

Vat Leaching and Box Leaching in Hydrometallurgy: Process Principles, Industrial Applications, and Future Perspectives

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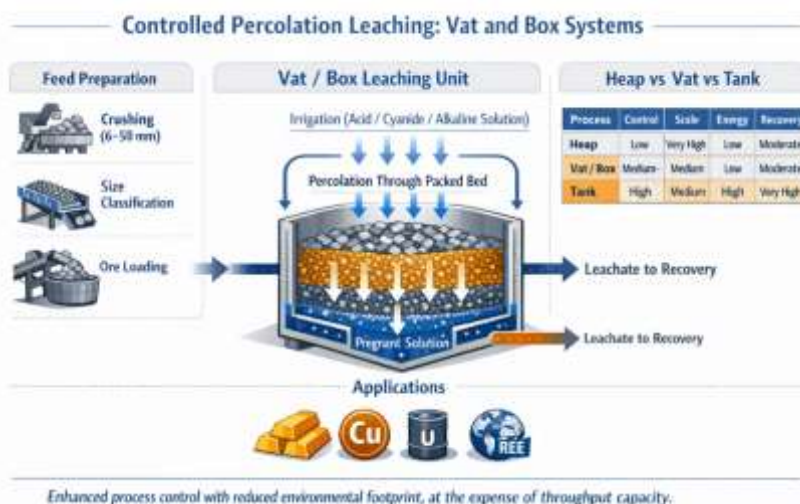
ABSTRACT: Vat leaching and box leaching are proven percolation-based hydrometallurgical methods that provide a controlled alternative to traditional heap and tank leaching. Unlike heap leaching, which works under large-scale, low-control conditions, and tank leaching, which involves fine grinding and intensive agitation, vat and box leaching systems process crushed ores in confined reactors. This allows for better distribution of solutions, faster recovery rates, and a smaller environmental impact. These methods are widely used to extract gold, copper, uranium, and, more recently, rare earth elements from both primary ores and secondary resources. Their main benefits include greater control over leaching parameters (such as residence time, irrigation rate, and solution chemistry), reduced reagent losses, and improved handling of effluents and emissions. However, limitations such as low throughput, the need for prior crushing and sizing, potential channeling effects, and higher capital costs per unit capacity hinder wider adoption. This review explores the fundamental principles of fluid flow, mass transfer, and reaction kinetics in vat and box leaching systems, assesses their industrial use across different commodities, and discusses recent technological developments, including modular setups, hybrid flowsheets, and digital process monitoring. It also highlights key knowledge gaps related to scale-up, modeling multiphase flow in packed beds, and integrating sustainable resource recovery strategies, providing a guide for future research and industry implementation.

KEYWORDS. Vat leaching; Box leaching; Hydrometallurgy; Percolation leaching; Rare earth processing; Gold extraction

Highlights.

- Vat and box leaching provide a controlled alternative to heap and tank leaching systems.
- Enhanced process control leads to improved recovery efficiency and reduced environmental impact.
- Widely applied in gold, copper, uranium, and emerging rare earth processing routes.
- Limitations include lower throughput capacity and the requirement for pre-crushing and size control.
- Future developments focus on hybrid flowsheets, modular systems, and advanced process monitoring.

Graphical abstract





1. INTRODUCTION

Vat leaching, one of the oldest hydrometallurgical methods, dates back to the nineteenth century for copper extraction and later for gold cyanide leaching in fixed beds and vats (Binnemans & Jones, 2025; Fedotov et al., 2022; Petersen & van Staden, 2025; Warhurst, 2024). The process involves placing crushed ore in a tank, letting a lixiviant percolate through under gravity. Its simplicity made it preferable before the advent of heap leaching and controlled tank circuits, representing a practical balance between metallurgical control and capital simplicity (Petersen & van Staden, 2025; Surimbayev et al., 2025).

From a process engineering view, vat leaching is between heap and tank leaching. Heap leaching suits larger ore volumes, coarser feeds, and weeks-to-months residence times. Tank leaching involves finely ground materials ($<75\ \mu\text{m}$), intense mixing, and precise chemical control. Vat leaching uses granular feed (3–12 mm) and bed heights of 2–6 m, depending on ore type and vessel design (Eftekhari et al., 2023; Nagar, 2021; Petersen & van Staden, 2025). This middle ground explains why it was partly replaced by heap leaching for large throughputs but remains useful where hydraulic control, shorter percolation paths, and smaller footprint are preferred (Adilov et al., 2025; Jia et al., 2024; León et al., 2025; Li et al., 2022).

Vat leaching remains relevant due to ore characteristics. It suits granular, permeable feeds with limited fines, allowing better solution flow control, less channeling, and predictable residence times. However, strict feed prep is crucial, with particle size control, permeability, and sometimes agglomeration necessary, as fines can hinder conductivity and percolation. This explains its use mainly in small to medium operations, high-grade ores, tailings reprocessing, or feeds where hydraulic control outweighs scale.

Within modern hydrometallurgy, vat leaching is not obsolete but part of a broader family of percolation-based systems, including heap, dump, in situ, and bioleaching variants (Jia et al., 2024; Kaksonen, 2025; Petersen & van Staden, 2025). These technologies support treating gold, copper, nickel, uranium, rare earths, antimony, slags, tailings, and waste feeds (Faris et al., 2023; Ling et al., 2024; Mamyrbayeva et al., 2025; Xing et al., 2020). The field now features multiple routes tailored to ore grade, mineralogy, permeability, reagent needs, environmental constraints, and project scale, reflecting technological differentiation rather than replacement.

Recent studies expand this discussion's relevance, showing that percolation leaching depends on factors beyond chemistry, such as hydrodynamics, capillary action, dual-phase flow, pore evolution, and reactive transport (Odidi et al., 2023; Robertson et al., 2022; Robertson & Petersen, 2024; Wang et al., 2020; Zheng, 2026). Concurrently, increased sustainability pressures drive interest in circular hydrometallurgy, lower-energy methods, residue valorization, and greener lixivants (Binnemans & Jones, 2023; Rötzer & Schmidt, 2020; Yu et al., 2024). This is especially relevant for vat and box leaching, which often operate in niches where process control, modularity, and smaller area needs outweigh their lower scale compared to heaps.

This review examines vat and box leaching from classical and modern viewpoints. It covers basic principles, equipment, hydrodynamics, mineral processing, and key chemistries. Comparisons are made with heap and tank leaching, highlighting industrial uses in gold, copper, uranium, and rare earths, along with operational benefits and drawbacks. The review also explores environmental issues, sustainability, and new trends like modular units, hybrid systems, digital control, and biological methods (Binnemans & Jones, 2023; Pereira, 2026; Yu et al., 2024). The following part details the methodology for literature selection and organization.

2. METHODOLOGY

This review was structured according to the PRISMA 2020 framework for literature identification, screening, eligibility assessment, and inclusion, ensuring transparency and reproducibility in source selection (Page et al., 2021). The methodology followed a systematic approach adapted to engineering review studies, combining structured database searches with targeted inclusion of highly relevant technical sources.

The literature search used major databases—Scopus, Web of Science, ScienceDirect, SpringerLink—and Google Scholar for broader coverage. Keywords included “vat leaching”, “box leaching”, “heap leaching”, “percolation leaching”, “hydrometallurgy”, and “ore leaching kinetics”. Focus was mainly on publications from 2020 to 2026, but earlier seminal works were included when needed for context.

The selection involved four stages: identification, screening, eligibility, and inclusion. After removing duplicates, titles and abstracts were screened to exclude unrelated topics like non-hydrometallurgical processes or environmental leaching tests. Full-text assessment verified relevance to vat and percolation leaching, with a focus on hydrodynamics, process design, chemistry, and industrial applications.

A total of 105 references included peer-reviewed articles, books, conference proceedings, theses, and relevant grey literature on vat, box, heap, or percolation leaching. Grey literature was used selectively for emerging tech, pilot studies, and industrial insights not in indexed journals.

The PRISMA flow diagram in Figure 1 shows records identified, screened, excluded, and included at each stage, illustrating how search results were narrowed to 105 references, ensuring transparency and rigor.

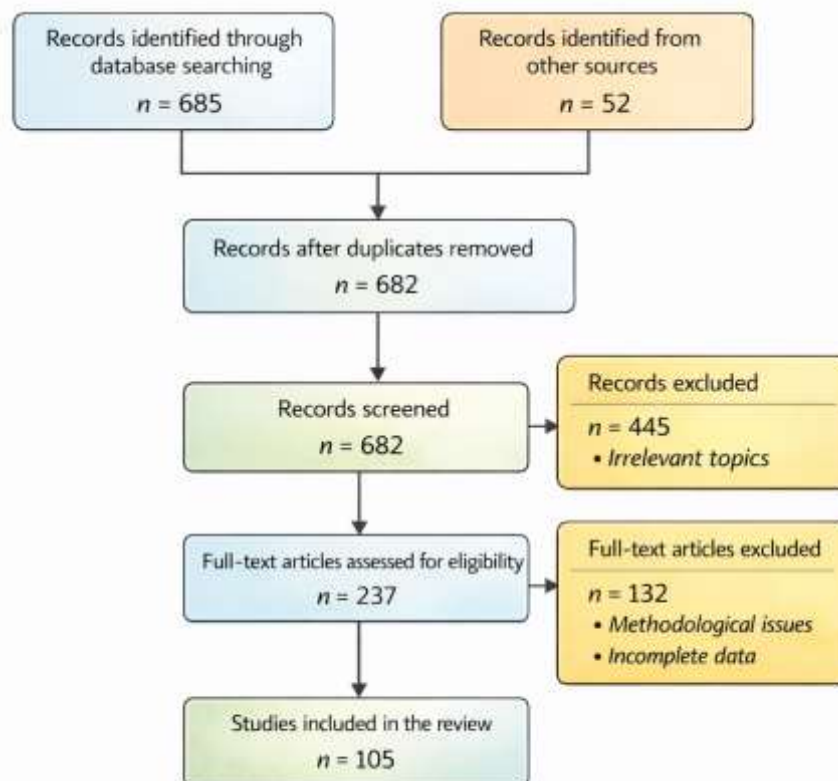


Figure 1. PRISMA 2020 flow diagram of the literature selection process used in this review (adapted from Page et al., 2021).

This methodology ensured balanced coverage of principles, studies, modeling, and industrial applications of vat leaching and percolation systems. The structured selection minimized bias and enhanced reproducibility. The following section explains the core concepts and principles of vat leaching systems.

3. PRINCIPLES OF VAT LEACHING

3.1. Basic process concept

In vat leaching, crushed ore is placed in a fixed bed inside a tank or box-like unit. A lixiviant is applied at the top and flows downward through the porous bed under gravity. The resulting pregnant leach solution (PLS) is collected at the bottom for further processing (Petersen & van Staden, 2025; Warhurst, 2024; Wankat, 2022; Anukiruthika et al., 2024; Eftekhari et al., 2023; Zheng, 2026).

The process involves four steps: (i) ore loading, (ii) irrigation with lixiviant, (iii) percolation, and (iv) PLS collection. Each step depends on the others; poor loading causes segregation and uneven flow, while inadequate irrigation reduces contact time and efficiency.

Typical residence times range from 12 to 72 hours, depending on ore type, reagent system, and bed height. Solution flow rates usually range from 0.5 to 5 m³/t, balancing contact and hydraulic stability (Nagar, 2021; Petersen & van Staden, 2025). Vats have shorter flow paths than heap leaching, enabling faster solution turnover and better control.

Vat leaching is a controlled process in which crushed ore is treated in confined reactors, enabling better control of flow, residence time, and reaction conditions than heap leaching. Unlike large heaps, vat systems are more compact with engineered drainage, improving mass transfer and reducing solution losses. Figure 2 shows the vat leaching unit and operation.

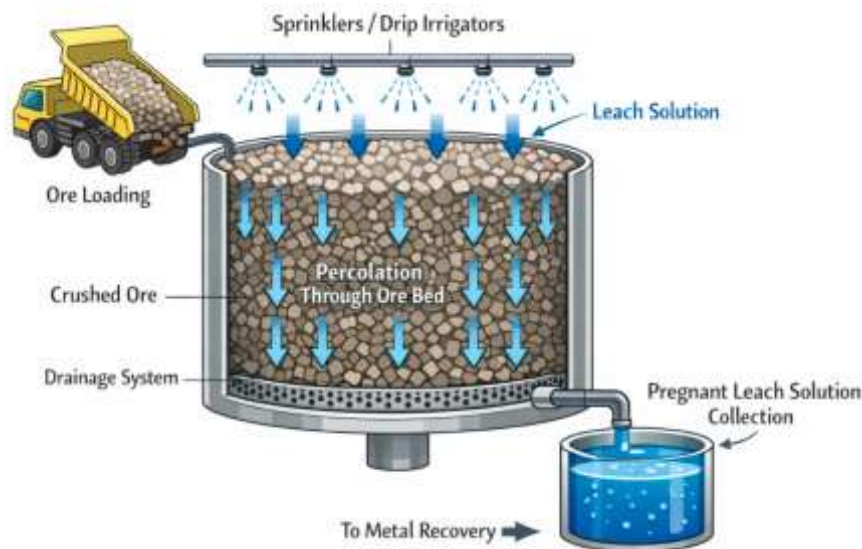


Figure 2. Schematic representation of the vat leaching process, showing ore loading, solution irrigation, percolation through the bed, and collection of pregnant leach solution (adapted from Petersen & van Staden, 2025).

As shown in Figure 2, the process starts with crushed, size-classified ore loading into a reactor vessel with a drainage system at its base. The leaching solution—acidic, alkaline, or cyanide-based depending on the target metal—is evenly distributed via sprinklers or drip irrigation. It percolates downward through the packed bed by gravity, dissolving metals through diffusion and surface reactions. The pregnant leach solution (PLS) is collected at the bottom and sent to recovery processes like solvent extraction, ion exchange, or precipitation.

The schematic highlights the need for uniform solution distribution to prevent channeling and ensure effective contact between the lixiviant and ore. Vertical flow and confined geometry improve hydrodynamics and mass transfer over heap leaching, without the high energy use of tank systems. However, vat leaching performance depends on ore permeability, particle size, and bed compaction, affecting flow uniformity and efficiency.

The schematic highlights the vertical flow regime and the importance of uniform solution distribution across the bed surface. It also illustrates the relatively compact geometry of vat systems compared to large-scale heap leaching operations.

3.2. Equipment configuration

Vat leaching equipment has evolved from simple wooden vessels to more durable concrete or steel systems, replacing early timber designs due to better resistance to chemicals (Warhurst, 2024; Petersen & van Staden, 2025).

Concrete vats are typically permanent and have large capacities. Steel vats are adaptable and quick to install, but may require corrosion protection depending on the lixiviant. Wooden vats are mostly historical, but are important for understanding early processes.

Recent developments include modular box leaching units, easier to transport and scale, ideal for pilot plants and small-to-medium operations (Fedotov et al., 2022; Wei et al., 2023; Pereira, 2026).

Vat leaching systems vary by scale, ore, and economic factors, evolving from wooden setups to modern modular systems thanks to advances in materials and process control. Key types are summarized in Table 1.



Table 1. Main types of vat leaching units and their characteristics (adapted from Warhurst, 2024; Petersen & van Staden, 2025).

Type	Description	Typical Applications	Advantages	Limitations	
Concrete vats	Permanent, large-scale structures reinforced concrete	large-scale civil in	Gold, copper, uranium	High durability; large capacity; long service life	High capital cost; low flexibility; fixed location
Steel vats	Engineered metallic tanks, often modular and prefabricated		Gold, copper, industrial minerals	Modular design; faster installation; scalable	Corrosion risk; higher maintenance requirements
Wooden vats	Traditional structures used in hydrometallurgical operations	timber-based used in early	Historical gold and silver processing	Low initial cost; simple construction	Limited durability; obsolete in modern operations
Box leaching units	Small, transportable containers or modules for batch leaching		Small-scale mining; pilot plants; REE	High flexibility; mobility; low CAPEX	Limited capacity; lower throughput

As shown in Table 1, the choice of vat leaching units is strongly influenced by the trade-off between operational flexibility and processing capacity. Concrete vats are common in large-scale industrial operations for their durability and long lifespan, while steel vats offer a balance between scalability and quick installation. Meanwhile, box leaching units have attracted increasing interest recently, especially for decentralized operations, pilot testing, and processing specialized materials such as rare earth elements and secondary resources. Despite their benefits in mobility and lower capital costs, these systems are naturally limited by lower throughput, making them more of a supplementary option rather than a primary processing method in most industrial settings.

Equipment choice depends on scale, ore, reagents, and costs. Modular systems are popular for staged and flexible operation.

3.3. Hydrodynamics of percolation

Hydrodynamics is a critical factor in vat leaching performance. The process is governed by gravity-driven flow through a porous medium, where permeability, pore structure, and fluid properties determine solution distribution and residence time (Robertson et al., 2022; Robertson & Petersen, 2024; Wang et al., 2020; Wang et al., 2022; Odidi et al., 2023; Zheng, 2026).

- a. Key parameters include:
- b. bed permeability
- c. particle size distribution
- d. solution viscosity
- e. irrigation uniformity

Small parameter variations can cause channeling, reducing lixiviant-ore contact. This is crucial in beds with fines or clay minerals, where permeability can decline quickly during operation.

Capillary forces and unsaturated flow influence liquid distribution. Studies show moisture retention, hysteresis, and pore connectivity affect solute transport and reaction rates (Odidi et al., 2023; Wang et al., 2022).

These effects are amplified in clay-rich, ion-adsorption ores like rare earth deposits, where seepage, pore evolution, and adsorption-desorption interactions lead to complex, non-linear, and time-dependent flow behaviors (Guo et al., 2023a, 2023b; Zhou et al., 2021; Ju et al., 2022; Huang et al., 2026; Jiang et al., 2024; Karimova & Kairalapov, 2022).

A key challenge in vat and percolation leaching systems is controlling fluid flow through heterogeneous packed beds. Variations in particle size, porosity, and compaction lead to non-uniform permeability, affecting solution distribution and mass transfer. Hydrodynamic instabilities lead to preferential flow paths, or channeling, which reduces metal recovery. Figure 3 illustrates the relationship between flow distribution and channeling in packed beds.

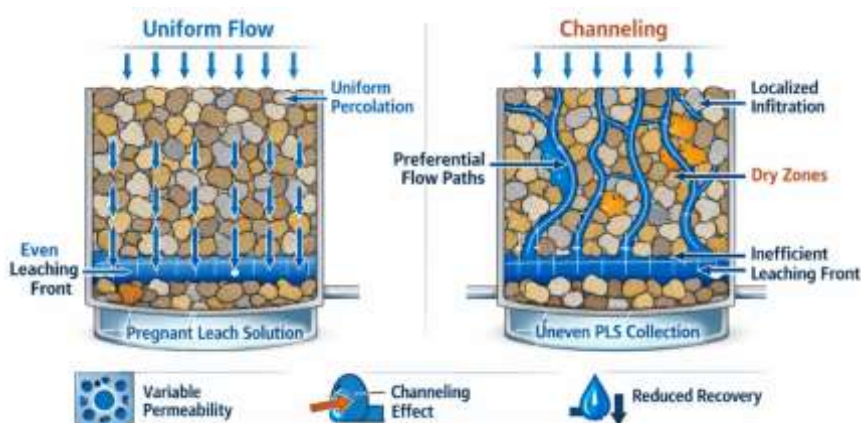


Figure 3. Conceptual representation of flow distribution and preferential channeling in packed beds during percolation leaching (adapted from: Robertson et al., 2022; Wang et al., 2022).

As shown in Figure 3, ideal percolation leaching occurs under uniform flow, with the solution passing evenly through the bed, ensuring consistent contact with ore particles. This causes the leaching front to move uniformly, maximizing metal recovery.

In practical systems, permeability heterogeneities often cause preferential flow channels, allowing the solution to bypass much of the ore bed. This creates 'dry zones' with little or no leaching, reducing efficiency and resulting in lower metal concentrations in the pregnant leach solution (PLS).

The figure shows that channeling mainly results from spatial variations in porosity and permeability, caused by poor prep, segregation, or bed compaction. Managing these requires optimizing particle size, agglomeration, irrigation, and loading techniques. Hydrodynamic control is crucial for stable, predictable vat leaching.

The following section compares vat leaching with other leaching technologies, highlighting key differences in scale, control, and operational requirements.

4. COMPARISON WITH OTHER LEACHING TECHNOLOGIES

Vat leaching relates to heap and tank leaching, the two main hydrometallurgical methods. They differ mainly in scale, control, particle size, and capital needs.

Vat leaching processes smaller ore volumes than heap leaching but provides better hydraulic control and shorter residence times. Heap leaching processes 10^4 – 10^6 t per campaign, with residence times ranging from weeks to months, depending on ore type and permeability. In contrast, vat leaching processes 10^2 – 10^4 t batches with residence times of 12–72 hours, due to shorter flow paths and more controlled irrigation (Eftekhari et al., 2023; León et al., 2025; Petersen & van Staden, 2025).

Tank leaching requires fine grinding below $75\ \mu\text{m}$, ensuring full suspension, high mass transfer, and tight control of temperature, pH, and reagent levels. This control results in higher capital and operating costs—2–5 times higher than heap or vat systems for similar throughput—and is influenced by ore and process complexity (Eftekhari et al., 2023; Manzila et al., 2022; Petersen & van Staden, 2025).

Vat leaching occupies an intermediate position. It does not require ultra-fine grinding but does require a controlled particle size (3–12 mm) and stable permeability. Its moderate cost and compact design make it suitable when heap leaching isn't feasible due to space constraints, environmental limits, or hydraulic control requirements (Heydarov et al., 2021; Petersen & van Staden, 2025).

Hydrometallurgical leaching methods include heap, vat, and tank systems, each balancing control, scale, and costs. Choosing the right method depends on ore properties, recovery needs, costs, and environmental factors. Table 2 compares these technologies.



Table 2. Comparison of heap, vat, and tank leaching processes in terms of operational characteristics (adapted from Petersen & van Staden, 2025; Eftekhari et al., 2023).

Process	Typical Characteristics	Particle Size	Process Control	Residence Time	CAPEX/OP EX	Recovery Efficiency	Typical Applications
Heap leaching	Large volumes; open-air operation; irrigation over heaps	Coarse (10–100 mm)	Low	Long (weeks–months)	Low CAPEX / Low OPEX	Moderate	Gold, copper oxides, uranium
Vat leaching	Confined reactors; percolation through packed beds	Medium (5–50 mm)	Medium–High	Moderate (hours–days)	Moderate	High (if well controlled)	Gold, copper, uranium, REE
Tank leaching	Agitated reactors; slurry-based processing	Fine (<0.1 mm)	High	Short (hours)	High CAPEX / High OPEX	Very high	

As shown in Table 2, each leaching technology occupies a distinct operational niche. Heap leaching involves a trade-off between process control, throughput, and cost. Its simplicity and low capital needs suit low-grade ores and large-scale use, but limited control over hydrodynamics and reaction conditions lead to longer residence times and inconsistent recovery.

Tank leaching offers high control through intensive mixing and fine particles, enabling rapid kinetics and high recovery. However, it requires significant energy, extensive comminution, and higher costs, limiting its use to higher-value ores or concentrates.

Vat leaching is an intermediate method combining features of heap and tank leaching. It provides better flow and chemistry control without the high energy use and grinding associated with tank leaching, making it ideal for medium-scale, controlled conditions and rare earth recovery. Its limits include low throughput and sensitivity to ore permeability and particle size.

Selecting an appropriate leaching technology involves balancing process control, throughput, energy, and costs. Heap, vat, and tank leaching are different regimes in this decision space. Heap leaching suits large-scale, low-cost operations; tank leaching is for high-efficiency processing of fine materials; vat leaching offers a middle ground in terms of control and capital costs. This can be visualized in a process selection framework, as shown in Figure 4.

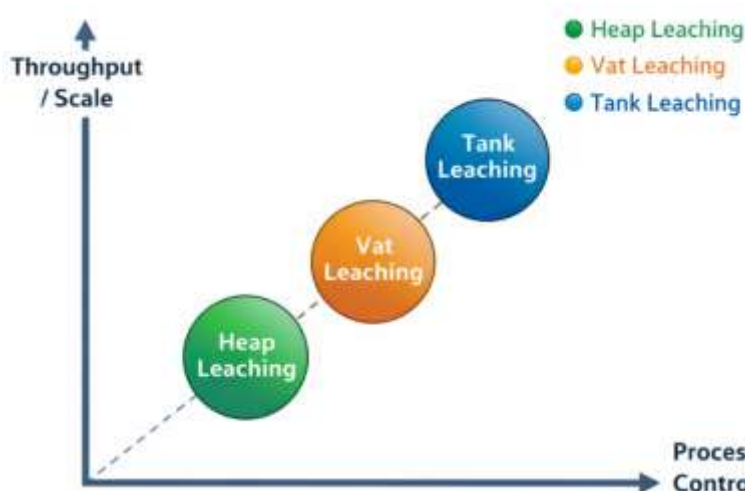


Figure 4. Conceptual process selection map for leaching technologies, illustrating the relative positioning of heap, vat, and tank leaching systems. Adapted from Brierley, J., et al. (2015), and Petersen, J., & van Staden, P. (2025).

Figure 4 shows leaching technologies along two axes: process control and throughput. Heap leaching is low control, high throughput, ideal for large volumes of low-grade ores but with limited regulation of hydrodynamics and reactions. Tank leaching in



the high-control region uses agitation, fine particles, and controlled environments to achieve fast kinetics and high recovery, but at a higher cost.

Vat leaching balances control and scale, with confined geometry improving solution regulation over heap leaching and avoiding the energy and comminution needs of tank leaching. This makes it ideal for medium-scale operations, ores needing precise conditions, and environmentally sensitive applications.

The figure shows that process selection is continuous, with overlaps and hybrids. Integrated flowsheets often combine leaching methods, such as vat leaching before tank leaching or as an alternative to heap leaching in sensitive areas.

The comparison shows no single best technology; choice depends on ore grade, mineralogy, permeability, water, and economics. Heap leaching is ideal for low-grade ores due to low costs (<USD 3/t), while tank leaching suits high-value ores for better recovery. Vat leaching offers a middle ground between cost and control.

In bioleaching, heap systems dominate large-scale operations for treating low-grade ores over long periods. Fixed-bed and vat systems are still used for process intensification, pilot testing, and controlled environments where managing residence time and solution chemistry is crucial (Jia et al., 2024; Kaksonen, 2025; Li et al., 2022).

Vat leaching's main limitation is lower scalability than heap systems, and it lacks the mixing needed for fast reactions in refractory ores. These trade-offs mean it's mainly used in niche applications rather than large-scale production. The next section covers mineral processing requirements that determine its viability.

5. MINERAL PROCESSING REQUIREMENTS

The performance of vat leaching depends strongly on upstream mineral processing. Unlike tank leaching, where mixing compensates for heterogeneity, or heap leaching, where scale dominates, vat systems require a controlled balance between particle size, permeability, and structural stability. Inadequate feed preparation often leads to channeling, reduced recovery, or unstable flow conditions.

5.1. Particle size

Particle size is crucial in vat leaching, as it balances mineral liberation and bed permeability. It falls between coarse heap and fine tank leaching (Petersen & van Staden, 2025; Eftekhari et al., 2023; Zheng, 2026; Sekisov & Rasskazova, 2021).

- a. Typical size ranges are:
- b. Heap leaching: 6–25 mm
- c. Vat leaching: 3–12 mm
- d. Tank leaching: <75 μm

These ranges show different transport mechanisms. Coarser particles boost permeability but lower surface area. Finer particles raise reaction rates but can block pores and impair drainage. In vat leaching, just small increases in fines (<1 mm above ~10–15%) can reduce hydraulic conductivity and slow percolation.

Particle size critically influences hydrometallurgical leaching performance by affecting permeability, mass transfer, and reaction kinetics. Different leaching methods operate within specific particle size ranges, balancing diffusion and flow constraints. Table 3 compares these ranges.

Table 3. Typical particle size ranges for different leaching technologies (adapted from Petersen & van Staden, 2025; Eftekhari et al., 2023).

Process	Particle Size Range	Permeability	Kinetics	Comminution Requirement	Operational Implication
Heap leaching	6–25 mm	High	Slow (diffusion-limited)	Low	Suitable for large-scale, low-grade ores
Vat leaching	3–12 mm	Moderate–High	Moderate	Moderate	Balanced performance between flow and kinetics
Tank leaching	<75 μm	Not applicable (slurry)	Fast (reaction-controlled)	High	High recovery; requires fine grinding and agitation



As shown in Table 3, particle size distribution differentiates leaching technologies and their regimes. Heap leaching uses coarse particles for permeability and solution flow in large heaps but results in slower kinetics due to longer diffusion paths and limited reactive surface area.

Tank leaching uses finely ground particles, typically smaller than 75 μm , to enable rapid reactions under well-mixed conditions. However, it requires intensive grinding and higher energy, raising costs.

Vat leaching uses particle sizes of 3–12 mm, balancing permeability and reactive surface area. This improves kinetics over heap leaching but requires stricter crushing to prevent segregation, compaction, and channeling, which can hinder flow and efficiency.

5.2. Ore permeability

Permeability ensures uniform percolation, thereby controlling solution flow, residence time, and contact between the lixiviant and the ore. In vat leaching, it must stay stable throughout, not just at the start.

- a. Several factors can reduce permeability:
- b. presence of fines and clays
- c. particle segregation during loading
- d. pore collapse under wetting conditions
- e. non-uniform irrigation
- f. precipitation or secondary mineral formation

These effects may create preferential flow paths that bypass much of the ore bed, reducing recovery (Toro et al., 2021; Wang et al., 2020; Robertson et al., 2022; Wang et al., 2022; Odidi et al., 2023).

Experimental and modeling studies reveal that permeability can decrease tenfold or more during leaching, especially in clay-rich systems. In rare-earth and ion-adsorption ores, mechanisms such as adsorption–desorption and pore evolution further complicate flow behavior (Guo et al., 2023a; Wang et al., 2023; Zhou et al., 2021).

Maintaining permeability is a key design goal, as it affects recovery, leaching time, and operational stability.

5.3. Pretreatment

To ensure permeability and flow, ore preparation is needed before vat leaching, including these main steps:

- a. crushing
- b. screening (classification)
- c. agglomeration (when needed)

Crushing reduces particle size to target range, while screening removes fines. Agglomeration is key for ores with high clay or fine content, improving bed stability and lixiviant distribution (Chitera et al., 2022; Guzman et al., 2024; Toro et al., 2021).

Agglomeration increases permeability 2–10 times, depending on ore, and reduces channeling. It also enhances mechanical strength, preventing bed collapse during irrigation (Fedotov et al., 2021a; Nwaila et al., 2020; Karimova et al., 2024; Rasskazova et al., 2020).

Particle size distribution and bed structure are crucial for flow and leaching in percolation systems. Fine particles can cause pore blockage, lower permeability, and create preferential flow paths. Agglomeration is a common pre-treatment to improve bed stability and hydraulic performance, affecting permeability and flow, as shown in Figure 5.

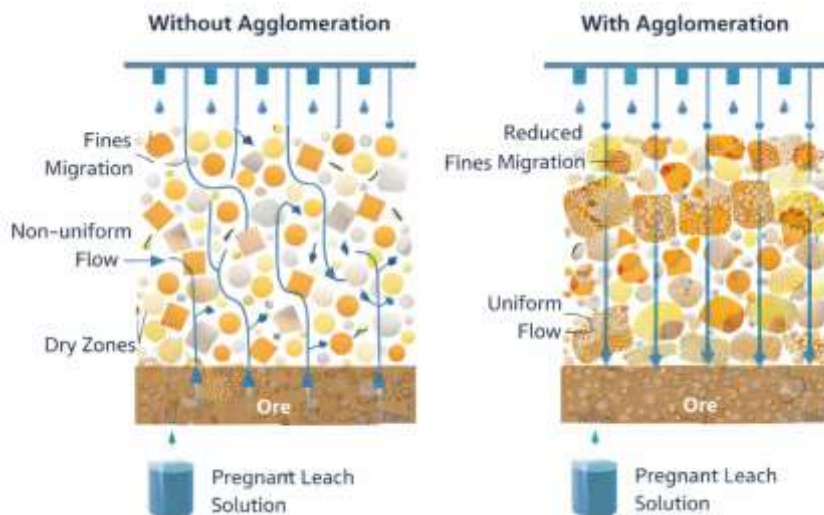


Figure 5. Conceptual effect of agglomeration on bed structure, permeability, and solution flow distribution in percolation leaching systems (adapted from: Guzman et al., 2024; Toro et al., 2021).

Figure 5 shows that non-agglomerated ore beds have heterogeneous particle packing, with fine particles migrating into pore spaces. This causes localized reductions in permeability, leading to uneven flow and preferential channels. As a result, parts of the ore bed stay poorly irrigated, creating dry zones and lowering leaching efficiency.

In contrast, agglomeration binds fine particles to coarser fractions, forming more stable This improves pore connectivity and maintains consistent permeability, ensuring uniform leaching solution distribution. This enhances contact with ore particles and boosts metal recovery.

The figure shows that agglomeration is not merely a mechanical change but also a key process parameter that affects hydrodynamics, mass transfer, and stability. Its effectiveness depends on binder type, moisture content, curing time, and particle size, all of which must be optimized for consistent vat leaching performance.

From a critical standpoint, mineral processing requirements represent one of the main limitations of vat leaching, including greater sensitivity to feed variability despite better control than heap leaching. Careful preparation and ore characterization are essential for success.

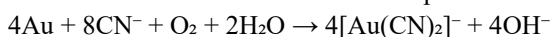
6. LEACHING CHEMISTRY

Leaching chemistry determines efficiency, selectivity, and cost-effectiveness of vat leaching. In fixed-bed systems, reactions are linked with mass transfer and flow. Rates depend on reagent type, permeability, solution distribution, and residence time. The main chemical systems are cyanide leaching, acid leaching, and other lixivants.

6.1. Cyanide leaching (gold)

Cyanidation is the most established method for vat leaching of gold, used in small- to medium-scale operations, tailings reprocessing, and artisanal mining (Manzila et al., 2022; Fedotov et al., 2021b, 2022; Shumilova et al., 2023; Surimbayev et al., 2025).

The overall reaction can be expressed as:



Gold dissolves at pH 10–11 with 0.01–0.1% NaCN, and oxygen impacts the reaction rate. Under ideal conditions, recoveries can exceed 85–95% for suitable ores, but cyanide use varies with mineralogy. Copper, sulfides, or organics increase reagent consumption and reduce selectivity. Adsorption and pre-robbing complicate performance, emphasizing the importance of geometallurgical characterization and ore-blending strategies (Nwaila et al., 2020).

The dissolution of gold in cyanide solutions is key in hydrometallurgy, especially in vat and heap leaching, where mass transfer and electrochemical processes are linked. Unlike tank leaching, which uses agitation to improve reactant transport, vat

leaching depends on diffusion and percolation. Oxygen and solution distribution are crucial for reaction rate. Figure 6 illustrates the gold cyanidation mechanism and its relation to mass transfer.



Figure 6. Simplified mechanism of gold dissolution in cyanide solutions, including oxygen reduction and complex formation (adapted from: Manzila et al., 2022; Fedotov et al., 2022).

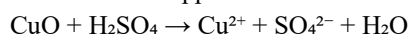
As shown in Figure 6, gold dissolves in cyanide media through an electrochemical process involving anodic oxidation of gold and cathodic reduction of oxygen. At the surface, oxidation forms soluble $\text{Au}(\text{CN})_2^-$ in the presence of cyanide ions. Oxygen acts as the main oxidant, getting reduced in the water, supporting the reaction.

The process efficiency relies on transporting cyanide ions and dissolved oxygen to the reaction interface. In vat leaching systems with limited mixing, mass transfer is the key rate-limiting step. Oxygen diffusion is often inadequate under static or poor aeration, causing slower reactions and incomplete gold dissolution.

The schematic shows hydrodynamic conditions, besides chemical kinetics, are crucial for cyanidation. Non-uniform flow, channeling, and poor oxygen transport can reduce efficiency. Optimizing solution flow, aeration, and bed permeability is key to improving gold recovery.

6.2. Acid leaching (copper and other metals)

Sulfuric acid leaching primarily processes copper oxide ores and is used for uranium, nickel laterites, and other metals. The reaction with copper oxide is summarized as:



Acid consumption ranges from 5 to 50 kg $\text{H}_2\text{SO}_4/\text{t}$ ore, depending on gangue and buffering capacity. Leaching efficiency depends on acid concentration, temperature, and diffusion limits within the porous bed (Sekisov & Rasskazova, 2021; Mokmeli, 2020; Gavrilov et al., 2022, 2024).

In vat systems, transport limits often matter more than kinetics. Poor permeability reduces contact between acid and the mineral, leading to incomplete extraction. Copper recovery in percolation systems ranges from 60% to 85%, depending on ore and conditions.

Acid leaching is increasingly used for secondary resources such as tailings and residues. Impurity control is challenging because elements such as iron, aluminum, and manganese dissolve together, affecting downstream processing (Bulaev & Melamud, 2020; Koizhanova et al., 2023; Abdulsattar et al., 2025).

6.3. Chloride systems and alternative lixivants

Beyond cyanide and sulfuric acid, alternative lixivants like chloride systems, glycine solutions, ozone leaching, organic acids, and deep eutectic solvents are being developed to enhance selectivity and reduce environmental impact (Abashina et al., 2022; Eksteen et al., 2020; Krylova, 2022; Khalafalla, 2022; Yamini et al., 2025).



Chloride systems are important for some base and precious metals, enabling faster reactions but requiring corrosion-resistant materials and careful chemical control (Rasskazov et al., 2022). Glycine leaching under alkaline conditions can selectively dissolve copper and gold with lower environmental risk than cyanide leaching.

Organic acids and bio-based lixivants are also gaining attention. These systems may operate at lower toxicity levels, but often require longer residence times or specific conditions to achieve comparable recoveries.

Rare-earth and strategic-metal processing rely more on selective leaching and solvent extraction. Managing pH, ionic strength, and complexation is crucial for effective separation (Laatikainen et al., 2021; Faris et al., 2023).

The choice of lixiviant in vat leaching critically affects metal recovery, selectivity, environmental impact, and costs. Different lixivants exhibit distinct chemical behavior, reaction kinetics, and ore compatibility, making selection context-dependent. Recent environmental and regulatory pressures have spurred the development of less toxic, more sustainable alternatives. Table 4 provides a comparative overview of the main lixivants used.

Table 4. Main lixivants used in vat leaching and their typical characteristics (adapted from Eksteen et al., 2020; Yamini et al., 2025).

Lixiviant	Main Application	Key Features	Advantages	Limitations	Environmental Aspects
Cyanide	Gold	Strong complexation with Au; well-established process	High selectivity; high recovery	Toxicity; strict regulations	High environmental concern; requires detox
Sulfuric acid	Cu, U, Ni	Acid dissolution of oxides and sulfates	Low cost; widely available	High consumption; acid handling issues	Acid effluents; potential environmental impact
Chloride systems	Cu, REEs, Au	Oxidative leaching; high solubility of metal chlorides	Fast kinetics; effective for refractory materials	Corrosion; reagent management complexity	Corrosive media; chloride discharge concerns
Glycine	Cu, Au	Amino acid-based complexation	Lower toxicity; selective under controlled pH	Slower kinetics; requires process optimization	Environmentally benign; recyclable
Organic acids	REEs, secondary ores	Weak organic acids (e.g., citric, oxalic)	Green alternatives; low toxicity	Slow kinetics; limited industrial scale	Low environmental impact; biodegradable

As shown in Table 4, selecting lixivants in vat leaching involves trade-offs between chemical performance, cost, environmental impact, and operational feasibility. Cyanide remains the main lixiviant for gold due to its high selectivity and established use, despite rising regulatory pressure over toxicity.

Sulfuric acid is widely used for base metals such as copper, uranium, and nickel due to its low cost and ability to dissolve oxide and sulfate minerals. However, its high use and environmental issues, especially with effluent management, can limit its application.

Chloride-based systems are noted for their rapid kinetics and for treating refractory ores such as gold and rare earth deposits. However, corrosion and reagent recycling issues hinder wider use.

Recently, alternative lixivants like glycine and organic acids have gained attention for sustainable processing. They reduce toxicity and are more environmentally friendly but often have slower kinetics and require further optimization.



No single lixiviant is universally optimal; selection depends on ore mineralogy, regulations, and processing needs, emphasizing integrated design and techno-economic evaluation.

Leaching chemistry in vat systems can't be evaluated independently of hydrodynamics and mineral processing. Transport limits reaction efficiency more than intrinsic kinetics, explaining why lab results may not always reflect industrial performance.

7. INDUSTRIAL APPLICATIONS

Vat leaching remains relevant for certain commodities despite the dominance of heap and tank leaching in large-scale operations. It is used for moderate throughput, controlled hydraulic conditions, and ores needing intermediate processing between coarse heaps and fine slurries. Its applications are niche, prioritizing selectivity, footprint, or process control over scale.

7.1. Gold extraction

Gold is one of the most traditional applications of vat leaching. The process is widely used in small- to medium-scale operations, as well as in tailings reprocessing and artisanal mining contexts (Manzila et al., 2022; Fedotov et al., 2021b, 2022; Chitera et al., 2022; Shumilova et al., 2023; Surimbayev et al., 2025).

Typical vat leaching operations for gold employ:

- particle sizes of 3–10 mm
- cyanide concentrations of 0.01–0.1%
- residence times of 24–72 h

Under favorable conditions, gold recoveries can surpass 85–95%, especially for free-milling ores. Vat systems are also used to reprocess historical tailings, which may have residual gold grades of 0.5 to 3 g/t.

In ASM, vat leaching poses environmental risks, especially in Tanzania, where tailings reuse and poor cyanide management threaten water pollution and governance (Roman, 2025; Roman & Saria, 2025; Tomassi, 2024; Lameck et al., 2025; Kinyondo & Huggins, 2021).

7.2. Copper processing

For copper, vat and percolation leaching mainly target oxide ores, low-grade materials, and tailings. These systems are sensitive to ore texture, clay content, and permeability (Sekisov & Rasskazova, 2021; Barriga, n.d.; Karimova & Kairalapov, 2022; Karimova et al., 2024; Rasskazova et al., 2020; León et al., 2025).

Typical conditions include:

- acid consumption: 5–50 kg H₂SO₄/t ore
- copper recoveries: 60–85%
- leaching times: 1–5 days

Vat leaching is less common than heap leaching in large copper operations but remains relevant for controlled environments, pilot testing, and feeds with problematic heap permeability.

Copper applications extend beyond primary ores; studies report successful use of percolation systems in:

- printed circuit boards and electronic waste
- chalcopyrite and complex sulfide ores
- metallurgical slags and secondary residues

These applications demonstrate vat systems' flexibility in treating diverse and unconventional feeds (Jorge et al., 2023; Mokmeli, 2020; Mamyrbayeva et al., 2025; Shengo et al., 2020; Adilov et al., 2025; Heydarov et al., 2021; Sun et al., 2025).

7.3. Uranium leaching

Uranium extraction is key for vat and percolation leaching, used where permeability and mineralogy permit controlled acid flow (Nagar, 2021; Ouassel et al., 2025; Zakia et al., 2020; Khalafalla, 2022; Reis & Monteiro, 2020).

Typical parameters include:

- acid consumption: 20–80 kg H₂SO₄/t ore
- recovery: 70–90%
- leaching time: 1–7 days

Uranium systems are sensitive to solution chemistry, with iron, carbonate, and competing ions affecting extraction efficiency.

Research in this field also includes:

- a. column and pilot-scale testing
- b. resin-based adsorption systems
- c. in-situ leaching analogues
- d. groundwater contamination and attenuation studies

These aspects highlight the strong link between process performance and environmental management in uranium operations (Aziman et al., 2024; Wei et al., 2023; Rasskazov et al., 2022; Li et al., 2024).

7.4. Rare earth processing

Rare earth element (REE) extraction involves percolation-based leaching, especially in ion-adsorption deposits where metals are weakly bound to clay minerals. Extraction is mainly driven by ion exchange and fluid flow rather than mineral dissolution (Miironen, 2023; Wang et al., 2020; Guo et al., 2023a, 2023b; Ju et al., 2022; Zhou et al., 2021; Huang et al., 2026).

Typical features include:

- a. low reagent concentration systems (e.g., ammonium salts)
- b. strong dependence on permeability and pore structure
- c. sensitivity to seepage and saturation conditions

Leaching efficiency is mainly governed by adsorption–desorption kinetics and pore evolution, not just chemical reaction rates.

REE applications are expanding into:

- a. mine waste and tailings recovery
- b. coal by-products
- c. drill cuttings and secondary resources
- d. environmentally driven recovery processes

These trends show the increasing demand for critical materials and sustainable extraction methods (Dushyantha et al., 2022; Yang et al., 2022; Rasool et al., 2025; Kamalesh, 2022; Tao et al., 2025; Yamini et al., 2025; Zhao et al., 2022).

Although vat leaching isn't usually linked to large-scale primary production, it is widely used in industries requiring precise process control, selectivity, and environmental compliance. Its flexibility and moderate scale suit niche operations, complex ores, and secondary resource reprocessing. Applications are summarized in Figure 7.



Figure 7. Main industrial applications of vat leaching across commodities, including gold, copper, uranium, and rare earth elements (adapted from Petersen & van Staden, 2025; León et al., 2025).



As shown in Figure 7, vat leaching has been successfully applied in the extraction of gold, copper, uranium, and rare earth elements, each with distinct operational drivers and process requirements. In gold processing, vat leaching is often used for ores where improved control of cyanide consumption and oxygen availability is necessary, particularly in tailings reprocessing or environmentally sensitive regions.

In copper operations, vat leaching is commonly used for oxide ores and certain secondary sulfides, where controlled acid consumption and solution management offer benefits over heap leaching. Likewise, in uranium processing, vat leaching is favored for low-grade ores and deposits that require strict environmental controls, especially in areas with limited water access or regulatory restrictions.

Vat leaching in REE processing is increasingly used, especially for ion-adsorption clays and secondary resources, requiring controlled conditions for selective recovery. It mainly functions in niche or intermediate-scale operations, not in large-scale primary production.

This positioning highlights its advantages—like better process control and less environmental impact—and limitations, such as lower throughput and sensitivity to ore. Consequently, vat leaching is often part of hybrid flowsheets or used in specialized applications where its benefits are clear.

From a critical perspective, vat leaching is a versatile but specialized technology. Its applicability depends on ore characteristics and operational constraints. While it can't compete with heap leaching in scale, it offers control and flexibility advantages that justify its use.

8. OPERATIONAL PARAMETERS

Operational performance in vat leaching is governed by a limited set of variables. These variables interact strongly, and small deviations can impact flow distribution, reaction kinetics, and recovery. Key parameters include leaching time, solution flow rate, bed height, solution composition, temperature, and ore-specific reagent demand (Nagar, 2021; Ouassel et al., 2025; Sekisov & Rasskazova, 2021; Pereira, 2026; Estay & Díaz-Quezada, 2020; Bárzaga-Martell et al., 2025; Gavrilov et al., 2024).

Leaching time usually ranges from 12 to 72 hours. Shorter durations decrease recovery rates. Longer durations might not enhance extraction if transport limitations are the main factor. For many oxide ores, most extraction occurs within the first 24 to 48 hours, after which diffusion becomes the limiting step.

Solution flow rate typically ranges from 0.5 to 5 m³/t. Low flow rates increase residence time but may lead to poor wetting, while high flow rates enhance irrigation but risk channeling and reagent waste. Optimal rates depend on permeability and particle size.

Bed height typically ranges from 2 to 6 meters. Taller beds boost throughput per unit area but also raise pressure drop and the risk of uneven flow. In practice, heights above 5–6 meters often need careful control of particle size and agglomeration to prevent permeability loss.

Temperature is generally ambient, with most vat leaching systems operating between 15 and 35°C. Higher temperatures can improve kinetics but are rarely used due to cost and complexity. Fixed-bed systems have limited thermal control compared to tank leaching.

Solution composition depends on the lixiviant. For acid systems, reagent consumption may range from 5 to 80 kg/t, while cyanide concentrations typically range from 0.01 to 0.1%. These values must be adjusted based on ore mineralogy and impurity content.

The performance of vat leaching systems depends on key parameters controlling fluid flow, mass transfer, and reaction kinetics. These are interdependent and must be adjusted based on ore, permeability, and lixiviant chemistry. Typical ranges are summarized in Table 5.

Table 5. Typical operating ranges for key vat leaching parameters (adapted from Nagar, 2021; Petersen & van Staden, 2025).

Parameter	Typical Range	Unit	Process Role	Operational Implications
Leaching time	12–72	h	Controls extent of metal dissolution	Longer times increase recovery but reduce throughput
Solution flow rate	0.5–5	m ³ /t	Governs percolation rate and mass transfer	High flow improves kinetics but may induce channeling
Temperature	Ambient (20–40)	°C	Influences reaction kinetics and diffusion	Limited control; heating rarely applied due to cost
Bed height	2–6	m	Affects residence time and pressure drop	Higher beds increase capacity but risk flow non-uniformity

As shown in Table 5, vat leaching operates within relatively broad parameter ranges, These values reflect the variability of ore properties and process setups, serving as typical ranges rather than optimal conditions, and should be adjusted for specific operations.

Leaching time affects metal dissolution and is limited by throughput. Longer times improve recovery but reduce productivity and may be uneconomical. Flow rate impacts mass transfer; too high a flow causes channeling and less contact between lixiviant and ore.

Temperature is kept near ambient to reduce costs, resulting in slower reaction kinetics than with tank leaching. This emphasizes optimizing parameters like particle size and permeability.

Bed height is another critical design parameter, influencing both hydraulic behavior and residence time. While taller beds increase processing capacity, they also increase the risk of non-uniform flow distribution and pressure drop, which can negatively impact leaching efficiency.

The table shows that vat leaching depends on hydrodynamic and kinetic factors. Good process design requires selecting suitable parameters and understanding their interactions to ensure system stability and recovery.

Scale-up is challenging; lab tests often miss heterogeneity seen in industrial beds. Larger scales reveal more variations in size, compaction, and moisture. Pilot testing is essential to validate conditions (Pereira, 2026; Robertson et al., 2022; Robertson & Petersen, 2024).

A major challenge in industrial vat leaching is scaling up from lab and pilot tests to full-scale operations. While column tests offer insights into leaching kinetics and reagent use, they don't fully capture the complexity of fluid flow and heterogeneity in large systems. As reactor size increases, deviations from ideal behavior become more significant, impacting hydrodynamics and process performance. The differences between lab and industrial-scale systems are shown in Figure 8.

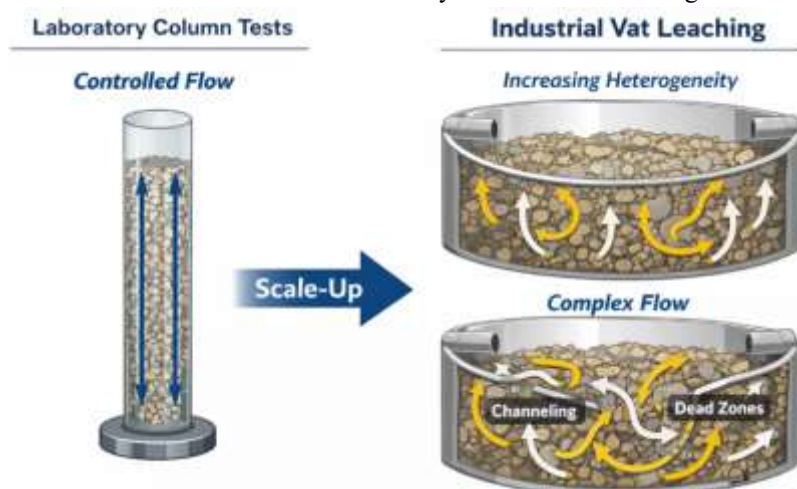


Figure 8. Conceptual scale-up from laboratory columns to industrial vat leaching systems, highlighting the increase in heterogeneity and flow complexity (adapted from Robertson et al., 2022; Pereira, 2026).

Figure 8 shows laboratory column tests generally have uniform flow, clear percolation paths, and consistent lixiviant-ore contact. These controlled settings allow reliable evaluation of mass transfer and reaction rates, aiding in process design.

Scaling the system to industrial vat sizes complicates the flow regime due to heterogeneities in particle packing, permeability, and ore bed structure. These cause preferential flow paths and dead zones, resulting in uneven solution distribution and lower leaching efficiency.

The figure shows scale-up isn't linear but involves new physical phenomena not seen at lab scale. Thus, parameters like flow rate, irrigation, and bed prep need re-optimization at industrial scale to account for these effects. Increased heterogeneity can cause higher reagent use and reduced recovery, as some ore remains under-leached.

These observations emphasize the need for hydrodynamic modeling, pilot testing, and advanced monitoring in scale-up. Grasping flow and mass transfer is key to linking lab results with industrial vat leaching performance. The next section covers the main advantages of vat leaching over other technologies.

9. ADVANTAGES OF VAT LEACHING

Vat leaching offers operational benefits between heap and tank leaching, mainly in hydraulic control, footprint, and predictability. Not ideal for very large-scale use, but useful in certain contexts.

Compared with heap leaching, vat leaching offers better control of solution flow and distribution. Its shorter flow paths and confined space reduce variability in residence time and improve contact between lixiviant and ore. This often leads to more stable performance and sometimes higher recovery, especially for ores sensitive to channeling (Eftekhari et al., 2023; Petersen & van Staden, 2025; Sekisov & Rasskazova, 2021; Shumilova et al., 2023; Manzila et al., 2022).

Another advantage is the reduced physical footprint. Vat systems typically operate with bed heights of 2–6 m in compact units, while heap leaching needs large pads over hectares. This makes vat leaching better for space-limited or environmentally constrained areas.

Solution management is more predictable. In vat systems, PLS collection happens in controlled conditions, reducing losses and easing downstream processing, unlike heap leaching where solution recovery is hindered by heterogeneity.

From an economic view, vat leaching needs less capital than tank leaching because it doesn't require fine grinding or mechanical agitation. It offers better control than heap leaching, reducing reagent loss and boosting efficiency. Operating costs are typically 2–10 USD/t, depending on ore and reagent use (Nagar, 2021; Petersen & van Staden, 2025).

Vat leaching supports modular and staged use, with box units deployed incrementally for scalable, lower-cost operations. This suits pilot plants, remote sites, and uncertain ore projects (Pereira, 2026).

In addition to kinetic and hydrodynamic factors, leaching technology choice is heavily influenced by spatial footprint, process control, and operational predictability. These are crucial in modern hydrometallurgy, where environmental constraints, land availability, and process stability are key. Heap, vat, and tank leaching vary considerably in these aspects, reflecting their respective design philosophies and operating principles. A comparison is shown in Figure 9.

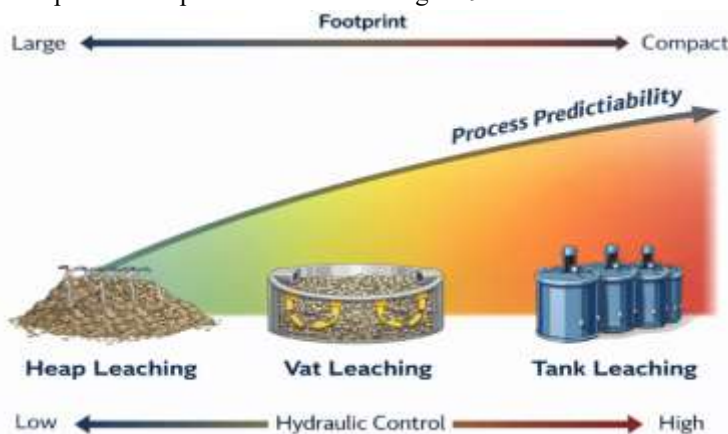


Figure 9. Conceptual comparison of footprint, hydraulic control, and process predictability in heap, vat, and tank leaching systems (adapted from Petersen & van Staden, 2025; Eftekhari et al., 2023).

Heap leaching has a large footprint and limited control, making it suitable for high-throughput, low-grade operations but leading to variability and reduced performance predictability.

Tank leaching systems have a compact footprint and high control due to intensive mixing, precise reagent dosing, and defined hydrodynamics. This improves predictability and recovery but increases costs and energy use.

Vat leaching is between heap and tank leaching. It has a smaller footprint than heap leaching due to its confined reactors and uses less energy than tank leaching. Vat systems also offer better control over solution distribution, residence time, and effluent, leading to more stable operation.

The figure shows vat leaching balances scale and control, suitable for moderate throughput, compliance, and stability. Its flexibility makes it ideal for niche and hybrid processes.

These features suit niche cases where heap leaching is inefficient or impractical, and tank leaching isn't cost-effective (Pereira, 2026; Nagar, 2021; Dushyantha et al., 2022).

From a critical perspective, these advantages are conditional, relying on the maintenance of adequate permeability and uniform flow. When unmet, vat leaching benefits can be lost. The next section addresses key limitations and technical challenges.

10. LIMITATIONS AND TECHNICAL CHALLENGES

Despite its advantages, vat leaching faces limitations mainly in scale, feed preparation, and flow stability. Consequently, it's often used only in niche applications, not large-scale production.

One main constraint is throughput. Vat leaching processes 10^2 – 10^4 t per batch, much less than heap leaching's 10^5 – 10^6 t over long campaigns. This affects economic viability for low-grade ores where scale matters (Petersen & van Staden, 2025; León et al., 2025).

Feed preparation is stricter. Vat leaching needs controlled particle size (3–12 mm) and low fines. Fines above 10–15% reduce permeability, impairing flow, raising costs and complexity (Toro et al., 2021; Chitera et al., 2022; Guzman et al., 2024).

Hydrodynamic instability creates preferential flow paths, reducing contact between the lixiviant and the ore. This can leave large bed parts poorly leached, with permeability loss from fines migration, precipitation, or collapse (Wang et al., 2020; Robertson et al., 2022; Zheng, 2026).

Despite its process control advantages, vat leaching faces a key challenge: permeability loss due to fine particle migration, pore clogging, and preferential flow paths, disrupting uniform solution flow. This causes ore to become hydraulically isolated, lowering recovery. Figure 10 illustrates channeling and permeability loss mechanisms.

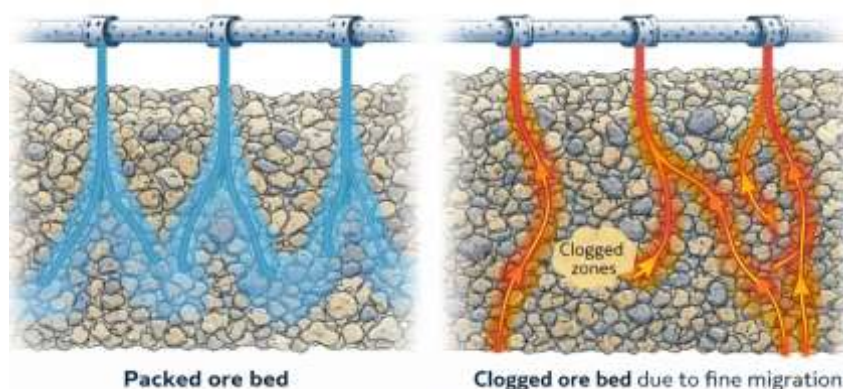


Figure 10. Development of preferential flow paths and permeability reduction in packed beds during vat leaching (adapted from Robertson et al., 2022; Wang et al., 2020).

Figure 10 shows that a well-structured packed bed ensures uniform leaching solution distribution, promoting consistent percolation, effective contact, and homogeneous mass transfer. This allows a predictable leaching front.

Over time, fine particles migrate in the bed due to hydraulic forces and settling, clogging pore spaces and reducing permeability. This causes the solution to bypass these zones, concentrating along flow paths, leaving large parts of the ore bed under-leached or uncontacted.



The figure shows that channeling and clogging are interconnected; decreased permeability redistributes flow, speeding fines migration and increasing heterogeneity. This feedback reduces recovery and raises reagent use in vat leaching.

Mitigation strategies include optimized particle size, agglomeration, controlled loading, and better irrigation design. However, fully eliminating these effects is challenging at industrial scale, highlighting the need to integrate hydrodynamics into process design.

Additional challenges stem from complex fluid–solid interactions, where moisture hysteresis and capillary effects cause uneven wetting, leading to saturation and dryness zones within the same bed. These effects are hard to control and often scale-dependent (Odidi et al., 2023; Wang et al., 2022).

Mechanical stability is a concern during leaching, as the ore bed can weaken from dissolution, particle rearrangement, and structural support loss. This may cause compaction and pore collapse, decreasing permeability (Wang et al., 2023; Zhou et al., 2021).

From a modeling perspective, these systems are hard to describe accurately. Traditional models like the shrinking-core model often miss the coupling among flow, reaction, and structural change. More advanced models are needed but are computationally intensive and rarely used in industry (Saldaña et al., 2022; Mubarak, 2020; Sun et al., 2025).

Economically, these limitations make the system more sensitive to operating conditions. Small changes in feed quality or flow can significantly affect recovery and reagent use, increasing operational risk relative to more robust large-scale systems such as heap leaching.

Vat leaching isn't a universal solution; its success relies on strict control of feed and hydrodynamic conditions. Failure to do so causes a rapid decline in performance. The next section discusses environmental considerations of vat leaching and related systems.

11. ENVIRONMENTAL CONSIDERATIONS

Environmental performance is crucial in vat leaching, which, despite its smaller scale than heap leaching, involves handling reactive solutions and metal effluents. Key factors include containment, seepage, drainage, residue stability, and water post-treatment (Warhurst, 2024; Ali et al., 2023; Ettler & Vitková, 2021; Vinodhkumar et al., 2025).

Well-designed systems use impermeable liners and controlled drainage to prevent seepage, but failures can cause leaks of acidic or cyanide solutions. Even small losses (1–5%) can cause significant environmental harm over time.

Effluent composition varies with ore type and lixiviant. Typical contaminants include:

- a. dissolved metals (Fe, Al, Cu, Mn)
- b. sulfate or chloride ions
- c. residual reagents (e.g., cyanide, acid)

These species must be treated before discharge using neutralization, precipitation, and adsorption. Treatment costs can make up 10–30% of operating costs in some hydrometallurgical operations, depending on regulations.

Case studies from artisanal and small-scale mining (ASM) highlight risks from poor process control. In these contexts, inadequate tailings containment and reuse can cause contamination, groundwater impact, and land degradation (Roman, 2025; Roman & Saria, 2025; Lameck et al., 2025; Kinyondo & Huggins, 2021; Tomassi, 2024).

Waste and residue behavior is complex, with contaminant release via diffusion and percolation, resulting in lasting environmental impacts even after active leaching ceases. Long-term tests show that metals can be released over months or years, depending on the material and conditions (Soares et al., 2022, 2023; Chen et al., 2024; Gao et al., 2023; Li et al., 2024; Wang et al., 2024).

Environmental integrity is vital in vat leaching, alongside process efficiency and metallurgical performance. While more contained than heap leaching, the process still poses contamination risks from seepage and drainage failures. Understanding contaminant pathways is crucial for safe, sustainable design. The main migration mechanisms are shown in Figure 11.

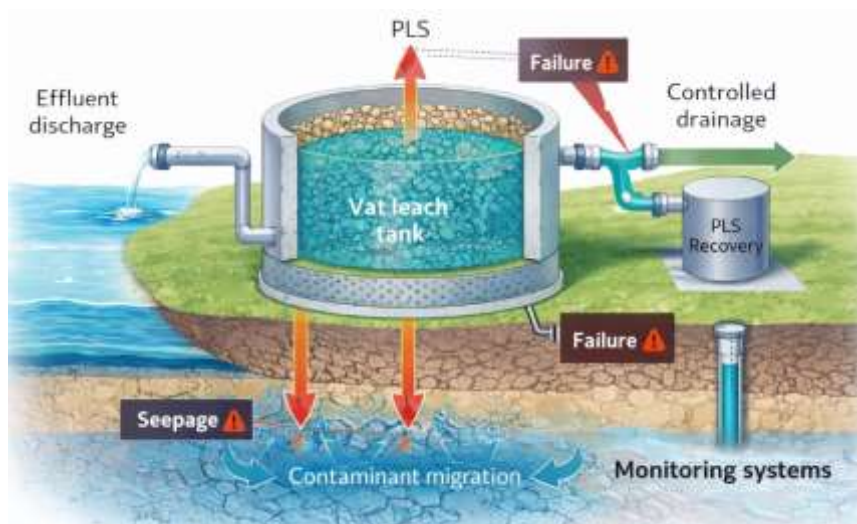


Figure 11. Main pathways of contaminant transport in vat leaching systems, including seepage, drainage, and effluent discharge (adapted from Ali et al., 2023; Ettler & Vítková, 2021).

Contaminant transport in vat leaching occurs via controlled drainage, seepage, and effluent discharge. Ideally, PLS is collected and recovered, but failures in liners or containment can lead to leakage into soil and groundwater.

Seepage is critical in systems with compromised liner or chemical degradation, allowing dissolved metals, reagents, and reaction products to migrate. Poor effluent management can cause surface contamination and environmental impacts.

The figure emphasizes the importance of engineered barriers like geomembranes and drainage layers, along with monitoring systems to detect leaks and control contamination. These are vital for regulatory compliance and reducing long-term risks of hydrometallurgical operations.

While vat leaching provides containment benefits, its environmental performance relies on design, control, and system integrity, highlighting the need for integrated management like monitoring, risk assessment, and maintenance.

Environmental assessment should address emissions, energy use, and resource efficiency. Hydrometallurgical methods consume less energy than pyrometallurgical ones, but reagent and water use still impact the environment (Rötzer & Schmidt, 2020).

Recent studies highlight circular hydrometallurgy and waste valorization, as recovering metals from tailings, slags, and secondary resources can reduce environmental impact and boost resource efficiency. Vat leaching aids these strategies thanks to its controllability and adaptability (Yu et al., 2024; Tezyapar Kara et al., 2023; Kelland et al., 2022; Manstein & Golovko, 2023).

From a critical standpoint, environmental performance in vat leaching depends heavily on engineering design and operational discipline. Although the process can be contained, control failures may cause significant localized impacts. The next section explores emerging developments and future directions.

12. EMERGING DEVELOPMENTS

Recent vat and percolation leaching advances emphasize process intensification, sustainability, and digitalization. While gravity-driven percolation stays the same, innovations aim to enhance kinetics, selectivity, and environmental impact.

Emerging directions include bioleaching, ozone-assisted leaching, radio-wave stimulation, organic-acid systems, and green lixiviants. Deep eutectic solvents and hybrid solvent–aqueous systems are explored for selective metal recovery (Moravvej et al., 2021; Krylova, 2022; Abashina et al., 2022; Khalafalla, 2022; Fahrurrozi et al., 2026; Yamini et al., 2025; Zhao et al., 2022). These aim to reduce reagent toxicity and improve metal selectivity. Some laboratory studies show alternative lixiviants consume 10–30% less reagent than conventional systems, but scale-up is limited.

Biohydrometallurgical advances show vat-type systems can be adapted for biologically assisted processes. Fixed-bed bioleaching, tested on sulfides, tailings, and low-grade ores, operates at 20–50 °C using microbes to enhance metal dissolution

(Cheru, 2021; Abashina & Vainshtein, 2023; Li et al., 2022; Jia et al., 2024; Manesh, 2025; Akhmet et al., 2025; Tezyapar Kara et al., 2023). It offers the benefit of reduced chemical use but has slower kinetics than acid systems.

Modularity is a key trend. Modern box leaching units are transportable modules with capacities from 50 to 5,000 t per cycle, suitable for remote or small-scale use, including tailings reprocessing and pilot validation. They also cut initial CAPEX by 20–40% compared to large fixed units.

Digitalization is advancing with studies on reinforcement learning, Kalman filters, and multi-physics simulation (Prisbrey, 2026; B rzsaga-Martell et al., 2025; Wang et al., 2024). These tools aim to predict permeability loss, optimize irrigation, and stabilize recovery. Early simulations show adaptive control can improve recovery by 5–15% under variable feed conditions.

Recent advances in hydrometallurgy have renewed interest in vat and percolation leaching, focusing on sustainability, process intensification, and digitalization. Challenges with flow control, scale-up, and reagent efficiency are increasingly tackled through innovative solutions like modular reactors, bioleaching integration, eco-friendly lixivants, and digital monitoring. An overview of these technologies is in Figure 12.

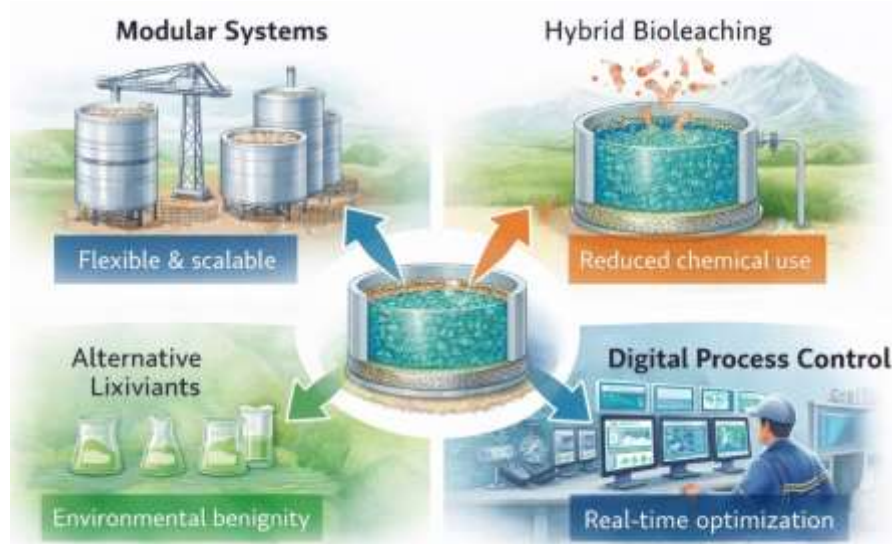


Figure 12. Emerging developments in vat leaching, including modular systems, hybrid bioleaching, alternative lixivants, and digital process control (adapted from: Krylova, 2022; Abashina et al., 2022; Prisbrey, 2026).

As shown in Figure 12, recent tech developments are reshaping vat leaching systems. Modular designs, gaining attention, enable flexible deployment, scalability, and lower capital costs, especially for remote or decentralized operations. They're especially suitable for small-to-medium processing and secondary resources.

Integrating bioleaching with vat systems offers a promising approach for sulfide ores and low-grade materials. These hybrid systems use microbes to improve metal dissolution and cut chemical reagent use, promoting more sustainable processing.

Meanwhile, alternative lixivants like glycine, organic acids, and chloride-based systems aim to reduce environmental impact and enhance selectivity. Though mostly at pilot or early industrial stages, they hold potential to replace conventional reagents like cyanide and strong acids.

Digitalization enables process optimization through sensors, real-time monitoring, and data-driven control, improving flow management, reagent dosing, and system performance. These technologies help address issues like channeling and permeability loss that traditional methods struggle to control.

The figure shows that future vat leaching depends on integrating technological innovations to enhance flexibility, reduce environmental impact, and improve control. These advances could broaden its role, especially in the circular economy and resource efficiency.

The next section identifies the main research gaps that must be addressed to enable broader industrial adoption.



13. RESEARCH GAPS

Despite long industrial use, vat leaching faces unresolved challenges. Many gaps stem from complex flow and reaction in granular media, where lab assumptions often do not hold at the industrial scale.

A major limitation is the multi-scale modeling of flow and reactive transport. Current models struggle to represent segregation, dual porosity, unsaturated flow, and time-dependent permeability changes (Zheng, 2026; Robertson et al., 2022; Robertson & Petersen, 2024; Wang et al., 2020; Guo et al., 2023a; Zhou et al., 2021). Permeability can drop 30–80% during operation due to fines migration and pore collapse, affecting recovery and residence time, yet these changes are rarely captured in predictive models.

The coupling between hydrodynamics and geomechanics is not well understood. During leaching, bed compaction, particle rearrangement, and structural weakening occur, especially in clay-rich ores and ion-adsorption materials. Permeability can vary greatly, causing channeling and dead zones (Guo et al., 2023b; Wang et al., 2020, 2023, 2024; Huang et al., 2026).

Chemical modeling reveals gaps due to simplified models like shrinking-core or diffusion that overlook adsorption–desorption, reactions, or interactions in complex ores. Research on alternative lixivants under real conditions is limited (Ouassel et al., 2025; Saldaña et al., 2022; Sun et al., 2025; Eksteen et al., 2020; Yamini et al., 2025). We need datasets combining kinetics, equilibrium, and transport.

Despite advances in vat leaching, key research gaps remain in flow behavior, permeability, reagent distribution, and scale-up, which impact industrial performance, recovery, stability, and economics. Table 6 summarizes these gaps and their effects.

Table 6. Main research gaps in vat leaching and their industrial implications, including flow modeling, permeability control, chemical systems, and scale-up challenges (adapted from Robertson et al., 2022; Wang et al., 2020; Zheng, 2026)

Research Gap	Technical Impact	Industrial Consequence
Flow modeling in granular beds	Poor prediction of channeling and flow paths	Recovery losses (5–20%); inconsistent performance
Permeability evolution	Time-dependent hydraulic instability	Increased cycle time (20–50%); reduced throughput
Lixiviant distribution	Non-uniform wetting and poor solution contact	Reagent inefficiency; higher consumption
Alternative lixivants	Limited validation at pilot/industrial scale	Uncertain scalability; operational risk
Scale-up methodology	Laboratory–industrial mismatch	CAPEX/OPEX uncertainty; design over/underestimation

Table 6 shows key research gaps in vat leaching mainly relate to hydrodynamic complexity and its interaction with chemical and operational parameters. The absence of reliable models for flow behavior in granular beds hampers prediction of channeling and optimization of solution distribution, leading to recovery losses of 5–20%.

Permeability evolution over time, especially under industrial conditions involving compaction, fines migration, and chemical reactions, remains poorly understood. These effects can increase cycle times by 20–50%, reducing process efficiency and productivity.

The challenge of achieving uniform lixiviant distribution further exacerbates these issues, leading to inefficient reagent use and incomplete metal recovery. While alternative lixivants offer promising environmental benefits, their limited validation at scale introduces additional uncertainty in process design and economic assessment.

Perhaps most critically, the scale-up from laboratory to industrial systems remains a major source of uncertainty, as highlighted in previous sections. The inability to accurately translate laboratory results into full-scale performance often leads to discrepancies in expected versus actual recovery, reagent consumption, and operational costs.

Overall, the table highlights that unresolved scientific and engineering challenges in vat leaching translate directly into economic penalties, reinforcing the need for integrated research efforts combining experimental studies, modeling, and industrial validation.

Scale-up methodology is another critical issue. The transition from column tests (typically 0.05–0.3 m diameter) to industrial vats (up to 5–10 m bed height) introduces pronounced heterogeneity. Fluid distribution, wall effects, and structural



variability become dominant (Pereira, 2026; Wei et al., 2023; Kaksonen, 2025). Current scale-up approaches remain empirical and often require pilot testing.

Integration with hybrid systems also requires further work. Bioleaching in fixed beds, combined chemical–biological systems, and modular process designs are promising but not yet standardized. Operational stability and control remain key barriers.

Digital tools represent an additional gap between research and practice. While advanced control methods—such as reinforcement learning and real-time simulation—have shown potential, their industrial implementation remains rare. Data availability, sensor reliability, and model validation are limiting factors (Prisbrey, 2026; Bázquez-Martell et al., 2025).

From a critical perspective, the main challenge is not the lack of individual studies but the lack of integration. Hydrodynamics, chemistry, mechanics, and control are often treated separately. This limits predictive capability and slows innovation.

Addressing these gaps will require coordinated experimental, modeling, and pilot-scale efforts, supported by high-quality datasets and standardized methodologies. The next section presents the overall conclusions of this review.

14. CONCLUSIONS

Vat leaching remains a relevant hydrometallurgical route, particularly for specific industrial niches. Its application is justified in cases where feed characteristics, scale, and process control requirements do not favor heap or tank leaching.

The analysis shows that vat leaching occupies an intermediate position between large-scale heap systems and highly controlled tank leaching. It offers improved hydraulic control, more predictable solution management, and shorter residence times than heap leaching, while avoiding the high grinding and capital costs associated with tank leaching (Petersen & van Staden, 2025; Eftekhari et al., 2023).

From an operational standpoint, vat leaching performs well with:

- granular and permeable ores
- medium to high-grade materials
- pre-treated feeds (crushed and agglomerated)
- tailings and secondary resources

Typical operating windows include bed heights of 2–6 m, leaching times of 12–72 h, and controlled particle sizes in the 3–12 mm range. Under these conditions, the process can achieve stable recoveries with moderate reagent consumption.

However, its limitations are significant. Throughput is lower than heap leaching, and performance is highly sensitive to fines, clays, and permeability loss. Channeling, non-uniform wetting, and structural changes in the bed remain major operational risks. These factors restrict large-scale deployment and require careful feed preparation and process control.

Environmental performance is generally favorable when systems are properly engineered. Containment, drainage, and effluent treatment can be effectively managed at the scale of vat operations. At the same time, failures in control may lead to localized impacts, particularly in small-scale or poorly regulated contexts.

Emerging developments indicate that vat leaching can be integrated with modern technologies. These include:

- bioleaching and hybrid systems
- green and selective lixiviants
- modular process design
- digital monitoring and control

Such innovations may improve efficiency, reduce environmental impact, and expand the applicability of vat leaching. However, most remain at laboratory or pilot scale.

From a critical perspective, the main challenge is not the viability of vat leaching itself, but its positioning within modern hydrometallurgy. The process is unlikely to replace heap leaching in large low-grade operations. Instead, it should be viewed as a flexible and controllable platform for:

- niche industrial applications
- pilot-scale validation
- treatment of complex or secondary materials



Future progress depends on better integration of hydrodynamics, chemistry, and process control, as well as improved scale-up methodologies and industrial validation of emerging technologies.

Overall, vat leaching remains a technically robust and adaptable process. Its continued relevance will depend on its ability to incorporate modern tools while maintaining its operational simplicity and reliability.

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The authors declare no conflicts of interest related to this study.

Author Contributions

Antonio Clareti Pereira: Conceptualization, methodology, investigation, writing – original draft, writing – review and editing.

Data Availability Statement

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

Consent for Publication

All authors have read and agreed to the published version of the manuscript.

REFERENCES

1. Abashina, T. N., Yachkula, A. A., & Vainshtein, M. B. (2022). Prevention of sulfuric acid pollution: Intensification of metal leaching with organic acids. *IOP Conference Series: Earth and Environmental Science*, 981, 032029. <https://doi.org/10.1088/1755-1315/981/3/032029>
2. Abashina, T., & Vainshtein, M. (2023). Current trends in metal biomining with a focus on genomics aspects and attention to arsenopyrite leaching—A review. *Microorganisms*, 11(1), 186. <https://doi.org/10.3390/microorganisms11010186>
3. Abdulsattar, S. M., Sayyid, F. F., & Al-Rubaiey, S. I. J. (2025). Advancements in copper recovery: A review of techniques for extracting copper by corrosion dezincificated brass waste. *AIP Conference Proceedings*, 3318(1), 050042. <https://doi.org/10.1063/5.0286891>
4. Adilov, G., Suleimen, B. & Kosdauletov, N. Challenges and Opportunities in the Recycling of Copper Slags. *J. Sustain. Metall.* 11, 2064–2074 (2025). <https://doi.org/10.1007/s40831-025-01137-9>
5. Ali, M. A. H., Mewafy, F. M., Qian, W., Alshehri, F., Almadani, S., Aldawsri, M., Aloufi, M., & Saleem, H. A. (2023). Mapping leachate pathways in aging mining tailings pond using electrical resistivity tomography. *Minerals*, 13(11), 1437. <https://doi.org/10.3390/min13111437>
6. Anukiruthika, T., Yoha, K. S., Dutta, S., Moses, J. A., & Anandharamakrishnan, C. (2024). Unit operations in food processing. In C. Anandharamakrishnan (Ed.), *Emerging technologies for the food industry* (1st ed.). Apple Academic Press. <https://doi.org/10.1201/9781003413592-4>.
7. Arpalahiti, A. (2021). *Heap leaching of nickel sulfide ore* (Doctoral dissertation, Aalto University). Aalto University publication series DOCTORAL DISSERTATIONS, 115/2021. <https://urn.fi/URN:ISBN:978-952-64-0490-5>
8. Aziman, E. S., Ismail, A. F., Rahmat, M. A., Rodzi, N. D., & Jamaludin, M. A. B. (2024). Column percolation leaching test for rare-earth processed residue: Standard laboratory column elution experiments towards development permanent disposal facility. *Progress in Nuclear Energy*, 171, 105172. <https://doi.org/10.1016/j.pnucene.2024.105172>
9. Bázquez-Martell, L., Diaz-Quezada, S., Estay, H., & Ruiz-del-Solar, J. (2025). Estimation of copper grade, acid consumption, and moisture content in heap leaching using extended and unscented Kalman filters. *Minerals*, 15(5), 521. <https://doi.org/10.3390/min15050521>
10. Binnemans, K., & Jones, P. T. (2023). The twelve principles of circular hydrometallurgy. *Journal of Sustainable Metallurgy*, 9(1), 1–12. <https://doi.org/10.1007/s40831-022-00602-7>



11. Binnemans, K., Jones, P.T. Lindy Effect in Hydrometallurgy. *J. Sustain. Metall.* 11, 2157–2174 (2025). <https://doi.org/10.1007/s40831-025-01119-x>
12. Bulaev, A., & Melamud, V. (2020). Selective acid leaching of copper and zinc from old flotation tailings. *Materials Science Forum*, 989, 554–558. <https://doi.org/10.4028/www.scientific.net/MSF.989.554>.
13. Chen, Q., Ma, C., Lee, Y. H., Dos Santos, M. M., Kim, M.-S., Meng, G., Snyder, S. A., Lee, J.-S., & Shi, H. (2024). Non-negligible toxicity to fish in the early life stages triggered by aqueous leachate of takeaway plastic containers. *Environmental Science & Technology*, 58(23), 10041–10051. <https://doi.org/10.1021/acs.est.4c01790>
14. Cheru, M. S. (2021). Bio hydrometallurgical technology, application and process enhancement. In M. K. Nazal & H. Zhao (Eds.), *Heavy metals: Their environmental impacts and mitigation*. IntechOpen. <https://doi.org/10.5772/intechopen.94206>
15. Dushyantha, N., Ilankoon, I. M. S. K., Ratnayake, N. P., Premasiri, H. M. R., Dharmaratne, P. G. R., Abeysinghe, A. M. K. B., Rohitha, L. P. S., Chandrajith, R., Ratnayake, A. S., Dissanayake, D. M. D. O. K., & Batapola, N. M. (2022). Recovery potential of rare earth elements (REEs) from the gem mining waste of Sri Lanka: A case study for mine waste management. *Minerals*, 12(11), 1411. <https://doi.org/10.3390/min12111411>
16. Eftekhari, F., Ardejani, F. D., Amini, M., Taherdangkoo, R., & Butscher, C. (2023). Enhancing tank leaching efficiency through electrokinetic remediation: A laboratory and numerical modeling study. *Water*, 15(22), 3923. <https://doi.org/10.3390/w15223923>
17. Eksteen, J. J., Oraby, E. A., & Nguyen, V. (2020). Leaching and ion exchange based recovery of nickel and cobalt from a low grade, serpentine-rich sulfide ore using an alkaline glycine lixiviant system. *Minerals Engineering*, 145, 106073. <https://doi.org/10.1016/j.mineng.2019.106073>
18. stay, H., Díaz-Quezada, S. Deconstructing the Leaching Ratio. *Mining, Metallurgy & Exploration* 37, 1329–1337 (2020). <https://doi.org/10.1007/s42461-020-00243-4>
19. Ettler, V., & Vitková, M. (2021). Slag leaching properties and release of contaminants. In N. M. Piatak & V. Ettler (Eds.), *Metallurgical slags: Environmental geochemistry and resource potential* (pp. 151–173). Royal Society of Chemistry. <https://doi.org/10.1039/9781839164576-00151>.
20. Fahrurrozi, M., Sujoto, V.S.H., Bagusantara, F. *et al.* Towards sustainable scandium extraction: atmospheric sulfuric acid leaching of Indonesian lateritic nickel ore. *Transit Met Chem* 51, 12 (2026). <https://doi.org/10.1007/s11243-025-00699-7>
21. Faris, N., Pownceby, M. I., Bruckard, W. J., & Chen, M. (2022). The direct leaching of nickel sulfide flotation concentrates— A historic and state-of-the-art review part I: Piloted processes and commercial operations. *Mineral Processing and Extractive Metallurgy Review*, 44(6), 407–435. <https://doi.org/10.1080/08827508.2022.2070617>
22. Fedotov, P., Fedotov, K., & Senchenko, A. (2021). Influence of the ore reduction method on the percolation leaching efficiency. *Obogashchenie Rud*, (2), 3–9. <https://doi.org/10.17580/or.2021.02.03>.
23. Fedotov, P.K., Senchenko, A.E., Fedotov, K.V. *et al.* Hydrometallurgical Processing of Gold-Containing Ore and its Enrichment Products. *Metallurgist* 65, 214–227 (2021). <https://doi.org/10.1007/s11015-021-01150-9>
24. Fedotov, P.K., Senchenko, A.E., Fedotov, K.V. *et al.* Hydrometallurgical Processing of Gold Ore. *J. Inst. Eng. India Ser. D* 103, 549–562 (2022). <https://doi.org/10.1007/s40033-022-00339-9>.
25. Gao, B., Liu, K., Li, F., & Fang, L. (2023). A chrysotile-based Fe/Ti nanoreactor enables efficient arsenic capture for sustainable environmental remediation. *Water Research*, 231, 119613. <https://doi.org/10.1016/j.watres.2023.119613>
26. Gavrilov, A.S., Krashenin, A.G., Petrova, S.A. *et al.* Extraction of Nickel from Oxidized Nickel Ores by Heap Leaching. *Metallurgist* 66, 593–604 (2022). <https://doi.org/10.1007/s11015-022-01364-5>
27. Gavrilov, A.S., Krashenin, A.G., Petrova, S.A. *et al.* Optimal parameters of the heap leaching of oxidized nickel ores by the box-wilson steep-ascent method. Part 1. *Metallurgist* 68, 913–921 (2024). <https://doi.org/10.1007/s11015-024-01798-z>
28. Guo, Z., Liu, L., Zhou, K., Wang, X., & Zhong, W. (2023). Research on the saturated/unsaturated seepage laws of ionic rare earth ore under different leaching conditions. *Frontiers in Earth Science*, 11, 1212017. <https://doi.org/10.3389/feart.2023.1212017>
29. Guo, Z., Liu, L., Tang, T., Zhou, K., & Wang, X. (2023). Influence of leaching solution on the soil-water characteristics of ion-absorbed rare earth minerals and its hysteresis effect. *Minerals*, 13(5), 637. <https://doi.org/10.3390/min13050637>



30. Guzman, A., Korsikas, S.S., Olson, T. *et al.* Agglomeration Scale: A Method to Improve Leaching Performance. *Mining, Metallurgy & Exploration* 41, 501–514 (2024). <https://doi.org/10.1007/s42461-024-00920-8>
31. Heydarov, A. A., Kashkai, C. M., Alyshany, G. I., & Jabbarova, Z. A. (2021). Processing of Zaglik alunite ore by heap and tank leaching. *Azerbaijan Chemical Journal*. <https://cyberleninka.ru/article/n/processing-of-zaglik-alunite-ore-by-heap-and-tank-leaching>.
32. Huang, Q., Zhang, C., Rao, Y., Rao, G., Wan, J., Xie, Y., & Lai, Q. (2026). Effect of height difference between adjacent liquid injection holes on wetting body evolution of ion-absorbed rare earth in situ leaching ore. *Metals*, 16(2), 232. <https://doi.org/10.3390/met16020232>
33. Jia, Y., Ruan, R., Qu, J., Tan, Q., Sun, H., & Niu, X. (2024). Multi-scale and trans-disciplinary research and technology developments of heap bioleaching. *Minerals*, 14(8), 808. <https://doi.org/10.3390/min14080808>
34. Jiang, Q., Jia, M., Yang, Y., & Zhang, C. (2024). Control of seepage characteristics in loose sandstone heap leaching with staged particle sieving-out method. *Minerals*, 14(10), 1039. <https://doi.org/10.3390/min14101039>
35. Jorge, A. S., Almeida, M. F., & Pinho, S. (2023). Copper recovery from printed circuit boards: Percolation leaching. In *Wastes: Solutions, treatments and opportunities IV* (1st ed.). CRC Press. <https://doi.org/10.1201/9781003345084-35>
36. Ju, W., Yang, J., Yao, C., Zhang, X., Ye, Z., & Liu, D. (2022). Experimental study on the permeability of rare earths with different particle composition for a novel heap leaching technology. *Applied Sciences*, 12(22), 11368. <https://doi.org/10.3390/app122211368>
37. Kaksonen, A. H. (2025). Bioleaching. In *Treatise on process metallurgy* (Vol. 2B: Unit processes, pp. 363–372). Elsevier. <https://doi.org/10.1016/B978-0-443-40294-4.00039-6>.
38. Kamalesh, A. K. (2022). *Efficient extraction of valuable metals from polymetallic shale using leaching and adsorption techniques* (Master's thesis, University of Calgary). PRISM <https://ucalgary.scholaris.ca/items/78b1f02e-639b-425b-b5ba-e34fa0751071>.
39. Karimova, L. M., & Kairalapov, Y. T. (2022). Percolation leaching of clay mixed copper ores. *iPolytech Journal*. <https://cyberleninka.ru/article/n/percolation-leaching-of-clay-mixed-copper-ores>
40. Karimova, L.M., Kairalapov, Y.T. & Mansurov, B.E. Research into the Percolation Leaching of Copper and Silver from Stale Tailings. *Russ. J. Non-ferrous Metals* 65, 42–51 (2024). <https://doi.org/10.1134/S1067821224700032>
41. Kelland, M. *et al.* (2023). Integrating Carbon Capture in Mining Through Metallurgy. Part 1: Leaching and Reclamation of Asbestos Tailings: Thetford Mines Carbon Capture and Remediation Project. In: Proceedings of the 61st Conference of Metallurgists, COM 2022. COM 2022. Springer, Cham. https://doi.org/10.1007/978-3-031-17425-4_66
42. Khalafalla, M.S. Biotechnological recovery of uranium (VI) from Abu Zeneima spent ore residue using green lixiviant. *J Radioanal Nucl Chem* 331, 2503–2513 (2022). <https://doi.org/10.1007/s10967-022-08249-6>
43. Koizhanova, A., Magomedov, D., Abdyldayev, N., Yerdenova, M., & Bakrayeva, A. (2023). The effect of biochemical oxidation on the hydrometallurgical production of copper. *Teknomekanik*, 6(1). <https://doi.org/10.24036/teknomekanik.v6i1.16072>
44. Krylova, L.N. Efficiency of Ozone Application for Extraction of Metals from Mineral Raw Materials. *Russ. J. Non-ferrous Metals* 63, 247–255 (2022). <https://doi.org/10.3103/S1067821222030087>
45. Kinyondo, A., & Huggins, C. (2021). State-led efforts to reduce environmental impacts of artisanal and small-scale mining in Tanzania: Implications for fulfilment of the sustainable development goals. *Environmental Science & Policy*, 120, 157–164. <https://doi.org/10.1016/j.envsci.2021.02.017>
46. Laatikainen, M., Makarova, I., Sainio, T., & Repo, E. (2021). Selective acid leaching of rare earth elements from roasted NdFeB magnets. *Separation and Purification Technology*, 278, 119571. <https://doi.org/10.1016/j.seppur.2021.119571>
47. Lameck, A.S., Rotich, B., Ahmed, A. *et al.* Land use/land cover changes due to gold mining in the Singida region, central Tanzania: environmental and socio-economic implications. *Environ Monit Assess* 197, 464 (2025). <https://doi.org/10.1007/s10661-025-13921-x>
48. León, F., Rojas, L., Bazán, V., Martínez, Y., Peña, A., & Garcia, J. (2025). A systematic review of copper heap leaching: Key operational variables, green reagents, and sustainable engineering strategies. *Processes*, 13(5), 1513. <https://doi.org/10.3390/pr13051513>



49. Li, C., Liu, Q., Liu, L. *et al.* Simulation of the natural attenuation of groundwater contaminated by acid in situ leaching at a uranium mine. *J Radioanal Nucl Chem* 333, 4907–4917 (2024). <https://doi.org/10.1007/s10967-024-09624-1>
50. Li, J., Yang, H., Tong, L., & Sand, W. (2021). Some aspects of industrial heap bioleaching technology: From basics to practice. *Mineral Processing and Extractive Metallurgy Review*, 43(4), 510–528. <https://doi.org/10.1080/08827508.2021.1893720>
51. Ling, H., Malfliet, A., Blanpain, B., & Guo, M. (2024). A review of the technologies for antimony recovery from refractory ores and metallurgical residues. *Mineral Processing and Extractive Metallurgy Review*, 45(3), 200–224. <https://doi.org/10.1080/08827508.2022.2132946>
52. Mamyrbayeva, K., Tulepbergenov, A., & Baikunurov, E. (2025). Review article on the technology of leaching of substandard copper concentrates: Methods and trends. *Canadian Metallurgical Quarterly*. Advance online publication. <https://doi.org/10.1080/00084433.2025.2546176>
53. Haghighat Manesh, M. J. (2025). *Harnessing thermoacidophilic archaea for recovery and separation of critical metals and elements* (Doctoral dissertation, North Carolina State University). ProQuest Dissertations & Theses. <https://www.proquest.com/openview/b88ccbce89f5969e262d1b912ead30db>.
54. Manstein, Y., Olenchenko, V., & Golovko, L. A. (2023). Increasing the environmental safety of heap leaching: Geophysical solutions. In *Book of Abstracts: 4th Atlas Georesources International Congress (AGIC): Geoscience innovations for resource management: Socio-economic challenges in an environmentally constrained world* (p. 182). <https://istina.ficp.ac.ru/publications/article/627957419/>.
55. Manzila, A. N., Moyo, T., & Petersen, J. (2022). A study on the applicability of agitated cyanide leaching and thiosulphate leaching for gold extraction in artisanal and small-scale gold mining. *Minerals*, 12(10), 1291. <https://doi.org/10.3390/min12101291>
56. Miiro, E. (2023). *Hydrometallurgical processing of rare earth elements from ion adsorption clays* (Master's thesis, University of Cape Town). <http://hdl.handle.net/11427/39674>
57. Mokmeli, M. (2020). Pre-feasibility study in hydrometallurgical treatment of low-grade chalcopyrite ores from Sarcheshmeh copper mine. *Hydrometallurgy*, 191, 105215. <https://doi.org/10.1016/j.hydromet.2019.105215>
58. Moravvej, Z., Mohebbi, A., Vakylabad, A. B., & Raeissi, S. (2021). The effect of radio-waves irradiation on copper-ore leaching. *Hydrometallurgy*, 201, 105584. <https://doi.org/10.1016/j.hydromet.2021.105584>
59. Mubarak, Y. (2020). Leaching of copper ores: Effects of operating variables. *International Journal of Emerging Trends in Engineering Research*, 8(8), 4226–4235. <https://doi.org/10.30534/ijeter/2020/31882020>.
60. Nagar, M. S. (2021). Techno-economic study on reagents consumption during uranium leaching, a case study: Gattar pilot plant, Egypt. *Cogent Engineering*, 8(1), 1985689. <https://doi.org/10.1080/23311916.2021.1985689>
61. Nwaila, G.T., Ghorbani, Y., Becker, M. *et al.* Geometallurgical Approach for Implications of Ore Blending on Cyanide Leaching and Adsorption Behavior of Witwatersrand Gold Ores, South Africa. *Nat Resour Res* 29, 1007–1030 (2020). <https://doi.org/10.1007/s11053-019-09522-4>
62. Odidi, M. D., Fagan-Endres, M. A., & Harrison, S. T. L. (2023). Moisture absorption rates via capillary suction within packed beds – The effect of material and fluid properties with implications for heap leaching operations. *Hydrometallurgy*, 215, 105975. <https://doi.org/10.1016/j.hydromet.2022.105975>
63. Ouassel, S., Guettaf, H., Khemaissia, S. *et al.* Parametric study of uranium ore acid leaching by percolation: experimental design, kinetic study and numerical modeling with the unreacted shrinking core model. *J Radioanal Nucl Chem* 334, 3599–3612 (2025). <https://doi.org/10.1007/s10967-025-10070-w>
64. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, n71. <https://doi.org/10.1136/bmj.n71>
65. Pereira, A. C. (2026). *From columns to industrial heaps: Critical design considerations for heap leach pilot plants*. *International Journal of Modern Research in Engineering and Technology (IJMRET)*, 11(3). <https://doi.org/10.5281/zenodo.18979542>



66. Petersen, J., & van Staden, P. (2025). Heap leaching: Process, principles, and practical considerations. In *Treatise on process metallurgy* (Vol. 2B: Unit processes, pp. 333–345). Elsevier. <https://doi.org/10.1016/B978-0-443-40294-4.00029-3>.
67. Rasool, M. H., Ridha, S., Ahmad, M., Shamsuddin, R. A. B., Zahoor, M. K., & Khan, A. (2025). A mineralogical perspective on rare earth elements (REEs) extraction from drill cuttings: A review. *Minerals*, 15(5), 533. <https://doi.org/10.3390/min15050533>
68. Rasskazova, A. V., Sekisov, A. G., Kirilchuk, M. S., & Vasyanovich, Y. A. (2020). Stage-activation leaching of oxidized copper–gold ore: Theory and technology. *Eurasian Mining*. <https://doi.org/10.17580/em.2020.01.10>
69. Rasskazov, I. Y., Sekisov, A. G., & Rasskazova, A. V. (2022). In-situ leaching of molybdenum and uranium by percarbonate and chloride-hypochlorite solutions. *Zapiski Gornogo Instituta*. <https://cyberleninka.ru/article/n/in-situ-leaching-of-molybdenum-and-uranium-by-percarbonate-and-chloride-hypochlorite-solutions>.
70. Reis, A. S., & Monteiro, R. P. G. (2020). Study of thorium and uranium isotopes activity concentration after percolation or agitation leaching, in mining lixiviation liquor samples. *Brazilian Journal of Radiation Sciences*, 8(1). <https://doi.org/10.15392/bjrs.v8i1.933>
71. Rito, B., Almeida, D., Coimbra, C., Vicente, D., Francisco, R., Branco, R., Weigand, H., & Morais, P. V. (2022). Post-measurement compressed calibration for ICP-MS-based metal quantification in mine residues bioleaching. *Scientific Reports*, 12, 16007. <https://doi.org/10.1038/s41598-022-20432>
72. Robertson, S. W., van Staden, P. J., Cherkaev, A., & Petersen, J. (2022). Properties governing the flow of solution through crushed ore for heap leaching. *Hydrometallurgy*, 208, 105811. <https://doi.org/10.1016/j.hydromet.2021.105811>
73. Robertson, S. W., & Petersen, J. (2024). Modelling unsaturated dual-phase flow through crushed ores for heap leaching. *Journal of the Southern African Institute of Mining and Metallurgy*, 124(12). <https://doi.org/10.17159/2411-9717/697/2024>.
74. Roman, P., & Saria, J. (2025). The influence of vat leach reprocessed tailings on heavy metals levels around Sekenke Gold Mine, Iramba District, Tanzania. *East African Journal of Biophysical and Computational Sciences*, 6(1). <https://journals.hu.edu.et/hu-journals/index.php/eajbcs/article/view/1209>
75. Rötzer, N., & Schmidt, M. (2020). Historical, current, and future energy demand from global copper production and its impact on climate change. *Resources*, 9(4), 44. <https://doi.org/10.3390/resources9040044>
76. Saldaña, M., Gálvez, E., Robles, P., Castillo, J., & Toro, N. (2022). Copper mineral leaching mathematical models—A review. *Materials*, 15(5), 1757. <https://doi.org/10.3390/ma15051757>
77. Sekisov, A., & Rasskazova, A. (2021). Assessment of the possibility of hydrometallurgical processing of low-grade ores in the oxidation zone of the Malmyzh Cu–Au porphyry deposit. *Minerals*, 11(10), 1097. <https://doi.org/10.3390/min11101097>
78. Shengo Lutandula, M., Kitobo, W. S., Kime, M. B., Mambwe, M. P., & Nyembo, T. K. (2020). Mineralogical variations with the mining depth in the Congo Copperbelt: Technical and environmental challenges in the hydrometallurgical processing of copper and cobalt ores. *Journal of Sustainable Metallurgy*, 6(4), 678–692. <https://doi.org/10.1007/s40831-020-00316-7>
79. Shumilova, L.V., Khatkova, A.N. & Razmakhnin, K.K. Development of a Combined Technology for Producing Base Gold Alloy from Waste of Different Types. *Metallurgi* 66, 1162–1170 (2023). <https://doi.org/10.1007/s11015-023-01428-0>
80. Soares, A.S.F., da Costa Marques, M.R. & da Cunha Costa, L. Physical-chemical characterization and leaching studies involving drill cuttings generated in oil and gas pre-salt drilling activities. *Environ Sci Pollut Res* 30, 17899–17914 (2023). <https://doi.org/10.1007/s11356-022-23398-7>
81. Sun, H.-Y., Ruan, R.-M., & Deng, J.-S. (2025). Kinetics of chalcopyrite dissolution in ammonia solution under sealed conditions and controlled redox potential. *Transactions of Nonferrous Metals Society of China*, 35(5), 1691–1703. [https://doi.org/10.1016/S1003-6326\(25\)66776-8](https://doi.org/10.1016/S1003-6326(25)66776-8)
82. Surimbayev, B., Bolotova, L., Akcil, A., Yessengarayev, Y., Khumarbekuly, Y., Kanaly, Y., et al. (2024). Gravity concentration of gold-bearing ores and processing of concentrates: A review. *Mineral Processing and Extractive Metallurgy Review*, 46(7), 726–750. <https://doi.org/10.1080/08827508.2024.2395824>
83. Tao, J.-L., Deng, Y.-C., Ye, D.-X., Chen, B.-F., Zhou, Y., Zhong, J.-G., Wang, X., & Wang, W. (2025). Fine exploration and green development of ion-adsorption type REE deposits in South China using multi-geophysical technology. *Frontiers in Earth Science*, 13, 1489870. <https://doi.org/10.3389/feart.2025.1489870>



84. Tezyapar Kara, I., Kremser, K., Wagland, S.T. *et al.* Bioleaching metal-bearing wastes and by-products for resource recovery: a review. *Environ Chem Lett* 21, 3329–3350 (2023). <https://doi.org/10.1007/s10311-023-01611-4>
85. Tomassi, O. D. (2024). Transitioning towards sustainability in artisanal and small-scale gold mining: A case study from Tanzania. *The Extractive Industries and Society*, 17, 101410. <https://doi.org/10.1016/j.exis.2024.101410>
86. Toro, N., Ghorbani, Y., Turan, M. D., Robles, P., & Gálvez, E. (2021). Gangues and clays minerals as rate-limiting factors in copper heap leaching: A review. *Metals*, 11(10), 1539. <https://doi.org/10.3390/met11101539>
87. Vinodhkumar, S., Balaji, S., Kulanthaivel, P. *et al.* Utilisation of magnesite mine tailings as sustainable structural fill material: a novel approach to mitigate environmental impact. *Int. J. Environ. Sci. Technol.* 22, 13661–13672 (2025). <https://doi.org/10.1007/s13762-025-06501-6>
88. Wang, D., Wu, F., Rao, Y., Zhao, Z., Xu, W., & Han, M. (2024). Microscopic simulation of RE³⁺ migration in ion-type rare earth ores based on Navier–Stokes equation—Exchange reaction—Ion migration coupling. *Metals*, 14(10), 1130. <https://doi.org/10.3390/met14101130>
89. Wang, H., Wang, X., Li, G. *et al.* Weakening of mechanical parameters of ion-absorbed rare-earth ores subjected to leaching. *Geomech. Geophys. Geo-energ. Geo-resour.* 9, 124 (2023). <https://doi.org/10.1007/s40948-023-00661-w>
90. Wang, H., Xu, C., Dowd, P. A., Wang, Z., & Faulkner, L. (2022). Modelling in-situ recovery (ISR) of copper at the Kapunda mine, Australia. *Minerals Engineering*, 186, 107752. <https://doi.org/10.1016/j.mineng.2022.107752>
91. Wang, Lm., Yin, Sh. & Wu, Ax. Visualization of flow behavior in ore-segregated packed beds with fine interlayers. *Int J Miner Metall Mater* 27, 900–909 (2020). <https://doi.org/10.1007/s12613-020-2059-3>
92. Wang, L., Yin, S., Zhang, X., Yan, Z., & Liao, W. (2022). Hydrodynamic hysteresis and solute transport in agglomerated heaps under irrigation, stacking, and bioleaching controlling. *Minerals*, 12(12), 1623. <https://doi.org/10.3390/min12121623>
93. Wang, X., Shen, J., Fan, L., & Zhang, Y. (2024). Research on salt drainage efficiency and anti-siltation effect of subsurface drainage pipes with different filter materials. *Water*, 16(10), 1432. <https://doi.org/10.3390/w16101432>
94. Wang, X., Wang, H., Sui, C., Zhou, L., Feng, X., Huang, C., Zhao, K., Zhong, W., & Hu, K. (2020). Permeability and adsorption–desorption behavior of rare earth in laboratory leaching tests. *Minerals*, 10(10), 889. <https://doi.org/10.3390/min10100889>
95. Wankat, P. C. (2022). *Separation process engineering: Includes mass transfer analysis* (3rd ed.). Pearson.
96. 21. In *Environmental Policy in Mining*.
97. Wei, C., Su, X., Que, W., Chen, X., Li, J., & Du, Z. (2023). Design of U-shaped tower based on the integrated process of saturated re-adsorption and leaching of uranium-bearing resin. *Hydrometallurgy of China*, 42(3), 312–317. <https://doi.org/10.13355/j.cnki.sfyj.2023.03.016>
98. Xing, W. D., Sohn, S. H., & Lee, M. S. (2020). A review on the recovery of noble metals from anode slimes. *Mineral Processing and Extractive Metallurgy Review*, 41(2), 130–143. <https://doi.org/10.1080/08827508.2019.1575211>
99. Yamini, K., Dyer, L. G., Tadesse, B., & Alorro, R. D. (2025). Toward expanding the utilisation of deep eutectic solvents: Rare earth recovery from primary ores and process tailings. *Clean Technologies*, 7(4), 111. <https://doi.org/10.3390/cleantechnol7040111>
100. Yang, J., Bauer, S., & Verba, C. (2022). *Strategies to recover easily-extractable rare earth elements and other critical metals from coal waste streams and adjacent rock strata using citric acid* (Report No. DOE/NETL-2022/3732). U.S. Department of Energy, National Energy Technology Laboratory. <https://doi.org/10.2172/1884275>.
101. Yu, H., Zahidi, I., Fai, C. M., Liang, D., & Madsen, D. Ø. (2024). Mineral waste recycling, sustainable chemical engineering, and circular economy. *Results in Engineering*, 21, 101865. <https://doi.org/10.1016/j.rineng.2024.101865>
102. Zakia, S. A., Rashad, M. M., Mohamed, S. A., El Sheikh, E. M., Mira, H. E., Abd El Wahab, G. M., . (2020). Kinetics of uranium leaching process using sulfuric acid for Wadi Nasib ore, South western Sinai, Egypt. *Aswan University Journal of Environmental Studies*, 1(2), 171–182. <https://doi.org/10.21608/aujes.2020.127584>.
103. Zhao, Z., Feng, S., Xiao, C., Luo, J., Song, W., Wan, Y., & Li, S. (2022). Exploring ions selectivity of nanofiltration membranes for rare earth wastewater treatment. *Separation and Purification Technology*, 289, 120748. <https://doi.org/10.1016/j.seppur.2022.120748>



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104. Zheng, Q. (2026). *X-ray imaging of fluid flow and reactive transport in dual-porosity media: Implications for heap leaching* (Doctoral dissertation). UNSW Sydney.
105. Zhou, L., Wang, X., Huang, C., Wang, H., Ye, H., Hu, K., & Zhong, W. (2021). Development of pore structure characteristics of a weathered crust elution-deposited rare earth ore during leaching with different valence cations. *Hydrometallurgy*, 201, 105579. <https://doi.org/10.1016/j.hydromet.2021.105579>

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