Adapted from Page et al. (2021).

The structured approach adopted in this work enables a consistent comparison of leaching technologies based on measurable engineering parameters, while acknowledging the heterogeneity and contextual dependence of the available data.

3. Classification of Leaching Technologies (Comparative Core Section)

3.1. Overview of hydrometallurgical leaching routes

Hydrometallurgical leaching includes various configurations, from large-scale, low-control dump and heap leaching to engineered tank leaching with fine particles and forced mixing to improve contact and kinetics (Free, 2021).

Intermediate configurations, such as vat, box, and in situ leaching, occupy specific niches based on ore permeability, geology, particle size, and economics. They differ mainly in control over fluid flow, residence time, and access to reactive surfaces, which affect mass transfer and recovery (Brown & Moses, 2020).

Table 1 summarizes key operational parameters, including particle size, metal recovery, leaching time, flow conditions, and costs, for comparison. These values are indicative ranges from diverse sources, not universal design parameters. Variations in mineralogy, climate, hydrodynamics, and scale can affect process performance.

Table 1. Summary of indicative ranges for particle size, recovery, leaching time, irrigation/flow conditions, and relative CAPEX/OPEX across major hydrometallurgical leaching systems. Adapted from Free (2024) and Schlesinger et al. (2021). Values represent orders of magnitude and comparative trends, not standardized design criteria.

Process	Particle size	Recovery (%)	Time	Irrigation / Flow	CAPEX	OPEX
Dump	50–500 mm	30–70	6–36 months	5–10 $L\cdot h^{-1}\cdot m^{-2}$	1x	Low
Heap	5–50 mm	60–90	30–180 days	10–20 $L\cdot h^{-1}\cdot m^{-2}$	2–4x	Moderate
Vat/Box	5–25 mm	70–95	5–30 days	Controlled percolation	3–6x	Moderate
Tank	<0.1 mm	90–99	6–48 h	Agitated	5–10x	High
In-situ	in-place	50–80	months–years	Injection wells	1–3x	Low

As shown in Table 1, dump leaching typically involves low capital costs, coarse particles, longer leaching times, and lower recovery. These traits depend on ore type, permeability, and operational conditions and are not fixed limits.

Heap leaching is a more controlled evolution of percolation systems, often achieving higher recoveries through better particle size, agglomeration, and solution management. However, these improvements require additional infrastructure, which raises costs.

More intensive systems, such as vat/box and tank leaching, use higher control levels to improve mass transfer and speed up processing. They need finer particles and more uniform conditions, but are limited by higher energy requirements, reagent use, and costs.

In-situ leaching occupies an intermediate position, characterized by minimal surface disturbance and relatively low capital requirements. However, its performance is highly dependent on geological and hydrogeological conditions, which can introduce significant uncertainty in fluid flow behavior and recovery efficiency.

These leaching routes are part of a continuum of increasing control, where better fluid distribution, particle prep, and containment improve recovery but also add process complexity and cost.

Choosing the right leaching technology depends on balancing recovery efficiency, processing time, investment, and site constraints, rather than a single optimal setup. These ranges offer a comparative framework for understanding process behavior, not strict design values.

3.2. Dump leaching

Dump leaching involves minimal ore prep, relying on gravity percolation through large, irregular rock masses with particle sizes from 50 to 500 mm. This creates uneven pore structures and limited fluid control. Irrigation rates are usually low, under 10 $L \cdot h^{-1} \cdot m^{-2}$, but vary by site.

Reported metal recoveries vary widely, e.g., 30–70% for copper and 30–60% for gold, with leaching times ranging from months to years (Lizama, 2021). These ranges depend heavily on mineralogy, permeability, climate, and operational practices, not intrinsic process limits.

The main limitation of dump leaching is hydrodynamic issues such as preferential flow, incomplete wetting, and limited access to reactive surfaces (Litvinov et al., 2023). These reduce lixiviant-mineral interaction, but overall performance depends on transport, mineralogy, and reaction kinetics, not just hydrodynamics.

3.3. Heap leaching

Heap leaching is a controlled form of percolation leaching in which crushed ore (5–50 mm), often agglomerated to improve permeability, is irrigated at high rates using engineered systems to prevent channeling.

Recoveries range from 60–90%, with leaching typically taking 30–180 days (Arpalahti, 2021). These values vary by ore type, mineralogy, and conditions, and should be seen as estimates rather than universal.

The improved performance over dump leaching is mainly due to better control of hydrodynamics and particle size. However, it requires additional infrastructure such as crushing, agglomeration, and containment, thereby increasing CAPEX and complexity.

Heap leaching isn't a strict categorical transition but part of a continuum of increasing engineering control, with hybrid configurations emerging in some contexts.

3.4. Vat and box leaching

Vat and box leaching systems are batch processes with controlled percolation, offering more uniform hydraulic conditions than dump or heap systems. Particle sizes are usually 5–25 mm, with residence times of 5-30 days.

Reported recoveries may reach 70–95%, reflecting improved solution distribution and reduced channeling (Pereira, 2026b). However, these values depend on ore and process, and should be seen as context-dependent performance ranges.

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These systems suit medium-scale operations or ores needing tighter control. Their main limitation is scalability, as increased structural and handling requirements raise costs and limit their use in very large-tonnage operations.

3.5. Tank leaching

Tank leaching offers the highest process control in hydrometallurgical leaching. Ores are finely ground (<100 µm) and agitated for uniform solid-liquid contact.

Leaching times are short (6–48 hours), with recoveries often above 90–99% under controlled conditions (Free, 2021). These high recoveries result from optimized mass transfer and kinetics but depend on mineralogy and reagent chemistry.

The process is energy-intensive due to grinding and mixing, with higher CAPEX and OPEX than percolation systems. Consequently, tank leaching is used for higher-grade ores or when maximizing recovery justifies the cost.

3.6. In-situ leaching

In-situ leaching avoids the traditional mining and crushing steps by injecting a lixiviant directly into the ore. Fluid flow is managed via injection and recovery wells, with the formation's permeability being the key factor.

Typical recoveries range from 50–80%, with leaching lasting months to years (Chamberlin, 2020). These values vary widely depending on geological continuity, permeability, and hydrogeological conditions.

While CAPEX is lower than for surface systems, operational uncertainty and environmental risks—especially groundwater contamination- are major constraints. The applicability of in-situ leaching depends on regulatory, geological, and environmental factors.

3.7. Comparative techno-economic and operational analysis

The comparison of hydrometallurgical leaching technologies highlights trade-offs among recovery efficiency, processing time, capital costs, and operational complexity.

Dump leaching has low capital, but limited control and variable recovery. Heap leaching improves recovery with better hydraulic management, but costs more. Vat/box and tank leaching offer higher recoveries and faster processing, but require more capital and energy.

Reported reagent and resource use—like acid (5–50 kg H_2SO_4/tonne), water (0.5–1.5 m^3/t), and energy—are ranges that vary widely depending on ore, process, and conditions (Schlesinger et al., 2021).

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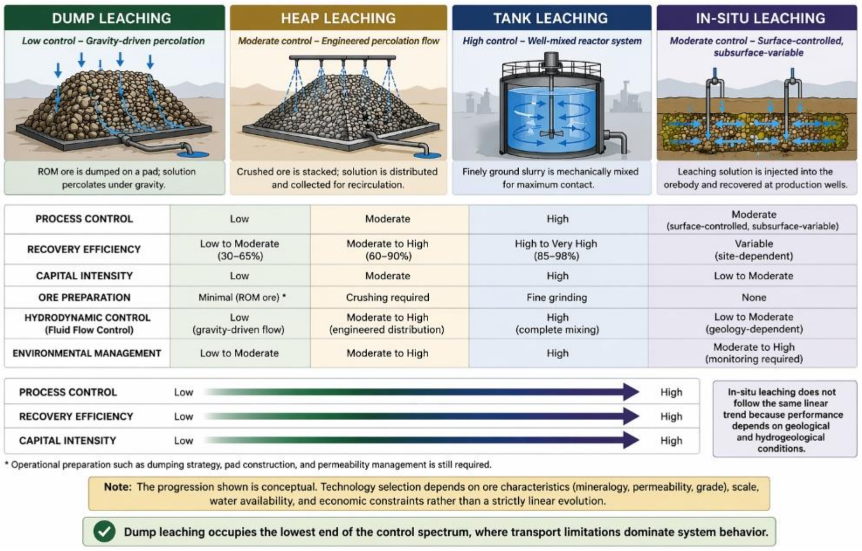
At an industrial scale, controlled percolation systems are crucial. Heap leaching with solvent extraction–electrowinning (SX–EW) accounts for a large share of global copper output, demonstrating how engineered flow control ensures consistent results (Sole et al., 2025).

Figure 2 shows the relationship among process control, recovery efficiency, and capital intensity. This reflects a general trend, not a strict or linear one.



DUMP LEACHING
Low control – Gravity-driven percolation
ROM ore is dumped on a pad; solution percolates under gravity.

HEAP LEACHING
Moderate control – Engineered percolation flow
Crushed ore is stacked; solution is distributed and collected for recirculation.

TANK LEACHING
High control – Well-mixed reactor system
Finely ground slurry is mechanically mixed for maximum contact.

IN-SITU LEACHING
Moderate control – Surface-controlled, subsurface-variable
Leaching solution is injected into the orebody and recovered at production wells.

PROCESS CONTROL	Low	Moderate	High	Moderate (surface-controlled, subsurface-variable)
RECOVERY EFFICIENCY	Low to Moderate (30–65%)	Moderate to High (60–90%)	High to Very High (85–98%)	Variable (site-dependent)
CAPITAL INTENSITY	Low	Moderate	High	Low to Moderate
ORE PREPARATION	Minimal (ROM ore) *	Crushing required	Fine grinding	None
HYDRODYNAMIC CONTROL (Fluid Flow Control)	Low (gravity-driven flow)	Moderate to High (engineered distribution)	High (complete mixing)	Low to Moderate (geology-dependent)
ENVIRONMENTAL MANAGEMENT	Low to Moderate	Moderate to High	High	Moderate to High (monitoring required)

In-situ leaching does not follow the same linear trend because performance depends on geological and hydrogeological conditions.

* Operational preparation such as dumping strategy, pad construction, and permeability management is still required.

Note: The progression shown is conceptual. Technology selection depends on ore characteristics (mineralogy, permeability, grade), scale, water availability, and economic constraints rather than a strictly linear evolution.

✓ **Dump leaching occupies the lowest end of the control spectrum, where transport limitations dominate system behavior.**

Figure 2. Conceptual comparison of leaching technologies based on process control, recovery efficiency, and capital intensity. Adapted from Schlesinger et al. (2021); Free (2021).

Leaching systems are better seen as a continuum of increasing control rather than as discrete categories, in which improved fluid distribution, particle prep, and containment improve recovery but increase cost and complexity.

Process selection is site-specific, depending on ore characteristics, hydrodynamics, economics, and environment. Dump leaching suits low-cost, large-scale operations, but controlled systems are preferred when efficiency and predictability matter more.

4. Fundamentals of Dump Leaching

4.1. Process concept

Dump leaching applies lixiviant to large piles of uncrushed ore or waste rock, usually 50 to 500 mm in size. This coarse granulometry creates heterogeneous pore structures and makes fluid flow control difficult (Lizama, 2021).

The process uses gravity-driven percolation, with solutions passing through porous media to interact with minerals. Unlike engineered systems like heap or tank leaching, dump leaching lacks direct control over residence time, solution uniformity, and reactive surface exposure.

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Process performance often suffers from limitations in fluid distribution and mass transport. However, overall recovery depends not only on transport phenomena but also on the interaction of hydrodynamics, mineralogy, and reaction kinetics, which can vary over time and space.

Typical irrigation rates are usually 5–10 $L \cdot h^{-1} \cdot m^{-2}$, depending on conditions. The heterogeneous dump causes uneven contact, leaving parts partially wetted and thereby extending leaching over months or years, depending on permeability, mineralogy, and environmental conditions.

Many leaching reactions, like copper oxide dissolution in acidic systems ($pH < 2$), are thermodynamically favorable but rarely reach equilibrium. Instead, their progress depends on the accessibility of reactive surfaces, local transport, and the extent to which the lixiviant penetrates and redistributes within the porous structure.

4.2. Process steps and operational logic

Although conceptually simple, dump leaching involves a sequence of coupled physical and chemical processes that collectively determine system performance. These processes are only weakly controlled and strongly interdependent, reflecting the absence of engineered unit operations typical of more controlled leaching systems (Pereira, 2026a).

The internal behavior of dump leaching systems depends on ore structure, gravity-driven flow, and permeability. Fluid movement is non-uniform, leading to variable reagent distribution and metal dissolution. Figure 3 illustrates the main stages of solution infiltration, percolation, and recovery, highlighting the development of preferential flow paths and poorly contacted regions.

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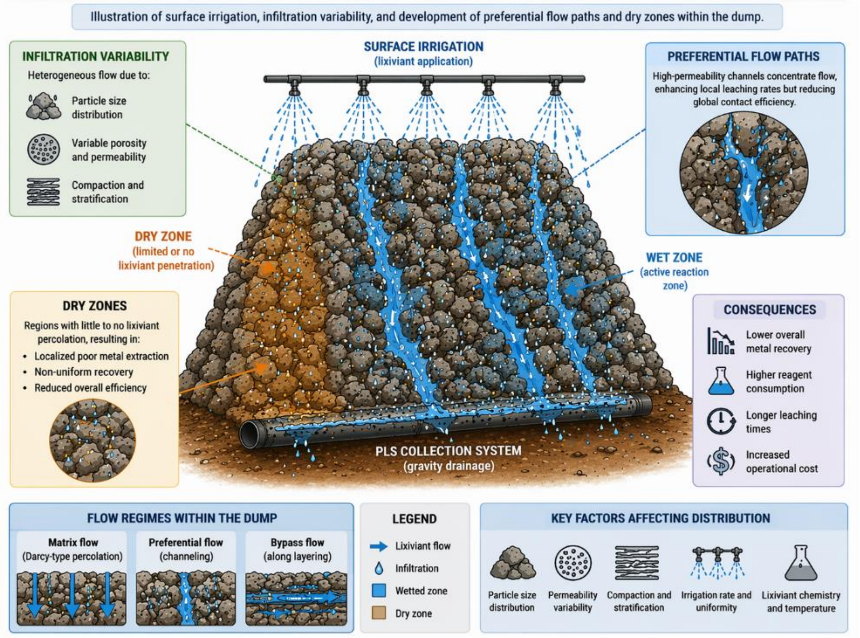

Figure 3. Illustration of ore deposition, surface irrigation, solution percolation, and pregnant leach solution (PLS) collection, highlighting preferential flow and heterogeneous contact zones. Adapted from Wang et al. (2020) and Lizama (2021)

The schematic highlights that solution distribution in the dump is highly heterogeneous. Surface irrigation causes localized infiltration and preferential flow channels, leaving other areas partially saturated or bypassed.

Fluid flow concentrates in high-permeability zones, accelerating leaching reactions but reducing overall contact efficiency because low-permeability areas remain insufficiently wetted. This mixture leads to variability in recovery, longer leaching times, and greater operational uncertainty.

This behavior aligns with a system in which transport limitations often constrain large-scale performance, though local reaction kinetics and mineralogy remain relevant at smaller scales. Dump leaching isn't solely transport-limited or reaction-controlled but reflects an evolving balance between both mechanisms.

The process can be described through the following interrelated stages:

(1) **Ore deposition and stacking**

Material is deposited with minimal preparation, usually by truck or conveyor, forming large piles up to 100 m high. These structures are heterogeneous, with variable particle size, packing density, and void connectivity.

Over time, mechanical compaction from self-weight and environmental effects such as wetting–drying cycles can reduce permeability in deeper regions, altering flow pathways and increasing channeling.

(2) **Irrigation with lixiviant**

Lixiviant solutions, often acidic, such as H_2SO_4 in copper systems, are applied via drip emitters or sprays. However, surface irregularities and material heterogeneity cause uneven solution distribution.

As a result, infiltration rates vary spatially, and the effective wet area may be significantly smaller than the nominal irrigation area.

(3) **Percolation through the dump**

Variations in gravity and permeability drive solution movement through the dump. Preferential flow pathways form in high-permeability areas, enabling fluids to bypass much of the material.

This reduces the solid–liquid contact area and limits metal dissolution in less accessible areas. Meanwhile, local saturation and capillary effects can temporarily redistribute fluid, adding variability to flow patterns.

(4) **Collection of pregnant leach solution (PLS)**

The solution at the dump's base is sent to recovery processes like solvent extraction, electrowinning, or precipitation. Flow-path diversity leads to variable residence times in the system (Wang et al., 2020).

This sequence highlights a key trait of dump leaching: performance depends on geometry, permeability, and flow, not just controlled parameters.

Recovery varies over time, influenced by porosity, moisture, and flow channels. Although hydrodynamic limits often dominate the system scale, reaction kinetics and mineral heterogeneity also significantly impact the process.

From a design perspective, parameters such as dump geometry, stacking method, and solution strategy are crucial to process performance, even without strict operational control.

5. Engineering Design of Dump Leaching Systems

The engineering design of dump leaching systems usually requires less intervention than that of controlled hydrometallurgical operations, such as heap or tank leaching. These systems often reflect legacy practices, large-scale material handling, and low capital

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constraints. Therefore, performance depends more on geometric configuration, stacking, and solution distribution than on tightly controlled parameters.

5.1. Dump construction and stacking practices

Dump construction involves depositing run-of-mine ore or waste rock without crushing, resulting in large, heterogeneous particles and packing structures (Dixon & Lizama, 2022).

Material is stacked by truck dumping or conveyor discharge, resulting in irregular layering, particle segregation, and localized compaction. Over time, self-weight and environmental factors, such as wetting–drying cycles, reduce permeability, especially in deeper layers. Unlike engineered heap leaching, early dump leaching lacked liners, drainage, or controlled stacking, reducing costs but increasing variability and environmental risks (Zhang, 2022).

Dump construction is driven more by throughput needs than by process optimization. Reported stacking rates at large copper operations range from 50,000 to 150,000 t/day, but these are site-specific and reflect production priorities rather than hydrodynamic design.

5.2. Geometry and scale effects

Dump geometry affects fluid flow, residence time, and recovery. Typical heights are 10-100 m, with lateral extents from a few to over 100 hectares, depending on the operation. Table 2 summarizes key geometric and physical ranges from industrial studies, showing variability across ore types, stacking, and conditions.

Table 2. Summary of indicative ranges for dump height, area, particle size, and permeability-related properties. Adapted from Kinyua et al. (2022) and Wang et al. (2023). Values represent orders of magnitude rather than universal parameters.

Parameter	Typical range
Height	10–100 m
Area	1–100+ ha
Particle size	50–500 mm
Porosity	0.15–0.35
Permeability	10^{-6}–10^{-3} m/s

Large-scale geometry and coarse particles create heterogeneous porous media with variable porosity and permeability, affecting solution distribution and solid–liquid contact. Scale effects in dump leaching are not just quantitative. Increased dump height and size cause vertical stress, leading to compaction, reduced permeability, and the formation of preferential

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flow paths. This results in a wider range of residence times, from fast-flowing channels to stagnant zones.

Scale-up in dump leaching induces qualitative changes in hydrodynamics beyond what lab results indicate, challenging traditional models and highlighting the need for methods that account for heterogeneity and pore evolution. Imaging shows pore connectivity is irregular and dynamic, impacting transport and recovery (Wang et al., 2023).

5.3. Solution distribution systems

Solution distribution in dump leaching systems is inherently heterogeneous due to coarse particle size, irregular stacking, and limited hydraulic control. Irrigation rates are typically 5–10 L·h^{-1}·m^{-2}, but actual infiltration often varies significantly from nominal rates.

Fluid flow is affected by gravity, capillary effects, and permeability changes, leading to uneven solution distribution, partial saturation, and preferred flow paths. Figure 4 shows variability in infiltration, channeling, and contact zone patterns.

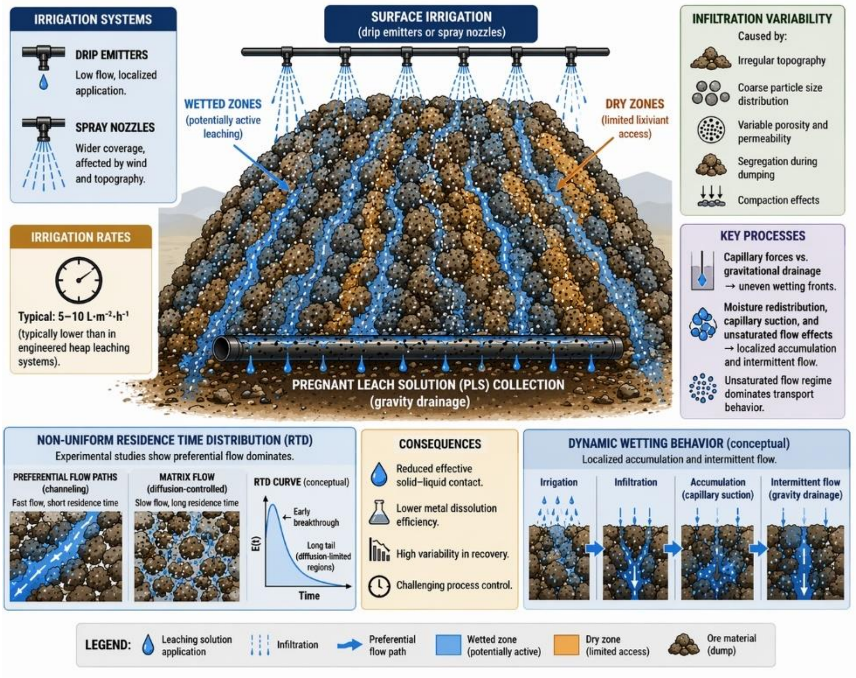

Figure 4. Illustration of surface irrigation, infiltration variability, and development of preferential flow paths and dry zones within the dump. Adapted from Odidi et al. (2023a, 2023b).

Experimental studies show that the residence time distribution is uneven, with solutions primarily traversing preferential pathways. This lessens lixiviant-mineral contact and hampers leaching efficiency (Odidi et al., 2023a).

Capillary suction and moisture redistribution can cause localized solution buildup and intermittent flow, leading to variable flow patterns and fluctuations in recovery (Odidi et al., 2023b).

Solution distribution in dump leaching systems is not strictly uncontrolled but weakly controlled, influenced heavily by structural heterogeneity. Interventions such as irrigation management or re-engineering can improve distribution but may increase costs and complexity.

Engineering design analysis shows that dump leaching systems prioritize handling large material volumes at low cost rather than hydrodynamic control. Therefore, geometry, stacking, and solution strategies mainly influence flow and performance.

However, performance isn't solely dictated by hydrodynamics. Recovery results from flow distribution, reactive transport, and mineralogical factors evolving as the dump structure changes.

This interplay is crucial for analyzing fluid flow, mass transfer, and reaction mechanisms, detailed in the next section on hydrodynamics and reactive processes transport.

6. Hydrodynamics and Reactive Transport (Core Section)

Hydrodynamics crucially influences dump leaching, but process behavior results from the interaction of fluid flow, mass transport, mineral heterogeneity, and reaction kinetics.

Unlike engineered systems, fluid flow in dump leaching is uneven and loosely controlled. Reactive transport depends on permeability, flow pathways, reactive-phase accessibility, and the porous medium's structure.

6.1. Flow regimes and percolation behavior

Fluid flow in dump leaching systems is mainly gravity-driven within partially saturated porous media. Transitions between capillary- and gravity-dominated flow occur depending on saturation and pore structure (Maghsoudy et al., 2022).

Percolation occurs through a complex network of voids. Studies show local flow velocities can vary widely, from 10^{-6} to 10^{-3} m/s, indicating strong spatial heterogeneity (Zheng, 2026). These ranges depend on ore structure, compaction, and practices.

This variability leads to incomplete wetting and uneven reagent distribution, so only part of the volume participates in leaching at any given time. The inactive volume varies with saturation, compaction, and chemical changes and reactions.

6.2. Permeability and compaction effects

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Permeability is a key parameter governing flow distribution in dump leaching systems. It is inherently heterogeneous and evolves due to mechanical, hydraulic, and chemical processes.

Initial permeability values are commonly reported in the range of 10^{-3} to 10^{-5} m/s, but may decrease by one or more orders of magnitude in deeper regions due to compaction, fines migration, and pore collapse (Kinyua et al., 2022). These changes are not uniform and can lead to localized high- and low-permeability zones.

Chemical effects further contribute to the evolution of permeability. The precipitation of secondary phases, the accumulation of reaction products, and changes in mineral structure may partially block pore spaces and alter flow pathways (Wang et al., 2022).

As a result, permeability should be treated as a dynamic, spatially variable parameter rather than a fixed property. Its evolution plays a critical role in shaping flow distribution, residence time, and ultimately recovery performance.

6.3. Channeling and preferential flow

Channeling is a major hydrodynamic constraint in dump leaching, causing fluid to flow through preferential pathways and bypass significant material.

Figure 5 presents a conceptual framework linking flow regimes, mass transport processes, and reaction behavior within the dump.

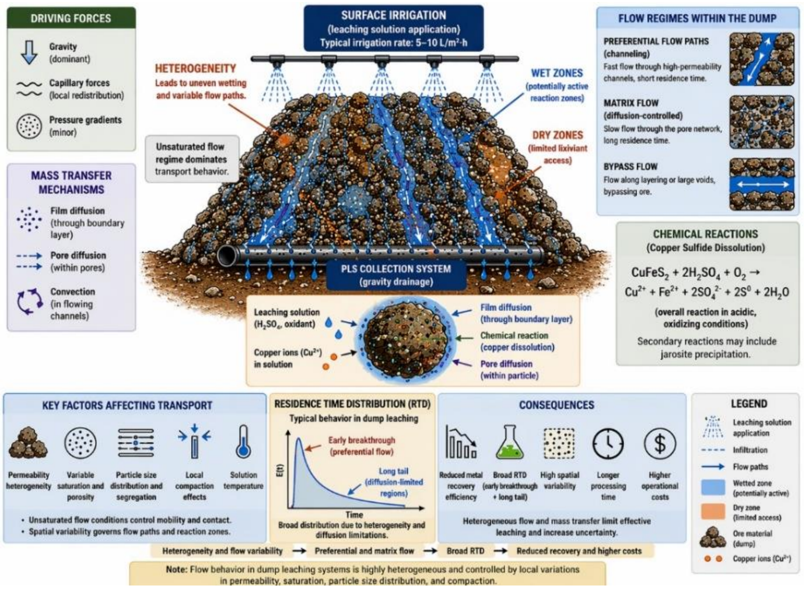

Figure 5. Conceptual framework of hydrodynamics and reactive transport in dump leaching systems. Illustration of preferential flow, matrix flow, and low-permeability zones, and their influence on mass transfer and mineral dissolution. Adapted from Odidi et al. (2023a) and Saldaña et al. (2022).

The framework highlights the coexistence of different flow domains:

a. Preferential channels, characterized by rapid flow and limited contact time.
b. Matrix regions, where flow is slower, and contact is more effective.
c. Low-permeability zones, which may remain partially or intermittently wet.

This heterogeneity leads to spatial variability in dissolution rates and metal recovery. While preferential pathways may enhance local reaction rates, they reduce overall efficiency by limiting contact with large portions of the material.

Quantitative estimates reported in the literature suggest that a significant fraction of the dump volume (often on the order of tens of percent) may experience limited contact with the solution. However, such values should be interpreted with caution, as they depend strongly on ore characteristics, operational conditions, and measurement methodology (Wang et al., 2023).

Preferential flow pathways typically arise from local permeability contrasts, irregular particle packing, and uneven irrigation. Once established, they may persist and evolve, further reinforcing flow heterogeneity over time.

Importantly, increasing reagent concentration or extending leaching duration does not necessarily yield proportional improvements in recovery, because system performance is constrained by the accessibility of reactive surfaces and mass-transfer conditions, rather than solely by chemical availability.

6.4. Residence time distribution and mass transfer limitations

Residence time distribution (RTD) in dump leaching systems is broad and non-ideal, showing a range of flow behaviors from rapid channel flow to stagnant regions.

Table 3 shows ranges of flow velocity, permeability, residence time, and contact fraction. These are indicative and vary across systems and measurement methods.

Table 3. Indicative ranges of flow velocity, permeability, residence time, and effective contact fraction in dump leaching systems. Adapted from Odidi et al. (2023b) and Saldaña et al. (2022)

Parameter	Typical range	Impact
Flow velocity	10^{-6}–10^{-3} m/s	Non-uniform dissolution
Permeability	10^{-6}–10^{-3} m/s	Controls flow pathways
Residence time	days–months	Broad distribution
Effective contact volume	40–70%	Limits recovery

Preferential pathways and diffusion-limited zones lead to uneven reagent distribution and incomplete metal extraction, with some solution bypassing reactive areas while others are trapped or recirculated.

Mass transfer limitations result from convection, diffusion, and interfacial constraints. Often, the controlling factor changes from chemical equilibrium to reactive accessibility, so increasing reagent concentration or leaching time yields diminishing returns.

RTD analyses show that much of the dump may remain under-leached even after prolonged use, with variation depending on the system setup, underscoring the need to consider transport and reaction processes.

Dump leaching performance is not solely transport-limited or reaction-controlled but arises from a dynamic interplay among hydrodynamics, mass transfer, and chemical kinetics that evolves as the dump structure changes.

Understanding this interplay is essential for evaluating process performance and for identifying strategies that combine improvements in fluid distribution, mass transfer, and chemical reactivity.

7. Leaching Chemistry

Leaching chemistry establishes the thermodynamic framework for metal dissolution, but in dump leaching, effectiveness is often limited by fluid access, mass transfer, and heterogeneity within the porous medium (Free, 2024).

Operating performance often deviates from thermodynamic expectations because metal recovery depends on reaction kinetics, transport processes, and mineral accessibility, not just chemical potential. The next sections review main leaching routes, focusing on operational conditions, limitations, and hydrodynamics.

7.1. Acid leaching (oxide ores)

Acid leaching, the main method for copper oxide ores, is thermodynamically favorable under strongly acidic conditions ($pH < 2$) using sulfuric acid as the primary reagent. A simplified reaction is:

$$CuO + H_2SO_4 \rightarrow Cu^{2+} + SO_4^{2-} + H_2O$$

In industrial practice, acid consumption ranges from 5 to 50 kg H_2SO_4 per tonne of ore, depending on gangue composition, secondary reactions, and operating conditions (Bárzaga-Martell et al., 2025). Carbonate and silicate minerals can increase the consumption of non-productive acid.

Leaching efficiency depends on chemical conditions, solution distribution, and contact time. Even under favorable thermodynamic conditions, incomplete wetting and limited

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transport can restrict metal extraction (Harichandan & Mandre, 2021). Reported recoveries in dump systems range from 40–70%, which are indicative and context-dependent, not fixed limits.

7.2. Cyanide leaching (gold systems)

Cyanide leaching is commonly used for low-grade gold ores because of its high selectivity and effectiveness at low metal concentrations. It occurs under alkaline conditions (pH 10–11) to stabilize cyanide and reduce volatilization.

Gold dissolves via cyanidation with oxygen. In dump leaching, limited oxygen from poor aeration and uneven saturation can slow reactions.

Typical cyanide consumption ranges from 0.1 to 1.0 kg NaCN per tonne of ore, depending on ore reactivity and cyanide-consuming species (Togtokhbaatar, 2022). Under dump conditions, recoveries are usually 30% to 60%, limited by fluid and oxygen distribution rather than chemical inefficiency.

Increasing reagent concentration alone does not always improve recovery, as system performance is often limited by mass transfer and access to the reactive zone.

7.3. Bioleaching (sulfide ores)

Bioleaching uses acidophilic microorganisms to oxidize sulfide minerals, regenerating ferric iron and sulfuric acid, which sustain metal dissolution (Cheru, 2021; Dash et al., 2025). Figure 6 illustrates the coupling among microbial activity, iron cycling, and sulfur oxidation pathways.

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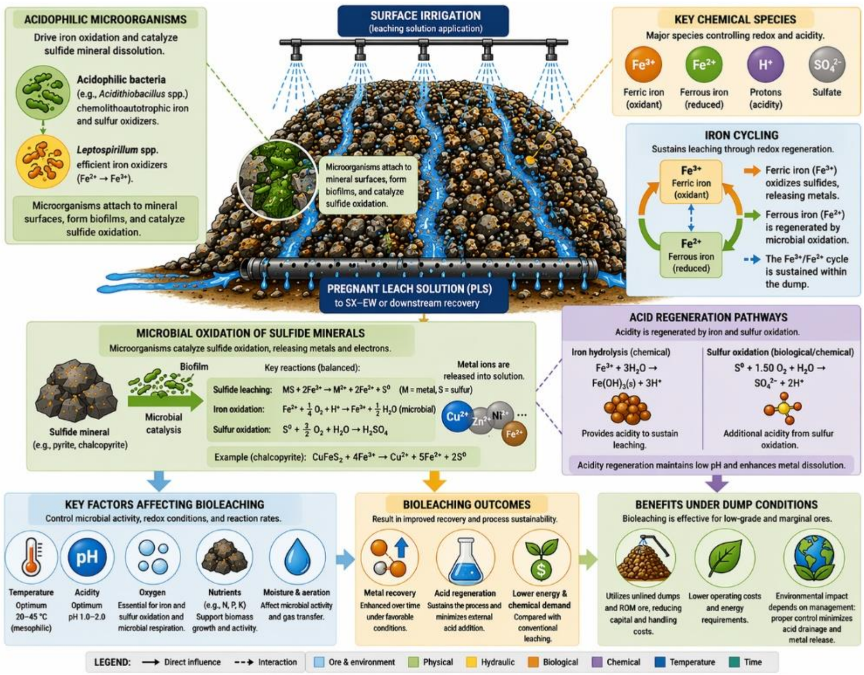

Figure 6. Schematic representation of microbial oxidation of sulfide minerals, ferric/ferrous iron cycling, and acid regeneration pathways. Source: Adapted from Johnson & Roberto (2022); Li et al. (2022).

Bioleaching effectiveness depends on oxygen, moisture, microbes, and reactive minerals, but these conditions are often uneven in dump systems, leading to variability in activity. Hydrodynamic factors, like oxygen transfer and fluid flow, greatly influence microbial processes. Favorable conditions may still result in limited recovery if transport processes are hindered, especially in poorly aerated or wet zones (Bryan & Harrison, 2023; Keke et al., 2023).

Typical operating conditions include temperatures of 25–50 °C and pH values of 1.5–3.0. Reported improvements in recovery relative to purely chemical leaching are often 10–20% under favorable conditions. However, these improvements are highly dependent on system configuration and should be interpreted as context-specific rather than universally achievable.

Bioleaching should therefore be understood as a process intensification strategy that enhances chemical pathways, but its effectiveness remains dependent on hydrodynamic and transport conditions

7.4. Emerging leaching chemistries

Alternative leaching systems, such as halide-based systems, catalytic additives, and modified oxidizing environments, have been proposed to overcome the limitations of conventional reagents (Moravvej et al., 2021; Li et al., 2023; Muravyov & Panyushkina, 2023).

For example, halide leaching has been shown to improve chalcopyrite dissolution by modifying surface passivation behavior, while catalytic additives may enhance reaction kinetics under control conditions (Fukano & Miura, 2021; Ren et al., 2020).

Most approaches have been validated in controlled lab or pilot-scale setups. Their effectiveness in dump leaching systems is uncertain, as hydrodynamic and transport constraints may limit their success, similar to conventional chemistry.

Consequently, improvements in chemical formulation alone are unlikely to result in proportional gains in recovery unless accompanied by enhanced fluid distribution and mass transfer. Table 4 summarizes operating conditions and performance ranges for main leaching routes, representing variability across ore types, process setups, and environments.

Table 4. Comparison of pH range, reagent consumption, temperature, and typical recovery for major leaching routes. Adapted from Bárzaga-Martell et al. (2025); Johnson & Roberto (2022). Values represent orders of magnitude and context-dependent performance ranges, not standardized operational targets

Leaching type	pH	Temp (°C)	Reagent consumption	Recovery (%)
Acid (Cu oxides)	<2	20–40	5–50 kg H_2SO_4/t	40–70
Cyanide (Au)	10–11	20–30	0.1–1 kg NaCN/t	30–60
Bioleaching	1.5–3	25–50	Low acid + Fe^{3+}	40–80

Across different leaching chemistries, recovery under dump conditions often falls within comparable ranges. This convergence does not necessarily reflect similar reaction efficiencies, but rather the influence of shared transport and hydrodynamic limitations.

Under controlled conditions, these chemistries can achieve significantly higher recoveries. However, in dump systems, performance is constrained by fluid accessibility, oxygen availability, and effective contact between reagents and mineral phases.

Chemical optimization alone isn't enough to maximize recovery. Process performance relies on integrating chemical reactivity with hydrodynamic control and system design to shape how reactions occur within the dump's heterogeneous structure (Lee et al., 2025).

8. Operational Performance

Operational performance in dump leaching systems is governed by the interplay among hydrodynamics, ore characteristics, and leaching chemistry. While recoveries are generally lower than in more controlled systems, this difference arises not from intrinsic thermodynamic limitations but from constraints on fluid distribution, mass transfer, and access to reactive zones within the dump structure.

8.1. Recovery efficiency

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Metal recovery in dump leaching is usually moderate, depending on ore type, mineralogy, dump geometry, and fluid flow, which all affect reagent access and the extent of reaction.

Table 5 shows representative recovery ranges for metals under dump leaching, indicating variability across ores and conditions.

Table 5. Indicative recovery ranges for copper and gold in dump leaching operations under heterogeneous flow conditions. Values represent context-dependent performance ranges, not universal recovery limits. Adapted from Neira et al. (2021) and Velásquez-Yévenes et al. (2022).

Metal	Recovery (%)
Copper	40–70
Gold	30–60

Reported recovery levels for copper and gold typically fall within the ranges shown in Table 5 but are strongly influenced by hydrodynamic conditions, particularly fluid distribution and contact efficiency.

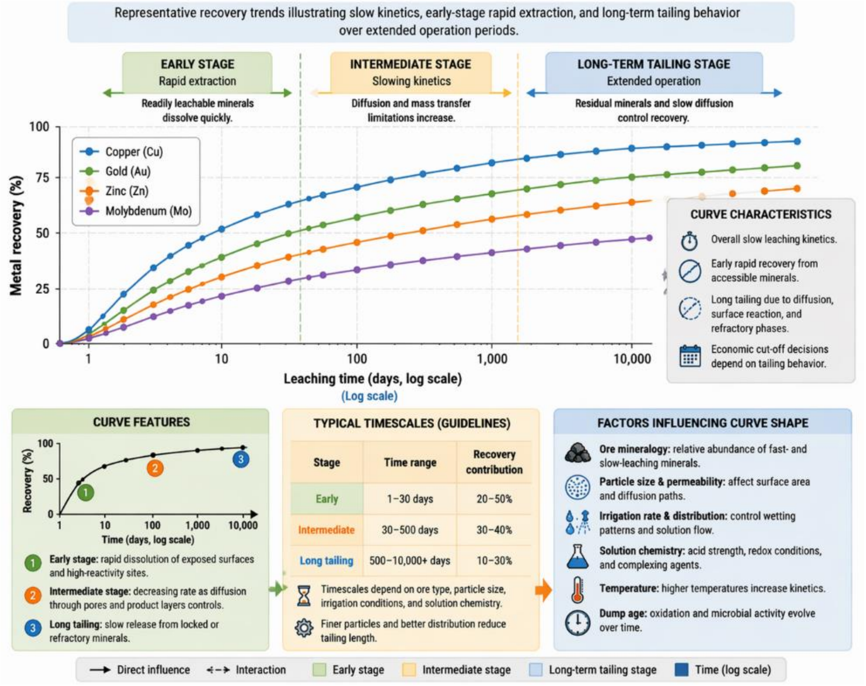
Leaching chemistry offers the thermodynamic basis for metal dissolution, but recovery depends on reagent access to mineral surfaces. Hydrodynamics often dominate system-scale influence, though chemical efficiency matters too. Recovery results from transport, mineral variability, and reaction kinetics.

Dump leaching yields are lower than heap and tank systems due to incomplete wetting, preferential flow, and restricted surface access. In sulfide systems, oxidation kinetics and oxidant transport also constrain recovery.

Improvements in recovery mainly come from better fluid distribution, increased contact efficiency, and greater access to reactive zones, not just from chemical modifications.

8.2. Leaching kinetics and time scales

Leaching kinetics in dump systems unfold over months to years. Recovery depends on reaction kinetics, mass transfer, and fluid flow. Figure 7 shows typical recovery trends in dump leaching.



Stage	Time range	Recovery contribution
Early	1–30 days	20–50%
Intermediate	30–500 days	30–40%
Long tailing	500–10,000+ days	10–30%

Figure 7. Representative recovery curves illustrating multi-stage behavior, including early-stage extraction, transitional regimes, and long-term tailing effects. Adapted from Ouassel et al. (2025) and Bruce et al. (2024).

Recovery profiles commonly exhibit a multi-stage evolution:

a. an initial phase of relatively rapid extraction, associated with readily accessible minerals in well-contacted regions;
b. a transitional phase, where recovery rates decline as accessible surfaces are depleted and mass transfer limitations increase;
c. a long-term tailing phase, characterized by slow dissolution and restricted fluid access.

This behavior reflects a shift in controlling mechanisms: early extraction depends on surface reaction kinetics and accessibility, whereas long-term performance is governed by hydrodynamic heterogeneity, residence time, and diffusion limits.

However, it is important to emphasize that this transition is not uniform across the system. Different regions of the dump may simultaneously exhibit reaction-controlled and transport-limited behavior, reflecting spatial variability in flow and mineral accessibility.

Extended operation time does not necessarily increase recovery proportionally. As accessible material is depleted, remaining ore becomes more difficult to leach due to limited contact and transport pathways.

This non-ideal behavior limits traditional kinetic models, which assume uniform flow and reactions. Dump leaching systems, however, show heterogeneous flow, broad residence times, and changing transport constraints (Ouassel et al, 2025).

8.3. Key influencing parameters

Operational performance in dump leaching hinges on physical, hydraulic, and mineralogical parameters. Table 6 summarizes key variables affecting recovery and kinetics.

Table 6. Indicative ranges of key parameters affecting recovery efficiency and leaching kinetics in dump leaching systems. Values represent orders of magnitude and context-dependent behavior, not fixed operational targets. Adapted from Kinyua et al. (2022) and Wang et al. (2020).

Parameter	Typical range	Effect
Particle size	50–500 mm	Controls surface area and permeability
Permeability	10^{-6}–10^{-3} m/s	Governs flow distribution
Irrigation rate	5–10 $L \cdot h^{-1} \cdot m^{-2}$	Affects wetting and contact
Acid consumption	5–50 kg/t	Influences dissolution
Mineralogy	variable	Determines reactivity

Particle size affects both reactive surface area and permeability. Coarse particles reduce the available surface area but may enhance permeability and fluid flow, creating a trade-off between reaction kinetics and transport efficiency.

Permeability and irrigation rate jointly control fluid distribution, affecting wetting patterns, residence time, and contact efficiency. Variability in these parameters contributes to preferential flow and uneven reagent distribution.

Acid consumption influences dissolution potential but is strongly dependent on the accessibility of reactive mineral surfaces. Mineralogical variability further complicates system behavior due to differences in reactivity, secondary reactions, and passivation effects.

Importantly, these parameters do not act independently but interact across scales, highlighting the need to view dump leaching as a coupled system where performance depends on hydraulic accessibility, mass transfer, and chemical reactivity.

9. Industrial Applications

Industrial applications best assess the viability of dump leaching by focusing on sustained recovery, solution stability, flow behavior, and long-term economic viability, rather than laboratory success alone.

Dump leaching is mainly used for commodities such as copper, gold, and uranium, as well as for reprocessing legacy dumps. Its industrial importance lies in low capital costs and the ability to process large volumes of low-grade material, not in high metallurgical complexity or efficiency.

9.1. Copper dump leaching

Copper represents the most established industrial application of dump leaching, particularly in large mining regions such as the United States and Chile, where low-grade oxide and secondary sulfide ores are treated at scale (Schlesinger et al., 2021).

In these operations, dump leaching enables the processing of large tonnages with relatively low capital investment. However, performance is typically characterized by moderate recovery, long leaching cycles, and sensitivity to ore variability (Shengo Lutandula et al., 2020).

Reported copper recoveries vary widely (e.g., 40–70%) depending on mineralogy, permeability, and practices. These ranges are indicative and site-specific, not standardized benchmarks.

Modern copper production often uses leaching combined with solvent extraction and electrowinning (SX–EW) to convert low-grade solutions into cathode copper. Heap leaching–SX–EW systems make up much of global copper output, while dump leaching is a lower-efficiency, lower-cost alternative (Sole et al., 2025).

Dump leaching becomes attractive when metal prices, ore grade, and stripping ratios render conventional processing uneconomic. Its competitiveness depends on cut-off grade policies, reagent use (especially acid), and long-term operations costs.

9.2. Gold dump leaching

Gold dump leaching is primarily used for low-grade and marginal ore piles, where the metal content does not justify more intensive processing methods. The approach enables long-term recovery of residual value from large volumes of material at relatively low capital cost (Dreier, 2025).

However, metallurgical performance is constrained by the requirements of cyanide leaching, which depend on adequate solution distribution, oxygen availability, and sufficient contact time. These conditions are difficult to achieve in large, heterogeneous dumps.

Reported recoveries range from 30–60%, but depend on ore characteristics, permeability, and cyanide-consuming species. The goal isn't always to maximize recovery but

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to extract resources economically. Operational viability depends on ore grade, permeability, reagent use, and process time.

9.3. Uranium leaching systems

Uranium has long been associated with percolation-based leaching, such as dump leaching and in situ recovery. Depending on ore mineralogy, operations use either acidic or alkaline leaching (Bhatti & Tuovinen, 2023).

These systems are particularly sensitive to solution chemistry, oxidation conditions, and groundwater management. Recovery performance is highly variable and strongly dependent on permeability, mineralogy, and hydrogeological conditions (Kiegiel et al., 2021).

Although dump leaching offers a relatively low-cost approach for treating low-grade uranium resources, its application is constrained by strict environmental and regulatory requirements. The need for containment systems, monitoring infrastructure, and long-term liability management may significantly increase total project cost

9.4. Reprocessing of legacy dumps

Reprocessing legacy dumps is a key application of dump leaching, focusing on metal recovery, environmental remediation, and lowering long-term liabilities. Table 7 summarizes applications, objectives, and constraints across commodities.

Table 7. Summary of representative applications of dump leaching, including typical objectives, indicative recovery ranges, advantages, and key constraints. Values should be interpreted as context-dependent and site-specific. Adapted from Schlesinger et al. (2021); Kiegiel et al. (2021); Bridge (2024)

Application	Typical objective	Typical recovery (%)	Main advantage	Main limitation
Copper	Treat low-grade oxide and secondary sulfide ores	40–70	Large-scale, low-CAPEX processing	Long cycles, moderate recovery
Gold	Recover value from marginal ore dumps	30–60	Low-cost treatment of residual material	Poor oxygen/solution distribution
Uranium	Treat low-grade ores or old dumps	Variable, site-dependent	Low mining intensity	High environmental control demand
Legacy dump reprocessing	Recover residual metals and reduce liabilities	Variable, site-dependent	Dual economic and remediation benefit	Strong heterogeneity and uncertain inventory

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Across these applications, dump leaching should not be interpreted as a standardized processing route, but rather as a context-dependent strategy governed by the interaction between resource characteristics, economic constraints, and environmental considerations.

In copper systems, it is widely used where large volumes and low grades favor low-cost processing. In gold applications, it is typically restricted to marginal or residual materials. In uranium systems, its use is conditioned by environmental and regulatory constraints. In legacy dump reprocessing, it serves a dual role in metal recovery and remediation.

The industrial record reveals a consistent selection logic: dump leaching is preferentially applied when resources are too low-grade, too large, or too heterogeneous to justify more intensive processing routes.

At the same time, these same characteristics introduce significant uncertainty in recovery, process control, and environmental performance. This duality defines both the strength and the limitation of the technology.

As shown in Figure 8, dump leaching is a niche technology with low capital costs, tolerance for heterogeneity, and suitability for long operational periods.

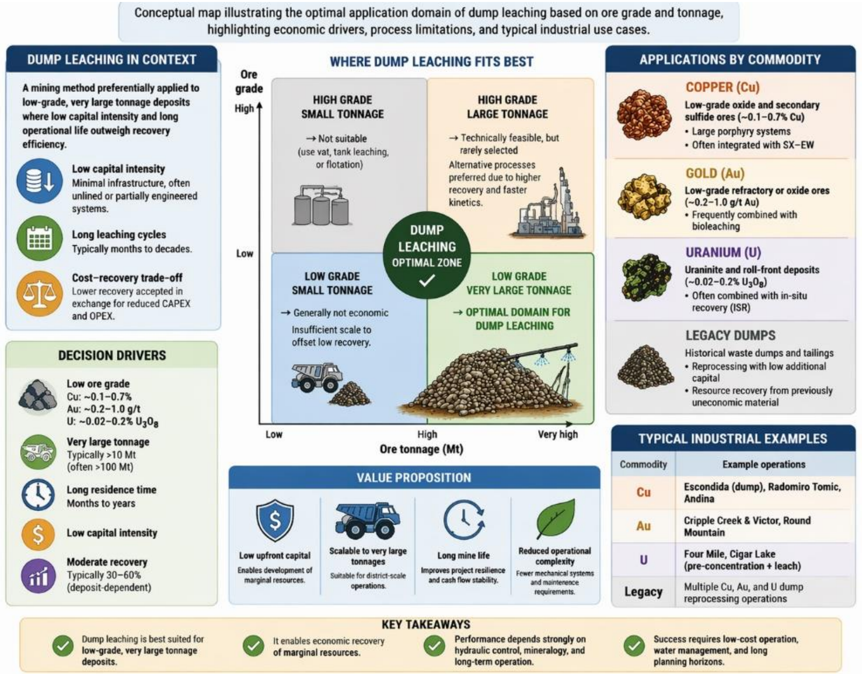

Figure 8. Conceptual representation of the industrial niche of dump leaching, highlighting its preferential application to low-grade, high-tonnage, long-cycle operations where capital minimization is prioritized over maximum recovery. Adapted from Schlesinger et al. (2021), Dreier (2025), and Bridge (2024)..

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Rather than competing directly with more controlled technologies, dump leaching operates within a specific domain of applicability, where economic viability is achieved despite lower recovery efficiency.

These considerations become particularly relevant when environmental constraints are introduced, as discussed in the following section.

10. Environmental Challenges

Environmental aspects of dump leaching are tied to the physical and chemical factors that affect metal recovery. Large scale, long residence times, and limited control can increase fluid migration, acid generation, and environmental liabilities (Roman & Saria, 2025).

Environmental risks in dump leaching result from hydrodynamics, geochemical reactions, and system design, not isolated issues. Therefore, environmental performance is key to process evaluation, alongside metallurgical efficiency and economic viability.

10.1. Acid mine drainage (AMD)

Acid mine drainage (AMD) is a major environmental concern from the leaching of sulfide minerals. Oxidation of sulfides produces sulfuric acid and dissolves metals, which can persist beyond active leaching (Mills, 2020).

The severity of AMD depends on mineralogy, oxygen, moisture, and drainage. Favorable sulfide oxidation can lead to acidic drainage with a pH below 3 and elevated sulfate and metal levels.

Once established, acid-generating zones are difficult to isolate or control due to the dump's heterogeneous structure. Field studies show acid generation and drainage can continue long after operational changes or closure, due to the coupling of unsaturated flow, reactive mineral exposure, and slow internal transport (Ma et al., 2020).

However, AMD formation varies greatly with ore composition and site conditions. Systems with oxide ores may have a lower risk of AMD, underscoring the need for mineralogical characterization in environmental assessments.

10.2. Groundwater contamination

Groundwater contamination is a key concern in dump leaching operations, particularly where containment systems, underdrainage, or monitoring infrastructure are limited or absent.

In older or unlined systems, leachate may infiltrate into the subsurface, transporting dissolved metals and acidic species. The extent of contaminant migration depends on hydraulic

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conductivity, infiltration rates, and geochemical interactions with surrounding materials (Guo et al., 2024).

Even relatively low infiltration fluxes may lead to significant cumulative loading over extended operational periods. This highlights the importance of long-term mass-balance considerations rather than short-term flow rates alone.

Economically, this behavior shows a trade-off: lower initial investment in containment may lead to higher long-term environmental costs. The economic benefit of dump leaching should be assessed over its entire life cycle, including monitoring, mitigation, and remediation.

Table 8. Summary of representative environmental risks in dump leaching systems, including their primary causes and potential long-term consequences. These risks are context-dependent and influenced by system design, mineralogy, and operational practices. Adapted from Mills (2020), Guo et al. (2024), and Bridge (2024)..

Environmental issue	Main cause	Typical consequence
Acid mine drainage	Sulfide oxidation in presence of water and oxygen	Persistent acidity, sulfate release, metal mobilization
Groundwater contamination	Seepage of acidic or metal-bearing solutions	Off-site plume migration, water quality deterioration
Surface water impact	Runoff and drainage discharge	Downstream contamination and ecological damage
Residual reagent release	Incomplete containment and prolonged drainage	Long-term chemical instability
Post-closure instability	Uncontrolled reactive zones within the dump	Extended monitoring and remediation needs

Environmental challenges in dump leaching stem from structural and hydrodynamic characteristics that affect performance. Non-uniform infiltration, limited flow control, and heterogeneity can reduce recovery and lead to uncontrolled fluid migration.

This shared basis shows that process inefficiency and environmental impact are connected through transport and reaction mechanisms.

However, it is important to recognize that environmental outcomes are not determined solely by inherent process characteristics. Engineering design, operational practices, and regulatory frameworks can significantly influence system performance and risk mitigation.

10.3. Long-term environmental liabilities

Long-term environmental liabilities from leachate can persist beyond the operational phase. Reactive zones may remain active for extended periods, leading to ongoing acid production and contaminant release. Figure 9 shows the pathways of acid generation, seepage, and long-term environmental impact.

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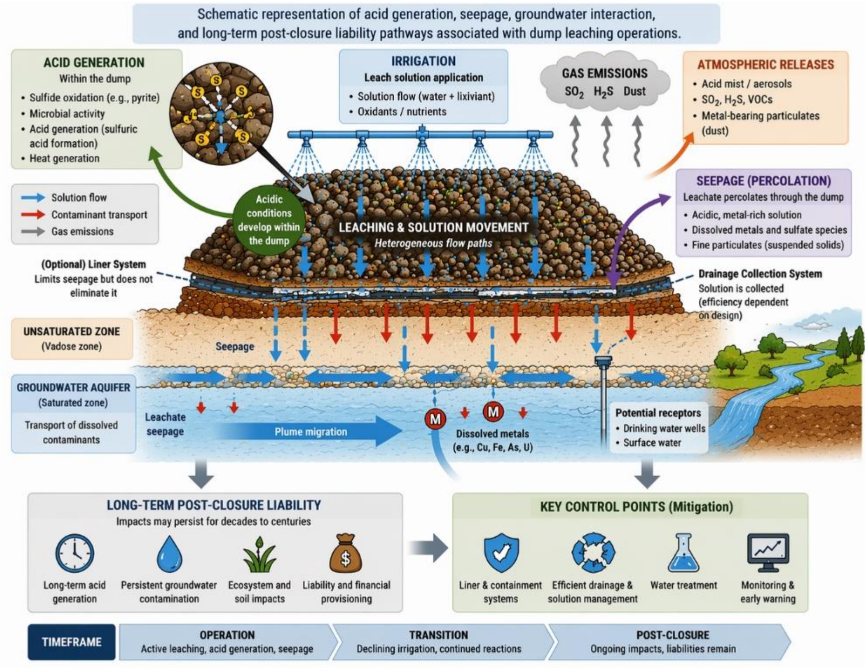

Figure 9. Conceptual representation of acid generation, seepage, groundwater interaction, and long-term post-closure pathways in dump leaching systems. Adapted from Ma et al. (2020) and Warhurst (2024).

These processes may require long-term management strategies, including monitoring, water treatment, cover systems, and, in some cases, structural re-engineering of the dump.

Economically, low-capital operations might face high deferred costs without environmental controls in design.

Modern dump leaching operations increasingly recognize liabilities and incorporate better containment, drainage, and monitoring systems. Consequently, environmental performance is a design-dependent variable rather than an inherent technology limitation.

From a critical perspective, historical evaluations of dump leaching have often emphasized short-term recovery and operational simplicity, while underestimating long-term environmental implications. Current assessments increasingly adopt a more integrated approach, in which environmental impact is treated as a core component of process economics and regulatory acceptance (Chattopadhyay & Chattopadhyay, 2020; Soares et al., 2023).

Overall, the environmental footprint of dump leaching systems reflects the interaction between geochemical processes and fluid migration pathways within large, heterogeneous structures.

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This implies that dump leaching cannot be evaluated solely in terms of extraction efficiency or operational cost. Its long-term viability depends on the integration of metallurgical performance, hydrodynamic control, and environmental management.

These considerations underscore the need for design strategies that integrate containment, monitoring, and closure planning from the earliest stages of project development.

11. Environmental Control and Mitigation Technologies

Environmental control in dump leaching systems should be treated not as an auxiliary function but as an integral component of engineering design. The same mechanisms that govern metal recovery—fluid flow, permeability, and residence time—also influence contaminant transport and environmental performance.

Mitigation strategies are most effective when integrated into system design from the start, rather than implemented as corrective measures after environmental impacts occur.

Modern dump leaching operations increasingly incorporate containment, drainage, and monitoring systems to reduce environmental risk. However, these measures introduce additional capital and operating costs, thereby influencing the overall economic balance of the process.

11.1. Liners and containment systems

Containment systems are designed to limit leachate migration into the surrounding environment through engineered barriers, including compacted clay layers, geomembranes (e.g., HDPE), and composite liner systems.

Effective liners typically exhibit hydraulic conductivities on the order of 10^{-9} to 10^{-11} m/s, lower than natural soils, reducing seepage and improving solution collection (Bridge, 2024). These are target ranges; actual performance depends on installation quality and long-term integrity.

While linear systems can substantially improve environmental performance, they introduce technical and economic challenges. Installation requires careful subgrade preparation and quality control, and long-term performance may be affected by mechanical damage, chemical degradation, or differential settlement.

In legacy dump leaching operations, the absence of engineered containment often represents a major environmental liability. Retrofitting such systems is frequently complex and costly, particularly for large or irregularly shaped dumps.

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11.2. Drainage and solution management

Drainage systems play a central role in dump leaching operations by enabling the collection of pregnant leach solution (PLS) while limiting uncontrolled seepage. Typical configurations include underdrain layers, collection piping networks, and solution ponds designed to accommodate variable, often irregular, flow conditions.

Figure 10 shows the main components of solution distribution and recovery systems. (Benzal et al., 2020; Georgiev et al., 2025).

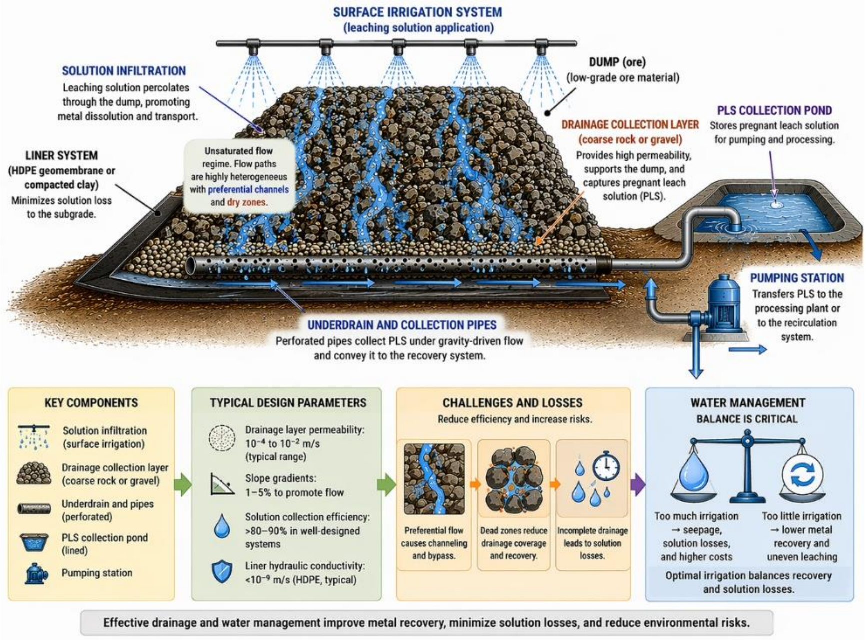

Figure 10. Schematic showing solution infiltration, drainage collection layers, piping systems, and PLS recovery infrastructure. Adapted from Ma et al. (2020).

Key design parameters include drainage layer permeabilities of 10^{-3} to 10^{-2} m/s, slope gradients of 1–5% for gravity flow, and solution collection efficiencies over 80–90% in well-designed systems. These ranges vary with dump geometry and heterogeneity.

In practice, complete recovery of the solution is rarely achieved. Losses may occur due to preferential flow pathways, poorly drained zones, and incomplete drainage system coverage, all of which are linked to the inherent heterogeneity of dump structures.

Water management is therefore a critical operational challenge. Recirculation strategies must balance the need to maximize metal recovery with the need to control solution inventory and minimize environmental losses. Excessive irrigation may increase the risk of seepage, while insufficient irrigation can reduce wetting efficiency and limit recovery.

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These considerations highlight that drainage and solution management are not purely design problems, but are intrinsically connected to the hydrodynamic behavior of the system

11.3. Monitoring and digital tools

Monitoring systems in dump leaching operations have evolved significantly, incorporating in situ sensors, remote sensing technologies, and data-driven approaches to improve system visibility and support decision-making.

Given the scale and heterogeneity of dump leaching systems, effective monitoring typically requires integrating multiple complementary techniques that capture both surface and subsurface behavior. Table 9 summarizes representative monitoring tools used in industrial practice.

Table 9. Summary of monitoring tools used to assess moisture distribution, flow behavior, and environmental performance in dump leaching systems. Adapted from Tang & Esmaeili (2021).

Monitoring method	Parameter measured	Application
Moisture sensors	Saturation, wetting front	Flow control
Drone imaging	Surface moisture distribution	Irrigation optimization
Geophysical methods	Internal structure	Permeability mapping
Chemical monitoring	pH, metal concentration	Environmental control

Moisture sensors provide localized measurements of saturation and wetting front progression, supporting short-term operational adjustments. Drone-based imaging enables large-scale mapping of surface conditions, facilitating irrigation optimization across extensive areas.

Geophysical techniques offer indirect insights into internal structures and permeability, addressing the limitations of subsurface access. Chemical monitoring is crucial for assessing process performance and environmental compliance.

Despite these advances, monitoring approaches operate across different spatial and temporal scales and are often only partially integrated. As a result, the transition from empirical operation to fully predictive, data-driven control remains limited.

Figure 11 illustrates the relationship between increasing levels of environmental control and associated economic cost

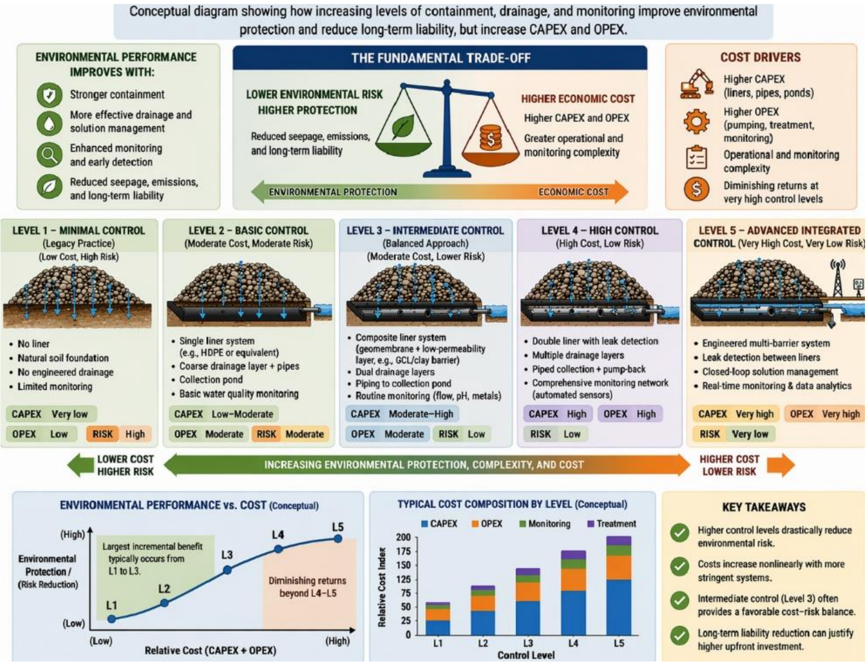

Figure 11. Conceptual diagram showing how increasing levels of containment, drainage, and monitoring improve environmental performance while increasing CAPEX and OPEX. Adapted from Bridge (2024) and Tang & Esmaeili (2021).

The link between monitoring intensity, environmental performance, and costs is key in dump leaching systems. Better control—via containment, drainage, and monitoring—can lower environmental risk and boost understanding, but demands more infrastructure, instrumentation, and operational complexity.

This trade-off shows that environmental mitigation is linked to economic considerations. More control shifts the system toward engineered setups, raising capital and operating costs.

Monitoring and control are necessary but not sufficient for process optimization; their success depends on translating data into actionable strategies within the system's physical and hydrodynamic constraints.

Overall, environmental control in dump leaching systems reflects a balance between engineering intervention, economic constraints, and process performance.

Effective mitigation strategies combine containment, drainage, and monitoring within a coherent design, supported by understanding hydrodynamics and reactive transport.

These considerations reinforce that improvements in environmental performance are closely linked to broader techno-economic trade-offs, which are examined in the following section.

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12. Techno-economic Analysis

Techno-economic performance influences the choice of leaching technologies. While dump leaching is considered low-cost, its economic viability depends on recovery efficiency, operating time, and environmental commitments.

A comprehensive assessment should consider capital investment, reagent use, water management, cash flow, and long-term liabilities. The simplicity of dump leaching can hide indirect costs due to lower efficiency and longer operation times.

12.1. CAPEX comparison across leaching systems

Capital expenditure (CAPEX) varies widely across hydrometallurgical leaching methods due to differences in infrastructure, ore prep, and process control. Table 10 shows typical CAPEX ranges normalized to dump leaching, intended as rough comparisons rather than precise cost ratios.

Table 10. Indicative CAPEX ranges for major hydrometallurgical leaching systems, normalized to dump leaching. Values represent relative orders of magnitude and depend on site-specific conditions. Adapted from Schlesinger et al. (2021) and Dreier (2025).

Process	Relative CAPEX	Main components
Dump leaching	1x	Minimal infrastructure, irrigation system
Heap leaching	2–4x	Crushing, agglomeration, liners
Vat/Box leaching	3–6x	Tanks, structural containment
Tank leaching	5–10x	Grinding, reactors, agitation systems

Dump leaching is generally associated with the lowest capital intensity, requiring relatively simple infrastructure focused on solution application and collection. This low initial investment enables the processing of large volumes of low-grade material.

In contrast, heap leaching entails additional capital requirements for ore preparation and engineered containment systems. Vat/box and tank leaching systems require progressively more complex installations, reflecting higher levels of process control.

Overall, CAPEX increases with the degree of engineering control. However, this relationship should be interpreted as a general trend, as actual costs depend on scale, location, and project-specific design choices.

12.2. OPEX drivers (acid, energy, water)

Operating expenditure (OPEX) in leaching systems is primarily influenced by reagent consumption, water use, energy demand, and environmental management.

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Acid consumption in oxide systems ranges from 5 to 50 kg H_2SO_4 per tonne, with higher values depending on gangue reactivity (Bárzaga-Martell et al., 2025). These are indicative ranges.

Water consumption is also significant. Irrigation rates of approximately 5–10 $L \cdot h^{-1} \cdot m^{-2}$ may correspond to total water usage on the order of 0.5–1.5 m^3 per tonne of ore over a leaching cycle, depending on duration, recirculation efficiency, and losses due to evaporation and seepage.

Energy consumption in dump leaching is relatively low compared to more intensive systems, primarily because comminution is not required. However, this advantage may be partially offset by longer operating periods and lower recovery efficiency.

In contrast, heap and tank leaching systems require higher energy input, particularly for crushing and grinding, but benefit from improved recovery and shorter processing times.

Global operating data indicate that heap leaching integrated with solvent extraction–electrowinning (SX–EW) represents a major contributor to copper production, highlighting the economic relevance of more controlled leaching systems (Sole et al., 2025).

Table 11 compares the main cost drivers across dump, heap, and tank leaching systems, highlighting differences in reagent consumption, energy demand, labor requirements, and environmental management.

Table 11. Indicative distribution of operating cost drivers across leaching technologies. Values represent relative trends and may vary significantly depending on system design and operating conditions. Adapted from Bárzaga-Martell et al. (2025) and Sole et al. (2025).

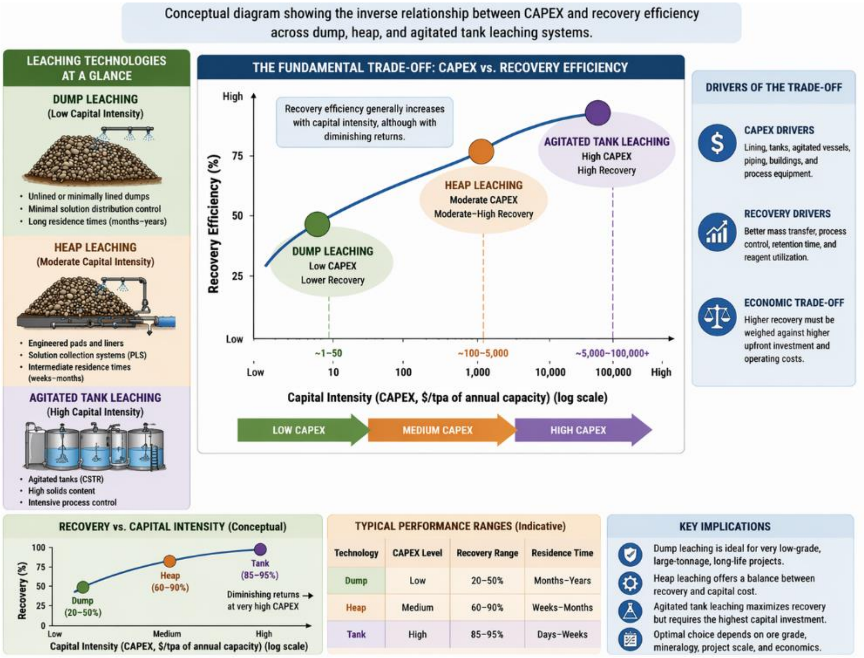
Cost component	Dump	Heap	Tank
Acid consumption	High variability	Moderate	Optimized
Water consumption	High	Moderate	Controlled
Energy	Low	Moderate	High
Labor	Low	Moderate	High
Environmental management	High (long-term)	Moderate	Controlled

Dump leaching is characterized by low energy and labor requirements, but often exhibits high variability in reagent consumption and significant long-term environmental management costs. These factors reflect the limited process control and extended operational duration associated with this approach.

More controlled systems tend to internalize costs through higher CAPEX and OPEX, but benefit from improved efficiency and predictability..

12.3. Economic trade-offs vs recovery

The relationship between recovery efficiency and capital investment is a central trade-off in selecting leaching technologies. Figure 12 illustrates this relationship, showing a general inverse correlation between CAPEX and recovery efficiency across dump, heap, and tank leaching systems.



Technology	CAPEX Level	Recovery Range	Residence Time
Dump	Low	20–50%	Months–Years
Heap	Medium	60–90%	Weeks–Months
Tank	High	85–95%	Days–Weeks

- Dump leaching is ideal for very low-grade, large-tonnage, long-life projects.
- Heap leaching offers a balance between recovery and capital cost.
- Agitated tank leaching maximizes recovery but requires the highest capital investment.
- Optimal choice depends on ore grade, mineralogy, project scale, and economics.

Figure 12. Conceptual diagram illustrating the trade-off between capital intensity and recovery efficiency across major leaching technologies. Adapted from Binnemans & Jones (2023) and Nkuna et al. (2022).

Dump leaching typically occupies the low-CAPEX, lower-recovery region, enabling the processing of large volumes of low-grade material with minimal infrastructure. Heap leaching is an intermediate configuration that balances recovery and cost by improving hydraulic control. Tank leaching achieves higher recoveries but requires significantly greater capital and operational intensity.

However, this relationship should not be interpreted as strictly linear. Economic performance also depends on time-dependent factors, including project duration, cash flow timing, and exposure to market fluctuations.

Long operational timeframes in dump leaching may delay revenue generation and increase sensitivity to commodity price variability. These temporal effects are often underrepresented in simplified economic comparisons.

In addition, environmental liabilities introduce deferred costs that may significantly affect long-term project economics. Monitoring, remediation, and regulatory compliance can

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offset the apparent advantage of low initial capital investment when evaluated over the full project lifecycle.

Taken together, these factors suggest that dump leaching is economically favorable primarily under specific conditions, such as low-grade resources, large available tonnage, limited capital availability, and manageable environmental risk.

Dump leaching is a context-dependent strategy, not a universally optimal solution, whose competitiveness depends on recovery, cost, time, and risk.

13. Technological Advances

Recent technological developments in dump leaching aim to improve recovery, reduce environmental impact, and enhance process predictability. However, these advances usually do not alter the process's fundamental characteristics; they mainly mitigate existing limitations.

Most innovations aim to improve fluid distribution, reaction pathways, or system monitoring. A key challenge is implementing these while maintaining the low-capital nature of dump leaching systems.

13.1. Bioleaching integration

Bioleaching is a promising method for enhancing metal recovery in sulfide systems by regenerating ferric iron and sulfuric acid, which aid mineral dissolution.

Under favorable conditions, improvements in recovery of 10–20 percentage points are often reported, depending on oxygen, temperature, moisture, and system setup (Aachhera, 2026). Typical conditions include temperatures of 25–50 °C and a pH of 1.5–3.0, with continuous oxygen to maintain microbial activity.

Despite its potential, the effectiveness of bioleaching in dump systems is limited by hydrodynamic constraints that affect fluid flow and mass transport. Microbial activity mainly occurs where solutions and oxygen are accessible, reducing impact in poorly wetted or low-permeability zones.

This dependency shows that improvements in leaching pathways are tied to transport conditions. Bioleaching should be seen as a process-intensification strategy that relies on hydraulic accessibility (Devi & Ganesh, 2024).

13.2. Process monitoring and digitalization

Advances in monitoring technology have greatly enhanced the observation and understanding of dump leaching systems. Combining sensors, remote platforms, and data tools

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enables detailed analysis of flow, temperature, and chemical concentrations. Figure 13 shows a framework for monitoring using moisture sensors, drones, and data analysis.

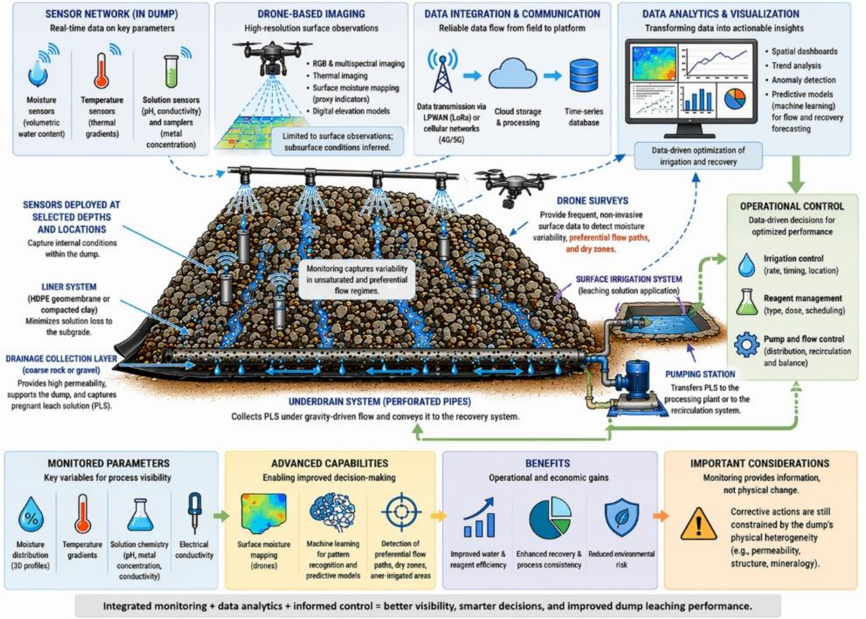

Figure 13. Integration of moisture sensors, drone imaging, and data analytics for real-time monitoring of flow distribution and process performance. Adapted from Tang & Esmaeili (2021).

Typical monitored parameters include moisture distribution, temperature gradients, and solution chemistry (e.g., pH and metal concentrations), which serve as indirect indicators of flow behavior, reaction zones, and process efficiency.

Drone imaging with data analysis enables high-res surface mapping, identifying dry zones and over-irrigated areas, aiding water and reagent management.

Monitoring alone does not always improve process control. Although these technologies improve system visibility, implementing corrective actions is often limited by the dump's physical structure and hydrodynamics.

Consequently, digitalization should be seen as a tool to enable decision-making rather than a direct fix for process limitations. Its success depends on how operational adjustments—such as irrigation or stacking—affect fluid distribution in a complex system.

13.3. Hybrid systems (dump + heap + bio)

Hybrid systems aim to bridge the gap between the low capital needs of dump leaching and the higher efficiency of engineered processes. They may include selective crushing, controlled stacking, localized agglomeration, and, in some cases, bioleaching with enhanced aeration.

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Such approaches allow partial control over key variables, such as fluid distribution and access to reactive surfaces, without requiring full-scale heap or tank leaching infrastructure. Table 12 compares conventional dump leaching and hybrid setups.

Table 12. Comparison of ore preparation, hydraulic control, recovery, environmental performance, and capital intensity between conventional dump leaching and hybrid configurations. Values represent indicative ranges and context-dependent trends. Adapted from Jia et al. (2024) and Li et al. (2022).

Parameter	Dump leaching	Hybrid systems
Ore preparation	Minimal	Partial crushing/agglomeration
Hydraulic control	Low	Moderate
Recovery	30–70%	50–85%
Environmental control	Limited	Improved
CAPEX	Low	Moderate

As shown in Table 12, hybrid systems can improve recovery compared with conventional dump leaching, primarily by enhancing fluid distribution and increasing access to reactive material. Reported improvements are typically 15–30% relative to baseline performance, though these values depend strongly on ore characteristics and system design.

From an environmental perspective, hybrid approaches may improve containment and solution management, thereby reducing the risk of uncontrolled seepage. However, these benefits come with higher capital requirements and greater operational complexity.

Overall, hybrid configurations can be viewed as transitional systems within a broader continuum of increasing engineering control. They deliver measurable performance improvements while maintaining moderate capital intensity, but do not fully eliminate the limitations of large-scale heterogeneous systems.

As the level of engineering increases, the characteristics of hybrid systems tend to converge toward those of heap leaching. This convergence raises important questions about their economic positioning and technological classification.

In this context, performance improvements in dump-based systems are achievable but are inherently associated with greater control, complexity, and cost. The long-term role of dump leaching as a distinct process, therefore, depends on how these trade-offs evolve in practice.

14. Research Gaps

Despite the long history of dump leaching, key knowledge gaps persist. These are mainly in prediction, control, and scale, especially under heterogeneous and weakly controlled conditions, rather than the chemical feasibility of metal dissolution, which is well understood.

A key challenge is the lack of robust frameworks that connect lab observations, field heterogeneity, and long-term industrial performance. Many studies remain descriptive, and the engineering basis for reliable design, optimization, and forecasting remains incomplete.

14.1. Hydrodynamic modeling limitations

Hydrodynamic modeling in dump leaching is underdeveloped, often relying on simplified assumptions that overlook the coarse, segregated, and dynamic features of real dumps. These systems have multi-scale pores, variable saturation, heterogeneous permeability, and evolving structures, challenging traditional models' ability to represent preferential flow and localized wetting.

Recent advances like high-resolution imaging and dual-porosity models enhance understanding but lack reliable industrial-scale predictions. A key unresolved issue is the lack of validated models that link flow velocity, wetting, contact efficiency, and recovery within a consistent framework. Process design still relies on empirical correlations and experience rather than predictive tools.

14.2. Reactive transport coupling

A second major gap lies in the limited integration of hydrodynamics with reaction modeling. In many studies, dissolution kinetics are treated independently of transport processes, despite the strong coupling between these mechanisms in dump leaching systems.

This decoupling introduces inconsistencies when extrapolating laboratory results to field conditions. Reaction rates measured under controlled conditions cannot be directly applied to dumps, where only a fraction of the mineral surface is effectively contacted by the lixiviant.

Accurate modeling therefore, requires fully coupled reactive transport frameworks that account for:

- heterogeneous flow distribution,
- diffusion and convection processes,
- accessibility of reactive mineral surfaces,
- formation of secondary phases, and
- time-dependent changes in permeability and structure.

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However, current modeling approaches rarely incorporate this level of integration with sufficient fidelity to support industrial-scale prediction or process optimization. This limitation represents a critical barrier to reliable performance forecasting and design.

14.3. Scale-up and industrial validation

Scale-up remains one of the most persistent challenges in dump leaching. Results obtained from laboratory columns or pilot-scale systems are frequently used to estimate industrial performance, but this transition is not straightforward.

Dump leaching systems operate under conditions that differ fundamentally from laboratory experiments, including:

a. larger particle sizes,
b. broader residence-time distributions,
c. greater structural heterogeneity, and
d. significantly longer operational cycles.

These differences cause non-linear effects that hinder direct extrapolation from small tests. A major issue is the lack of scale independence in control mechanisms, as parameters like permeability, irrigation rate, capillary behavior, and channeling can vary with dump height and size. Scaling up may lead to qualitative changes in the system, not just quantitative differences.

This uncertainty has direct economic implications. As shown in Table 13, limitations in hydrodynamic modeling, reactive transport coupling, and scale-up contribute to unreliable recovery predictions, misestimation of reagent consumption, and increased investment risk.

Table 13. Summary of key research gaps in hydrodynamic modeling, reactive transport coupling, and scale-up, along with their practical implications for industrial performance and decision-making. Values represent qualitative relationships and system-level limitations, rather than quantified design parameters. Adapted from Zheng (2026), Saldaña et al. (2023), and Dixon & Lizama (2022).

Research gap	Current limitation	Industrial consequence
Hydrodynamic modeling	Oversimplified representation of heterogeneous flow	Poor prediction of recovery and reagent distribution
Reactive transport coupling	Weak integration of kinetics and mass transfer	Limited ability to forecast long-term performance
Scale-up	Column and pilot tests not representative of full dumps	High uncertainty in design and investment decisions
Bioleaching optimization	Uneven microbial activity and oxygen distribution	Uncertain recovery gains in sulfide systems
Legacy dump reprocessing	Incomplete inventory and internal characterization	High project risk and variable economic outcome

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The gaps identified above highlight a common limitation: the absence of integrated, multi-scale modeling frameworks that capture interactions among hydrodynamics, reaction processes, and structural evolution.

As a result, dump leaching remains, to a significant extent, a semi-empirical process. Engineering decisions are frequently made under uncertainty, relying on conservative assumptions and operational experience rather than predictive models.

This uncertainty propagates across multiple domains:

- process design and optimization,
- recovery estimation and economic evaluation,
- environmental risk assessment, and
- long-term operational planning.

Additional factors—including climatic variability, limited internal characterization of dumps, and data scarcity—further amplify these uncertainties.

Particularly in the reprocessing of legacy dumps, incomplete knowledge of the internal structure, residual metal distribution, and geochemical reactivity introduces substantial variability in project outcomes.

Figure 14 highlights key uncertainty sources and their impact on industrial use, focusing on hydrodynamics, reactive transport, scale-up limits, and decision-making risks..

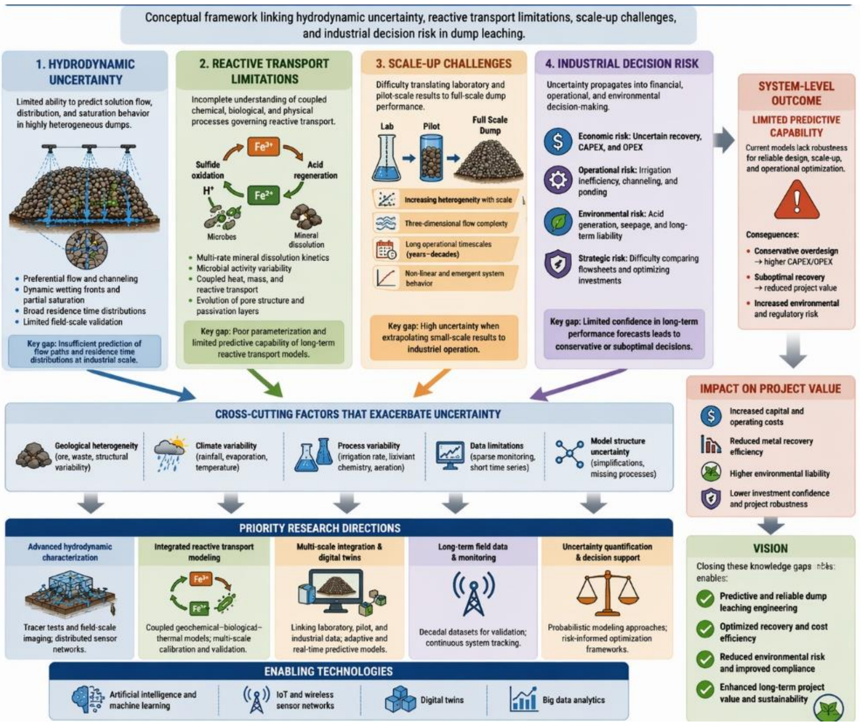

Figure 14. Conceptual framework linking hydrodynamic uncertainty, reactive transport limitations, scale-up challenges, and industrial decision risk in dump leaching. Adapted from Wang et al. (2023); Pereira (2026a).

Reducing these uncertainties requires the development of integrated approaches that combine:

a. improved internal characterization,
b. continuous monitoring, and
c. advanced data-driven and physics-based modeling.

Such developments are crucial for shifting dump leaching from empirical to predictive engineering.

The gaps highlight the ongoing relevance and limitations of dump leaching. While viable under certain economic and operational conditions, its future depends on improving predictability, control, and integration with advanced tools. The review concludes that dump leaching remains feasible but must evolve into a more controlled system, as summarized in the final section.

15. Conclusions

Dump leaching remains a relevant processing route under specific economic conditions, particularly for low-grade, large-scale resources where capital minimization is a primary constraint. Its continued application reflects its capacity to process large volumes of material at relatively low initial cost, rather than its ability to achieve high metallurgical efficiency.

Process performance is affected by limited hydraulic control, uneven fluid distribution, and restricted mass transfer in porous structures. These factors may limit recovery and cause variability in metallurgical and environmental outcomes.

The review shows that improving dump leaching depends more on controlling fluid flow, increasing access to reactive zones, and integrating hydrodynamic and reactive transport than on advances in chemistry alone.

Future developments are expected to focus on hybrid configurations that incorporate elements of heap leaching, bioleaching, and digital monitoring systems. While such approaches may partially mitigate current limitations, they also introduce increased operational complexity and higher capital and operating costs.

Dump leaching is part of a continuum of increasing engineering control, not a static technology. As systems evolve, they may approach the performance of more engineered leaching methods.

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Ultimately, the viability of dump leaching will depend on its ability to balance recovery, cost, operational duration, and environmental performance within a life-cycle framework. Rather than transitioning entirely into fully engineered systems, its long-term role is likely to remain tied to specific niches where low capital intensity, tolerance to heterogeneity, and extended processing times are economically justified.

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Conflicts of Interest / Competing Interests

The author declares that there are no conflicts of interest related to this work.

Availability of Data and Materials

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

Authors' Contributions

Antonio Clareti Pereira: Conceptualization, methodology, investigation, data curation, formal analysis, writing—original draft, writing—review and editing.

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