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Agglomeration of Fine Ores for Heap Leaching: Mechanisms, Design Parameters, and Scale-Up Limitations

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ABSTRACT

Original Research Article

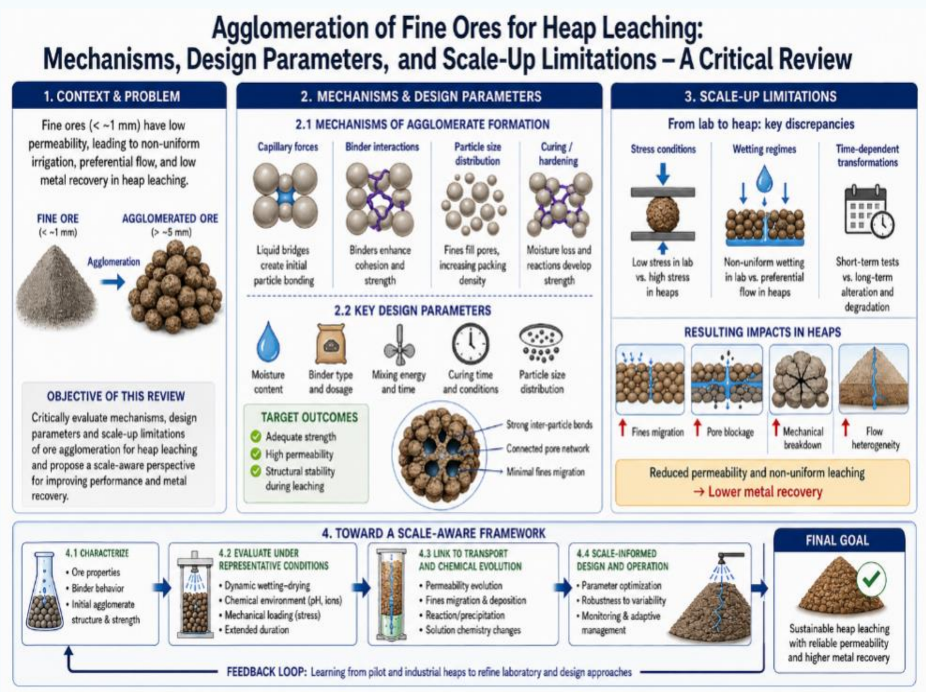
Agglomeration of fine ores is a critical pre-treatment step in heap leaching, directly influencing permeability, fluid distribution, and overall metal recovery. Despite its widespread industrial adoption, the mechanistic understanding of agglomeration and its scale-up reliability remains limited. This review critically examines the physicochemical mechanisms governing agglomerate formation, including capillary forces, binder interactions, particle size distribution, and curing processes. The role of operational parameters—such as moisture content, binder type and dosage, mixing energy, and curing time—is analyzed in relation to agglomerate strength, stability, and resistance to degradation under leaching conditions. Particular attention is given to the evolution of agglomerate structure during irrigation, highlighting the impacts of fines migration, precipitation, and mechanical breakdown on long-term permeability and flow heterogeneity. A comparative assessment of laboratory, pilot, and industrial practices reveals systematic discrepancies that limit direct scale-up, especially due to differences in stress conditions, wetting regimes, and time-dependent transformations. The review identifies common sources of bias in agglomeration testing and proposes a scale-aware framework linking laboratory characterization to heap performance. It concludes that agglomeration effectiveness cannot be assessed solely by initial strength metrics, emphasizing the need for integrated evaluation under representative hydraulic and chemical conditions.

Keywords: Heap Leaching, Agglomeration, Fine Ores, Permeability, Scale-Up, Hydrodynamics.

Highlights

- Agglomeration controls permeability and flow distribution in heap leaching systems.
- Laboratory tests often overestimate agglomerate stability and heap performance.
- Long-term degradation mechanisms are poorly captured in short-duration testing.
- Scale-up requires coupling agglomeration behavior with transport and chemical evolution.

Graphical Abstract



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Introduction

Heap leaching has become a dominant hydrometallurgical route for the processing of low-grade ores, particularly in copper, gold, and nickel systems, due to its low capital intensity and operational flexibility compared to pyrometallurgical alternatives (Petersen & van Staden, 2025; Mokmeli & Parizi, 2022). However, the efficiency of heap leaching is strongly constrained by the physical structure of the ore bed, especially when fine particles (<1 mm) are present in significant proportions. Fine particles promote pore clogging, reduce permeability, and induce preferential flow, ultimately leading to poor solution distribution and incomplete metal recovery (Yilmaz et al., 2020; Li et al., 2022).

Agglomeration is widely used as a pre-treatment step to mitigate these effects by transforming fine particles into mechanically stable granules, typically in the 5–25 mm range. This transformation aims to improve bed permeability, enhance fluid distribution, and stabilize the heap structure under irrigation and mechanical loading conditions (Quezada et al., 2021; Guzman et al., 2024). Target permeability values for well-agglomerated systems typically range from 10^{-11} to 10^{-9} m^2, depending on ore type and packing conditions, representing improvements of one to two orders of magnitude over non-agglomerated fines (Fernando et al., 2020; Robertson et al., 2022).

Despite its widespread industrial use, agglomeration is often treated as a secondary or preparatory operation, with limited integration into the broader framework of heap design and performance prediction. This perspective is problematic. Agglomeration directly controls hydraulic behavior, which in turn governs mass transport, reaction kinetics, and long-term system evolution. As a result, its influence extends beyond initial permeability, affecting acid consumption, structural stability, and ultimately metal recovery over the entire operational life of the heap (Pereira, 2026a; Dreier, 2025).

A critical limitation in current literature is the tendency to evaluate agglomeration based on short-term metrics, such as initial granule strength or laboratory-scale permeability, without accounting for time-dependent degradation mechanisms, including fines migration, binder dissolution, and precipitation-induced pore blockage. These processes evolve over weeks to months in industrial heaps but are rarely captured in laboratory testing protocols (Jia et al., 2024; Trinanda et al., 2026).

This review addresses these limitations by critically examining the mechanisms, design parameters, and scale-up constraints of agglomeration in heap leaching systems. The central hypothesis is that agglomeration is not merely a pre-treatment step but a controlling variable that defines the hydraulic and reactive behavior of the system across scales.

Methodology

This review followed the PRISMA 2020 framework to ensure transparency, reproducibility, and rigor in identifying, screening, and selecting relevant literature (Page et al., 2021).

The methodology aimed to include fundamental and applied studies on agglomeration in heap leaching, covering experimental, modeling, and industrial investigations.

A systematic literature search was conducted across major scientific databases, including Scopus, Web of Science, and ScienceDirect, covering the period from 2020 to 2026. The search strategy used combinations of keywords and Boolean operators, including:

"heap leaching" AND "agglomeration",
"ore agglomeration" AND "sulfuric acid",
"pelletization" AND "heap leaching", and related terms.

The search was limited to peer-reviewed journal articles, conference proceedings, and theses in English. Reference lists of key articles were also checked to find additional relevant studies not found initially.

Explicit inclusion and exclusion criteria were applied to ensure consistency and relevance. Inclusion criteria comprised studies that:

(i) directly address agglomeration processes in heap leaching systems;
(ii) investigate binder effects, permeability evolution, or structural stability;
(iii) provide experimental, modeling, or field-scale data; and
(iv) contribute to understanding scale-up behavior or long-term performance.

Exclusion criteria included studies that:

(i) are not directly related to heap leaching (e.g., sintering or pelletization in unrelated processes);
(ii) lack sufficient methodological detail or experimental validation;
(iii) focus exclusively on downstream processing without addressing agglomeration; or
(iv) consist of purely descriptive or non-technical content (e.g., editorials, opinion papers).

The selection workflow, summarized in Figure 1, follows the standard PRISMA stages of identification, screening, eligibility assessment, and final inclusion. After removing duplicates and applying screening criteria, a total of 81 studies were retained for detailed analysis. This relatively small dataset reflects the scarcity of studies that explicitly address agglomeration under conditions representative of industrial heap leaching.

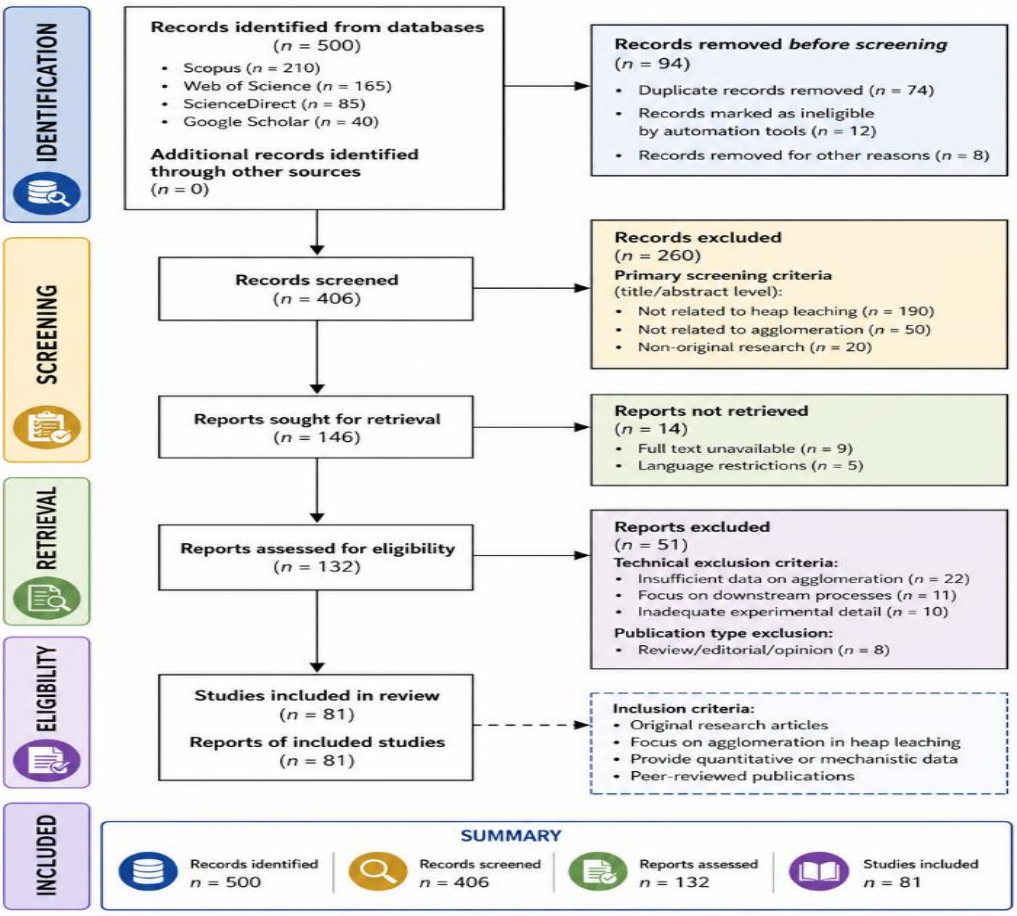


Figure 1. PRISMA 2020 flow diagram for literature selection, including identification, screening, eligibility, and inclusion stages. Adapted from Page et al. (2021).

Although the PRISMA framework provides a structured basis for evaluating the literature, it also highlights important limitations in the current body of knowledge. A significant proportion of the selected studies are conducted at laboratory scale, with limited validation under realistic hydraulic, mechanical, and chemical conditions. In addition, key variables—such as moisture content, particle size distribution, binder dosage, and curing protocols—are often reported inconsistently, limiting comparability across studies.

These methodological limitations introduce systematic bias in interpreting agglomeration performance, particularly regarding scale-up and long-term behavior. Consequently, this review adopts a critical, scale-aware perspective, emphasizing not only reported results but also their underlying assumptions, experimental constraints, and applicability to industrial systems.

Fundamentals of Agglomeration

Agglomeration in heap leaching systems is governed by a combination of physicochemical and mechanical processes that transform fine particles into stable, porous granules. These processes are typically described in terms of nucleation, growth, and coalescence mechanisms, which occur simultaneously under dynamic conditions in industrial agglomerators (Urtubia & Suárez, 2020; Moncada et al., 2025).

Nucleation involves the initial formation of particle clusters through liquid bridge formation, driven primarily by capillary forces. At moisture contents between 5% and 15%, liquid bridges generate attractive forces that bind particles together, with strength proportional to surface tension and inversely proportional to particle size (Wang et al., 2021; Yin et al., 2021). Growth occurs as additional particles adhere to these nuclei, whereas coalescence involves the merging of adjacent granules under mechanical agitation, resulting in a broader size distribution.

Beyond capillary forces, chemical bonding plays a critical role, particularly in acid-based agglomeration systems. The addition of sulfuric acid can induce partial dissolution and reprecipitation reactions, enhancing interparticle bonding. In cement-based systems, hydration reactions contribute to long-term mechanical strength, although they may also introduce rigidity that affects permeability (Chen et al., 2020; Kiaei & Golpayegani, 2023).

Mechanical forces, including shear and compressive stresses within agglomeration drums or conveyors, influence granule formation and stability. Excessive shear can lead to breakage, while insufficient mixing results in heterogeneous agglomerates with poor structural integrity (Guzman et al., 2024; Wang et al., 2024).

Agglomeration results from physicochemical and mechanical interactions that govern particle bonding and granule growth. These include nucleation, layering, and coalescence, influenced by capillary forces, binder chemistry, and mixing conditions (Urtubia & Suárez, 2020; Chen et al., 2020). Figure 2 shows the main stages of agglomerate formation and the mechanisms behind structure development and stability.

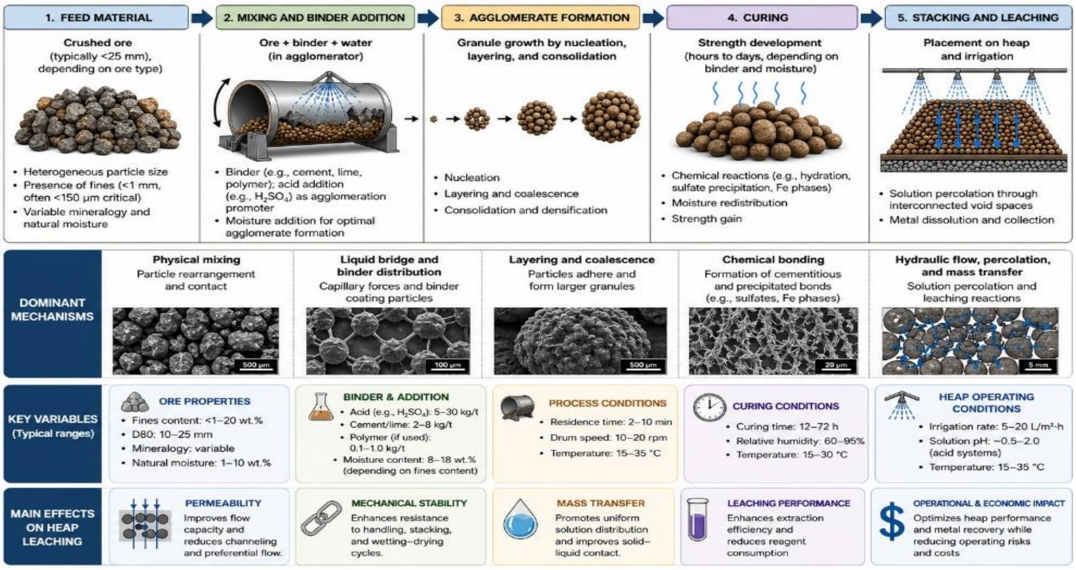


Figure 2. Schematic representation of agglomeration mechanisms, including nucleation, growth, and coalescence under combined capillary, chemical, and mechanical forces. Adapted from Urtubia and Suárez (2020), Chen et al. (2020), and Moncada et al. (2025).

Figure 2 illustrates the multi-scale nature of agglomeration, linking particle-level interactions to macroscopic granule formation. Importantly, these mechanisms are highly sensitive to process variables such as moisture content, binder dosage, and mixing intensity, which will be discussed in subsequent sections.

A key limitation in current understanding is the assumption that agglomerate properties remain constant after formation. In reality, agglomerates evolve during curing and leaching, undergoing structural changes that alter permeability and mechanical stability. This dynamic behavior must be considered when linking agglomeration mechanisms to heap performance.

This section examines how ore characteristics affect agglomeration, focusing on mineralogy and particle size as determinants of efficiency.

Ore Characteristics and Agglomerability

Agglomeration efficiency mainly depends on ore properties such as particle size, mineralogy, and moisture content. The critical factor is the fraction of fines (<1 mm); exceeding 10–20 wt.% fills pore spaces, reducing permeability and increasing the risk of collapse during irrigation (Karimova & Kairalapov, 2022; Toro et al., 2021).

Mineralogical composition influences agglomeration. Clay-rich ores with smectite or kaolinite show high plasticity and water retention, aiding initial agglomeration but causing swelling and permeability issues over time. Iron oxyhydroxides like goethite contribute to cohesion but increase acid use during leaching (Ivanov et al., 2022; Acquah et al., 2025). Siliceous gangue reduces cohesion, requiring more binder for stable agglomerates (Zappala et al., 2024).

Natural moisture content plays a dual role. Insufficient moisture (<5 wt.%) limits capillary bonding, while excessive moisture (>15–20 wt.%) leads to over-saturation, reducing mechanical strength and promoting particle segregation during handling (Urtubia & Suárez, 2020; Wang et al., 2021).

Ore characteristics set initial boundaries for agglomeration, affecting the feasibility and stability of granule formation. Fine content, mineralogy, and moisture range are key factors influencing agglomerability (Acquah et al., 2026; Toro et al., 2021). Table 1 summarizes their thresholds and impact on process performance.

Table 1. Influence of ore properties on agglomeration behavior, including fines content, mineralogy, and moisture range. Adapted from Acquah et al. (2026), Toro et al. (2021), Karimova and Kairalapov (2022), and Zappala et al. (2024).

Parameter	Typical Range	Effect on Agglomeration	Classification Impact
Fines content (<1 mm)	<10 wt.%	Limited pore filling; good permeability; stable granule formation	Easy to agglomerate
	10–20 wt.%	Moderate pore filling; increased binder demand; risk of heterogeneity	Moderate
	>20 wt.%	Significant pore clogging; poor permeability; high instability risk	Difficult
Mineralogy (clays)	Low clay content	Limited plasticity; weak natural cohesion	Requires binder
	Moderate clay content	Improved initial cohesion; risk of swelling	Moderate
	High swelling clays (smectite)	High water retention; structural instability during leaching	Difficult
Mineralogy (Fe oxides)	Goethite/limonite	Enhances cohesion; increases acid consumption	Moderate
Gangue composition (silica)	High SiO_2	Low cohesion; reduced bonding efficiency	Requires high erbinder dosage
Natural moisture content	<5 wt.%	Insufficient capillary bonding	Poor agglomeration
	5–15 wt.%	Optimalliquid bridge formation	Optimal
	>15–20 wt.%	Over-saturation; reduced strength; segregation risk	Unstable
Particle size distribution (D80)	10–25 mm (coarse fraction)	Supports structural framework	Favorable
	Broad PSD with fines	Improved packing but higher clogging risk	Moderate to difficult

Table 1 summarizes typical thresholds for agglomerability. Ores with low fines content (<10 wt.%) and limited clay minerals are generally classified as “easy to agglomerate,” while those exceeding 20 wt.% fines and containing swelling clays are considered “difficult.” These classifications, however, are not absolute and depend on binder selection and operating conditions.

A critical limitation in current practice is the reliance on static classification schemes that do not account for dynamic changes during leaching. Mineral dissolution, precipitation, and mechanical stress can alter agglomerate structure over time, reducing the predictive value of initial ore characterization. This limitation directly links ore properties to downstream performance, reinforcing the need for integrated evaluation across scales.

The next section examines how these intrinsic properties are translated into operational strategies through agglomeration technologies and process parameters.

Agglomeration Technologies and Operating Parameters

Industrial agglomeration is typically performed using rotating drums, disc pelletizers, or conveyor-based systems, each offering distinct advantages in terms of residence time, mixing intensity, and scalability (Cook & Scott, 2025; Guzman et al., 2024). Among these, drum agglomerators are the most widely used in heap leaching operations due to their robustness and ability to handle high throughput, often exceeding 5,000–20,000 t/d in large-scale copper operations (Dreier, 2025).

Disc pelletizers provide tighter control over particle size distribution but are more sensitive to feed variability and moisture fluctuations. Conveyor-based agglomeration systems, while simpler, generally offer limited mixing efficiency and are more suitable for ores with favorable agglomeration characteristics (Chitera et al., 2022).

Operating parameters strongly influence agglomerate formation. Residence times typically range from 2 to 10 minutes, with rotational speeds adjusted to maintain a cascading rather than a centrifuging regime. Feed rates and moisture addition must be carefully balanced to avoid under- or over-agglomeration. Excessive shear forces can lead to granule breakage, while insufficient mixing results in heterogeneous agglomerates with weak mechanical integrity (Wang et al., 2024; Gibson, 2020).

Agglomeration equipment selection influences granule formation by affecting mixing, residence time, and particle–binder interactions. Industrial systems vary in their ability to produce stable agglomerates, especially with high-fines ores or moisture variability (Cook & Scott, 2025; Guzman et al., 2024). Figure 3 compares key agglomeration technologies, their operating principles, and their effects on granules.

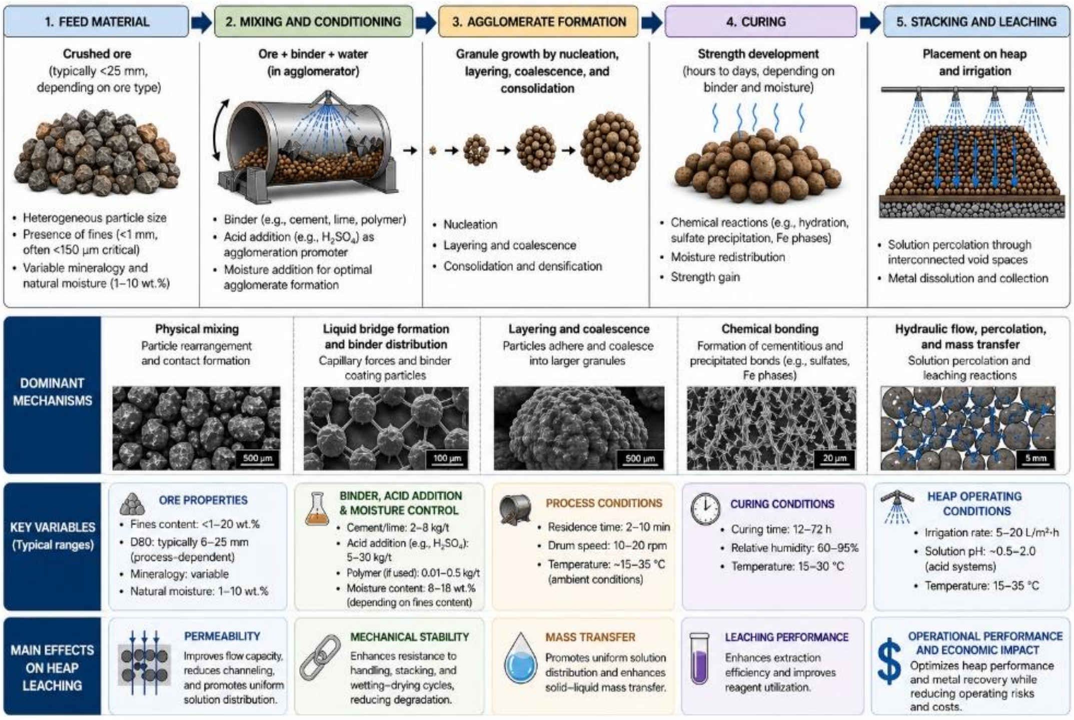


Figure 3. Schematic comparison of industrial agglomeration equipment, including drum agglomerators, disc pelletizers, and conveyor systems, highlighting differences in mixing intensity and residence time. Adapted from Cook and Scott (2025), Guzman et al. (2024), and Wang et al. (2024).

Figure 3 illustrates the relationship between equipment design and agglomeration efficiency. Drum systems provide higher residence time and mixing uniformity, which are critical for ores with high fines content. However, increased residence time also raises energy consumption and operational costs, typically in the range of 0.5–2.0 kWh/t depending on scale and material properties (Ghadiri, 2020).

A key challenge is the scale-up of agglomeration conditions from laboratory or pilot systems to industrial operations. Laboratory tests often operate under controlled conditions with uniform feed and moisture distribution, whereas industrial systems are subject to variability in ore composition, temperature, and feed rate. This discrepancy can lead to significant differences in agglomerate quality and downstream performance.

These operational constraints highlight the importance of binder selection and chemical interactions, which are addressed in the following section.

Binder Selection and Agglomerate Chemistry

Binder selection is a central parameter in agglomeration, influencing both the mechanical strength of agglomerates and their chemical behavior during leaching. The most commonly used binders in heap leaching include sulfuric acid, Portland cement, lime, and polymeric additives, each with distinct mechanisms of action (Kiaei & Golpayegani, 2023; Yin et al., 2021).

Sulfuric acid is used in copper and nickel heap leaching at 5-50 kg/t to promote chemical bonding by dissolving mineral phases and precipitating secondary phases, thereby improving interparticle cohesion (Chen et al., 2020; Acquah et al., 2025). However, it also increases reagent consumption and may cause long-term pore blockage due to gypsum or iron precipitates (Thomas, 2021).

Cement and lime binders, typically used at 2–10 kg/t, provide mechanical strength through hydration reactions that form rigid bonds between particles. While effective in improving initial stability, these binders may reduce porosity and limit fluid flow if used excessively (Quezada et al., 2021).

Polymeric binders offer enhanced flexibility and resistance to mechanical degradation, particularly in systems with high fines content. However, their higher cost—often 2–5 times that of conventional binders—limits their widespread industrial application (Kiaei & Golpayegani, 2023).

To understand how binders influence agglomerate formation and performance, compare their bonding mechanisms and structural effects at the particle scale. Figure 4 shows the main binder interaction mechanisms, highlighting differences between chemical, mechanical, and physicochemical bonding.

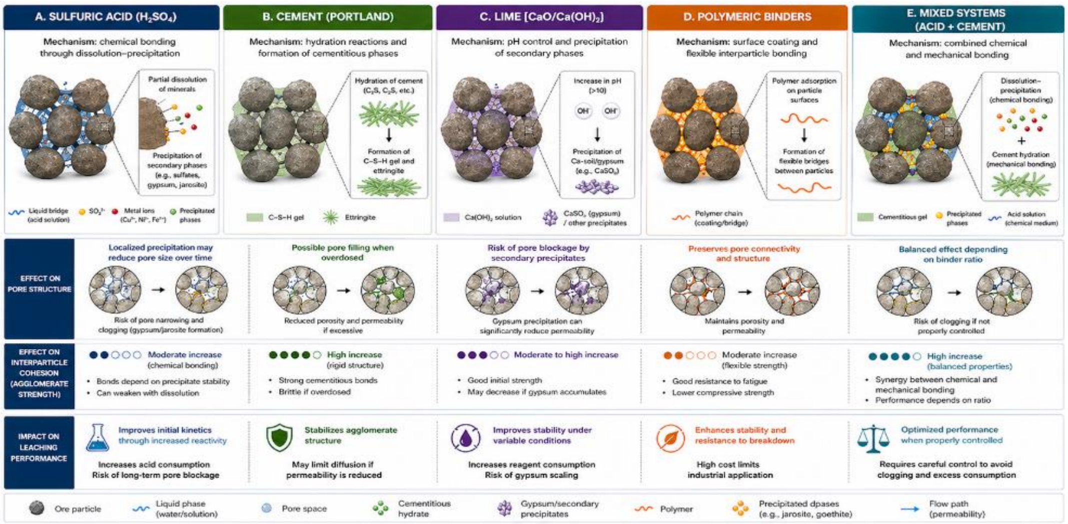


Figure 4. Schematic representation of binder interaction mechanisms in agglomeration, including acid-induced precipitation, cement hydration, polymer coating, and mixed bonding systems, and their effects on pore structure and interparticle cohesion. Adapted from Chen et al. (2020), Kiaei and Golpayegani (2023), Yin et al. (2021), and Thomas (2021).

Figure 4 shows binder performance depends on both interparticle bonding and pore structure. Acid binders improve cohesion via precipitation but can reduce permeability. Polymeric binders create uniform coatings, maintaining pore connectivity and lower rigidity.

Cementitious binders generate rigid frameworks via hydration reactions, significantly increasing compressive strength; however, excessive formation of solid phases can restrict pore space and limit fluid flow. Mixed binder systems seek to balance these effects, although their performance remains highly sensitive to dosage ratios and ore characteristics.

These observations highlight that binder selection cannot rely solely on initial strength metrics. Instead, it must account for the evolution of pore structure and transport properties during leaching, which ultimately governs permeability and reaction kinetics. In this context, Table 2 compares the main binder types, their typical dosages, bonding mechanisms, and their combined effects on agglomerate strength and leaching performance.

Table 2. Comparison of binder types, typical dosages, mechanisms, and impact on agglomerate strength and leaching performance. Adapted from Kiaei and Golpayegani (2023), Yin et al. (2021), Chen et al. (2020), and Thomas (2021).

Binder Type	Typical Dosage (kg/t)	Bonding Mechanism	Effecton Agglomerate Strength	Impacton Permeability	Impacton Leaching Performance
Sulfuric acid (H_2SO_4)	5–50	Partial dissolution + precipitation (e.g., sulfates)	Moderate increase (chemical bonding)	May decrease over time due to precipitation	Improves initial kinetics; increases acid consumption
Cement (Portland)	2–10	Hydration → formation of cementitious phases	High increase (rigid structure)	Can reduce porosity if overdosed	Stabilizes structure; may limit diffusion
Lime ($CaO/Ca(OH)_2$)	2–8	pH control + precipitation of secondary phases	Moderate to high	Risk of pore blockage ($CaSO_4$ formation)	Improves stability; increases reagent consumption
Polymeric binders	0.5–5	Surface coating + flexible interparticle bonding	Moderate (flexible strength)	Generally preserves porosity	Enhances stability; high cost limits use
Geopolymer-based binders	5–20	Aluminosilicate network formation	High (strong chemical bonding)	May reduce permeability if dense	Improves strength and bioleaching stability
Mixed systems (acid + cement)	5–30 (combined)	Combined chemical + mechanical bonding	High (balanced properties)	Depends on ratio; risk of clogging	Optimized performance if controlled

Table 2 highlights the trade-offs associated with binder selection. Acid-based systems enhance chemical reactivity but increase consumption, while cement-based systems improve mechanical stability at the expense of permeability. Polymeric binders provide a balance but introduce economic constraints.

A critical gap in the literature is the limited consideration of binder evolution during leaching. Many studies assume that binder effects remain constant, whereas in practice, chemical reactions, dissolution, and precipitation can significantly alter agglomerate structure over time. This dynamic behavior links binder chemistry to both permeability and kinetics, reinforcing the need for integrated evaluation.

The next section examines how agglomerate quality evolves during curing and aging, bridging the gap between initial formation and long-term performance.

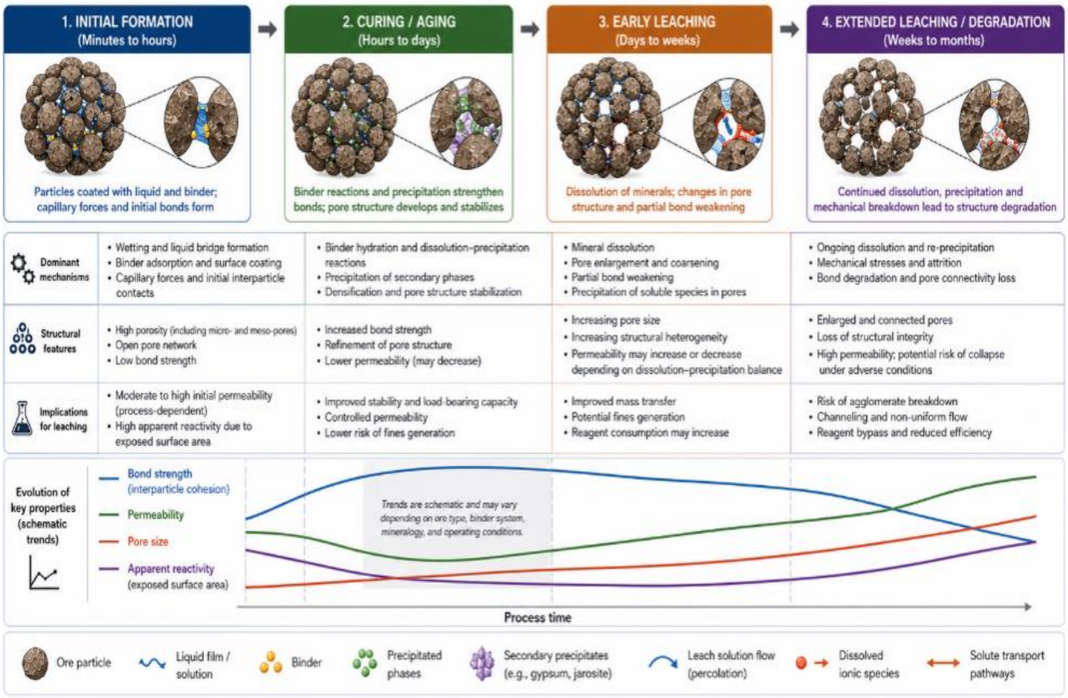
Agglomerate Quality, Curing, and Aging

Agglomerate quality is commonly assessed using initial metrics such as particle size distribution (typically 5–25 mm), compressive strength (50–300 kPa), and resistance to water-induced degradation. While these parameters are useful for process control, they do not adequately capture the time-dependent evolution of agglomerate structure under leaching conditions (Quezada et al., 2021; Salinas-Farran & Neethling, 2023).

Curing stabilizes agglomerates before stacking, lasting 12-72 hours for moisture and chemical reactions. Acid systems benefit from sulfation and secondary phase precipitation, improving bonding. Cement systems see hydration form rigid networks, increasing strength (Chen et al., 2021; Gao et al., 2021).

However, these strengthening mechanisms are not permanent. During leaching, agglomerates undergo wetting–drying cycles, chemical attack, and mechanical stress, causing degradation. Key processes include binder dissolution, fines liberation, and structural collapse, reducing permeability over time (Erskine et al., 2024; Wang et al., 2023).

Agglomerate properties change during curing and leaching due to mechanical, chemical, and hydraulic processes like binder reactions, mineral dissolution, and fines migration (Chen et al., 2021; Salinas-Farran & Neethling, 2023). Figure 5 shows the evolution from formation to long-term degradation.



	1. INITIAL FORMATION (Minutes to hours)	2. CURING / AGING (Hours to days)	3. EARLY LEACHING (Days to weeks)	4. EXTENDED LEACHING / DEGRADATION (Weeks to months)
	Particles coated with liquid and binder; capillary forces and initial bonds form	Binder reactions and precipitation strengthen bonds; pore structure develops and stabilizes	Dissolution of minerals; changes in pore structure and partial bond weakening	Continued dissolution, precipitation and mechanical breakdown lead to structure degradation
Dominant mechanisms	• Wetting and liquid bridge formation • Binder adsorption and surface coating • Capillary forces and initial interparticle contacts	• Binder hydration and dissolution-precipitation reactions • Precipitation of secondary phases • Densification and pore structure stabilization	• Mineral dissolution • Pore enlargement and coarsening • Partial bond weakening • Precipitation of soluble species in pores	• Ongoing dissolution and re-precipitation • Mechanical stresses and attrition • Bond degradation and pore connectivity loss
Structural features	• High porosity (including micro- and meso-pores) • Open pore network • Low bond strength	• Increased bond strength • Refinement of pore structure • Lower permeability (may decrease)	• Increasing pore size • Increasing structural heterogeneity • Permeability may increase or decrease depending on dissolution–precipitation balance	• Enlarged and connected pores • Loss of structural integrity • High permeability; potential risk of collapse under adverse conditions
Implications for leaching	• Moderate to high initial permeability (process-dependent) • High apparent reactivity due to exposed surface area	• Improved stability and load-bearing capacity • Controlled permeability • Lower risk of fines generation	• Improved mass transfer • Potential fines generation • Reagent consumption may increase	• Risk of agglomerate breakdown • Channeling and non-uniform flow • Reagent bypass and reduced efficiency

Figure 5. Time-dependent evolution of agglomerate structure, showing transitions from initial formation to curing and subsequent degradation during leaching. Adapted from Chen et al. (2021), Salinas-Farran and Neethling (2023), and Erskine et al. (2024).

Figure 5 illustrates the dynamic nature of agglomerates. Initial strength gains during curing are often offset by long-term degradation mechanisms, which are rarely captured in laboratory tests.

Agglomerate quality is typically evaluated using a combination of physical and mechanical parameters that define both initial performance and long-term stability. These parameters include granule size, compressive strength, curing time, and indicators of structural degradation during leaching. Table 3 summarizes the typical ranges of these agglomerate quality parameters and their implications for heap performance.

Table 3. Typical ranges of agglomerate quality parameters, including size, strength, curing time, and degradation indicators. Adapted from Quezada et al. (2021), Gao et al. (2021), and Wang et al. (2023).

Parameter	Typical Range	Measurement Method	Effect on Performance	Critical Limitations
Granule size	5–25 mm	Sieve analysis	Controls permeability and flow uniformity	Oversized granules → poor packing; undersized → clogging
Compressive strength	50–300 kPa	Compression test	Determines resistance to stacking and handling	High strength may reduce porosity
Tensile strength	5–50 kPa	Indirect tensile test	Indicates cohesion between particles	Sensitive to moisture and binder type
Curing time	12–72 h	Controlled curing tests	Enhances bond formation and stability	Insufficient curing → weak structure
Moisture content (during agglomeration)	8–15 wt.%	Gravimetric	Enables capillary bonding and particle adhesion	Excess moisture → segregation; low moisture → weak bonding
Permeability (initial)	10^{-11}–10^{-9} m²	Column permeability test	Governs fluid flow and leaching efficiency	Declines over time due to degradation
Permeability loss (long-term)	30–70% reduction	Long-term column tests	Indicates structural degradation	Rarely captured in lab tests
Fines generation (during leaching)	5–20 wt.% increase	Particle size analysis	Leads to pore clogging and flow heterogeneity	Strongly time-dependent
Binder durability	System-dependent	Chemical stability tests	Controls long-term cohesion	Dissolution/precipitation alters structure
Porosity evolution	±10–30% change	Imaging (µCT, SEM)	Affects permeability and diffusion	Highly heterogeneous

Table 3 highlights that while initial compressive strength may increase by 50–200% during curing, permeability can decrease by up to one order of magnitude over extended leaching due to structural degradation. This discrepancy underscores a critical limitation in current evaluation methods.

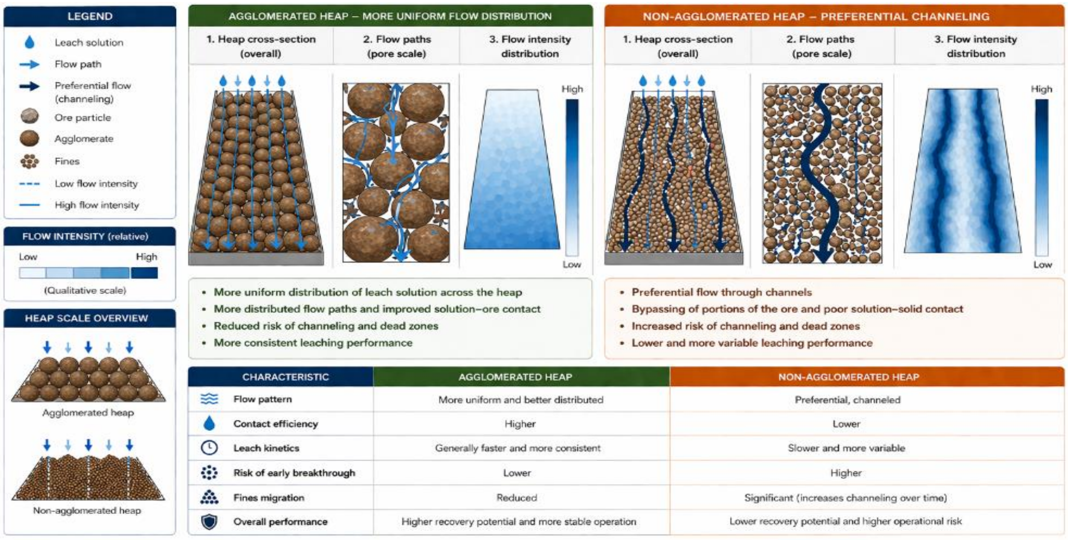
These findings establish that agglomerate quality is not a static property but a dynamic variable that evolves under operational conditions. This evolution directly impacts hydraulic behavior, which is examined in the next section.

Hydraulic Behavior: Permeability and Flow Distribution

The primary objective of agglomeration is to improve permeability and ensure uniform flow distribution within the heap. In non-agglomerated systems, fines migrate into pore spaces, reducing permeability to values as low as 10^{-12} m² and promoting channelized flow (Karimova & Kairalapov, 2022; Robertson et al., 2022).

Agglomeration can increase permeability by one to two orders of magnitude, typically reaching values between 10^{-11} and 10^{-9} m². However, this improvement is not uniform across the heap. Spatial variations in agglomerate quality, packing density, and moisture distribution lead to heterogeneous flow patterns, including preferential pathways that bypass large portions of the ore (Fernando et al., 2020; Wang et al., 2020).

Flow distribution within the heap affects leaching efficiency by controlling contact between solution and mineral surfaces. Even with improved initial permeability, heterogeneity can develop due to structural changes and fines migration (Fernando et al., 2020; Robertson et al., 2024). Figure 6 shows flow patterns in agglomerated and non-agglomerated systems, illustrating the shift from uniform flow to channeling and its impact on heap performance.



- More uniform distribution of leach solution across the heap
- More distributed flow paths and improved solution–ore contact
- Reduced risk of channeling and dead zones
- More consistent leaching performance

- Preferential flow through channels
- Bypassing of portions of the ore and poor solution–solid contact
- Increased risk of channeling and dead zones
- Lower and more variable leaching performance

CHARACTERISTIC	AGGLOMERATED HEAP	NON-AGGLOMERATED HEAP
Flow pattern	More uniform and better distributed	Preferential, channeled
Contact efficiency	Higher	Lower
Leach kinetics	Generally faster and more consistent	Slower and more variable
Risk of early breakthrough	Lower	Higher
Fines migration	Reduced	Significant (increases channeling over time)
Overall performance	Higher recovery potential and more stable operation	Lower recovery potential and higher operational risk

Figure 6. Flow distribution patterns in agglomerated and non-agglomerated heaps, illustrating uniform flow versus preferential channeling. Adapted from Fernando et al. (2020), Wang et al. (2020), and Robertson et al. (2024).

Figure 5 demonstrates that even in agglomerated systems, preferential flow can develop over time due to structural changes and fines migration.

Hydrodynamic hysteresis further complicates flow behavior. During wetting and drying cycles, pore structures reorganize, leading to irreversible changes in permeability. This effect is particularly pronounced in systems with high fines content or reactive mineral phases (Wang et al., 2022; Erskine et al., 2024).

Permeability and flow change with agglomerate structure, conditions, and time. Initially, agglomeration boosts hydraulic performance, but long-term trends are influenced by degradation, fines migration, and precipitation. Table 4 shows permeability ranges and flow traits for various agglomerated and non-agglomerated systems, highlighting their impact on leaching.

Table 4. Permeability ranges and flow characteristics for agglomerated and non-agglomerated systems under different operating conditions. Adapted from Robertson et al. (2022), Wang et al. (2022), and Fernando et al. (2020).

System Condition	Permeability (m^2)	Flow Pattern	Contact Efficiency	Risk of Channeling	Leaching Performance
Non-agglomerated (initial)	10^{-12} – 10^{-11}	Heterogeneous	Low to moderate	High	Low recovery, unstable kinetics
Agglomerated (initial)	10^{-11} – 10^{-9}	Relatively uniform	High	Low	Improved recovery and kinetics
Agglomerated (short-term operation)	10^{-11} – 10^{-10}	Moderately uniform	Moderate to high	Increasing	Stable but beginning of heterogeneity
Agglomerated (long-term operation)	10^{-12} – 10^{-10}	Heterogeneous	Moderate to low	Moderate to high	Declining recovery efficiency
Degraded structure (advanced stage)	$<10^{-12}$	Channelized	Low	Very high	Poorrecovery, high variability
Over-agglomerated (excess binder)	10^{-12} – 10^{-10}	Restricted flow	Low to moderate	Low (but clogging)	Limited kinetics due to diffusion constraints

Table 4 shows that while initial permeability improvements are significant, long-term values may decline by 30–70% due to structural evolution. This decline is often not accounted for in design calculations, leading to overestimation of heap performance.

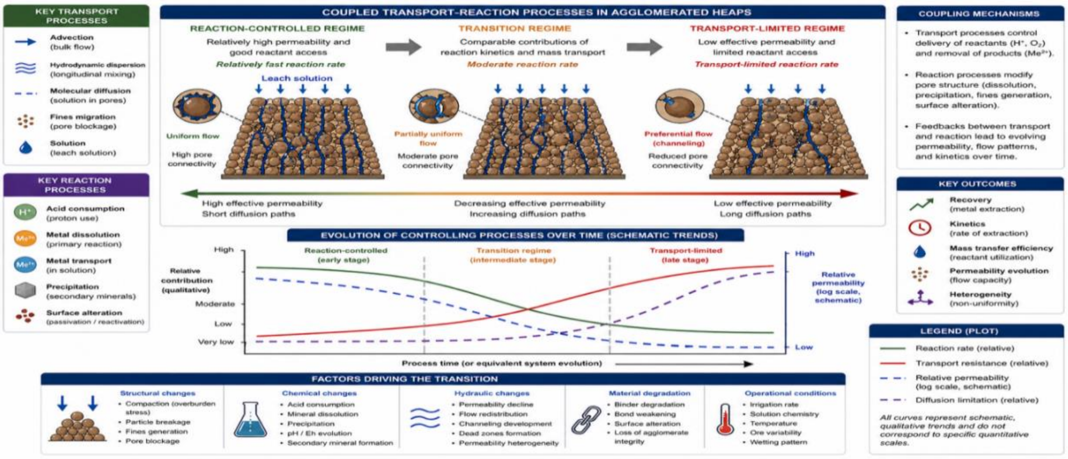
The hydraulic behavior of the heap directly influences mass transport and reaction kinetics. Therefore, understanding the coupling between flow and chemical processes is essential, as discussed in the following section.

Coupling With Leaching Kinetics and Transport

Leaching kinetics in heap systems are often interpreted as intrinsic reaction rates. However, in agglomerated systems, the observed kinetics are strongly influenced by transport limitations, including diffusion within agglomerates and convective flow through the heap (Faraji et al., 2022; Saldaña et al., 2022).

Agglomeration boosts solid–liquid contact by increasing surface access and permeability, improving initial leaching rates. But as structure changes, transport limits dominate, shifting from reaction to diffusion control (Li et al., 2022; Jia et al., 2024).

Leaching in agglomerated heaps depends on transport and reaction kinetics, which change over time as the internal structure evolves. Initially, high permeability allows good reactant access, favoring reaction-controlled conditions. However, structural changes from fines migration, precipitation, and binder degradation can shift the system toward transport limitation (Faraji et al., 2022; Saldaña et al., 2022). Figure 7 shows a model of these coupled processes, illustrating the shift from reaction-controlled to transport-limited regimes as the system evolves.



- Transport processes control delivery of reactants (H^+, O_2) and removal of products (Me^{2+}).
- Reaction processes modify pore structure (dissolution, precipitation, fines generation, surface alteration).
- Feedbacks between transport and reaction lead to evolving permeability, flow patterns, and kinetics over time.

Structural changes
- Compaction (overburden stress)
- Particle breakage
- Fines generation
- Pore blockage

Chemical changes
- Acid consumption
- Mineral dissolution
- Precipitation
- pH / Eh evolution
- Secondary mineral formation

Hydraulic changes
- Permeability decline
- Flow redistribution
- Channeling development
- Dead zones formation
- Permeability heterogeneity

Material degradation
- Binder degradation
- Bond weakening
- Surface alteration
- Loss of agglomerate integrity

Operational conditions
- Irrigation rate
- Solution chemistry
- Temperature
- Ore variability
- Wetting pattern

All curves represent schematic, qualitative trends and do not correspond to specific quantitative scales.

Figure 7. Conceptual model of coupled transport–reaction processes in agglomerated heaps, showing transitions from reaction-controlled to transport-limited regimes. Adapted from Faraji et al. (2022), Saldaña et al. (2022), and Jia et al. (2024).

Figure 7 highlights that the apparent kinetics observed in column tests are system-dependent and cannot be directly extrapolated to industrial heaps.

A critical issue is how binder dosage affects transport properties. Excess binder reduces porosity, creates diffusion barriers, and slows reactions. Insufficient binder causes structural instability and permeability loss (Yin & Chen, 2021).

Leaching kinetics in agglomerated systems depend on chemical reactions and transport, influenced by parameters like binder dosage, permeability, and pore structure. These determine if the process is reaction-controlled or transport-limited. Table 5 summarizes these effects.

Table 5. Influence of agglomeration parameters on leaching kinetics and transport limitations, including binder dosage, permeability, and dominant rate-controlling mechanisms. Adapted from Faraji et al. (2022), Yin and Chen (2021), and Li et al. (2022).

Parameter	Typical Range	EffectonTransport	Effect on Kinetics	Dominant Control Regime	Performance Implications
Binder dosage (low)	<5–10 kg/t	High porosity; unstable structure	High initial rates; poor stability	Reaction-controlled (initial)	Fast early leaching; risk of collapse and channeling
Binder dosage (optimal)	10–40 kg/t	Balance dpermeability and stability	Sustained leaching rates	Mixed control (reaction + transport)	High recovery; stable performance
Binder dosage (high)	>40–60 kg/t	Reduced porosity; diffusion barriers	Slower rates due to transport limitation	Transport-limited (diffusion-controlled)	Reduced recovery efficiency
Permeability (high)	$>10^{-9}$ m^2	Efficient convective transport	Reaction-limited behavior	Reaction-controlled	High leaching efficiency
Permeability (moderate)	10^{-11} – 10^{-9} m^2	Balanced transport conditions	Mixed kinetic behavior	Mixed control	Optimal performance window
Permeability (low)	$<10^{-12}$ m^2	Restricted flow; poor reagent access	Slow kinetics	Transport-limited	Low recovery; strong heterogeneity
Agglomerate size (small)	<5–10 mm	Short diffusion paths	Faster kinetics	Reaction-controlled	High initial recovery
Agglomerate size (large)	>20–30 mm	Longer diffusion paths	Slower kinetics	Diffusion-controlled	Reduced efficiency
Pore structure (connected)	High connectivity	Efficient mass transfer	Sustained reaction rates	Reaction-controlled	Uniform leaching
Pore structure (disconnected)	Low connectivity	Limited transport	Reduced kinetics	Transport-limited	Channeling and dead zones
Time (early stage)	Days	Minimal transport limitation	Rapid extraction	Reaction-controlled	High initial recovery
Time (long-term)	Weeks–months	Increasing transport resistance	Declining rates	Transport-limited	Reduced efficiency and plateau

Table 5 shows that optimal binder dosages balance mechanical stability and transport efficiency, typically within narrow operating windows. Deviations from these conditions can significantly impact recovery, often reducing overall extraction by 10–30% in poorly optimized systems.

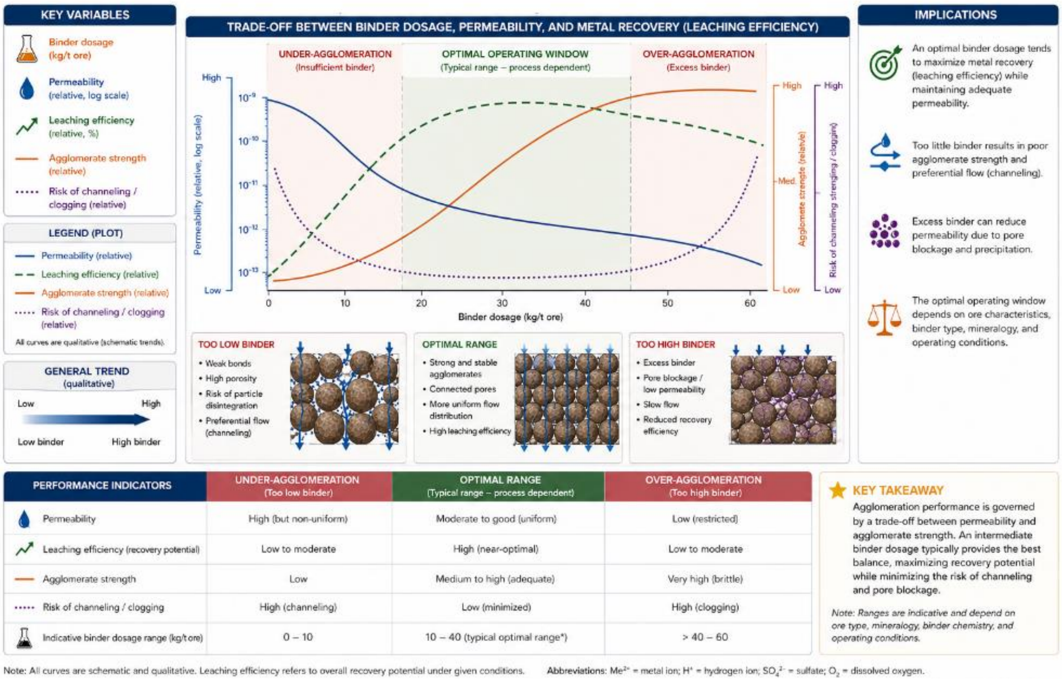
These results demonstrate that agglomeration, hydraulic behavior, and kinetics are intrinsically coupled. This coupling challenges the conventional separation of these phenomena in experimental studies and highlights the need for integrated approaches to process design and scale-up.

Reagent Consumption and Process Trade-Offs

Agglomeration involves a trade-off between reagent use and leaching efficiency. Binderssuch as sulfuric acid improve agglomerate formation and permeability but increase reagent demand. In copper and nickel heap leaching, acid use for agglomeration averages 5-50 kg/t, making up 20–40% of total acid depending on ore composition (Thomas, 2021; Araya et al., 2020).

This additional consumption should be weighed against potential improvements in metal recovery. Enhanced permeability and flow can boost recovery by 5–20%, especially in ores with high fines or poor permeability (Agatzini-Leonardou et al., 2021; Aghazadeh et al., 2025). However, excessive binder may cause pore blockage due to secondary-phase precipitation, reducing permeability and negating benefits (Sracek et al., 2024).

The relationship between binder dosage, permeability, and metal recovery is non-linear, showing trade-offs between stability and transport. More binder boosts strength but can reduce pore connectivity and fluid flow. Figure 8 shows this trade-off, with an optimal window balancing permeability, integrity, and leaching.



An optimal binder dosage tends to maximize metal recovery (leaching efficiency) while maintaining adequate permeability.

Too little binder results in poor agglomerate strength and preferential flow (channeling).

Excess binder can reduce permeability due to pore blockage and precipitation.

The optimal operating window depends on ore characteristics, binder type, mineralogy, and operating conditions.

PERFORMANCE INDICATORS	UNDER-AGGLOMERATION (Too low binder)	OPTIMAL RANGE (Typical range – process dependent)	OVER-AGGLOMERATION (Too high binder)
Permeability	High (but non-uniform)	Moderate to good (uniform)	Low (restricted)
Leaching efficiency (recovery potential)	Low to moderate	High (near-optimal)	Low to moderate
Agglomerate strength	Low	Medium to high (adequate)	Very high (brittle)
Risk of channeling / clogging	High (channeling)	Low (minimized)	High (clogging)
Indicative binder dosage range (kg/t ore)	0 – 10	10 – 40 (typical optimal range*)	> 40 – 60

KEY TAKEAWAY

Agglomeration performance is governed by a trade-off between permeability and agglomerate strength. An intermediate binder dosage typically provides the best balance, maximizing recovery potential while minimizing the risk of channeling and pore blockage.

Note: Ranges are indicative and depend on ore type, mineralogy, binder chemistry, and operating conditions.

Note: All curves are schematic and qualitative. Leaching efficiency refers to overall recovery potential under given conditions. Abbreviations: Me^{2+} = metal ion; H^+ = hydrogen ion; SO_4^{2-} = sulfate; O_2 = dissolved oxygen.

Figure 8. Trade-off between binder dosage, permeability, and metal recovery, illustrating optimal operating window for agglomeration. Adapted from Thomas (2021), Araya et al. (2020), and Sracek et al. (2024).

Figure 8 shows that optimal binder dosage lies within a narrow range, beyond which diminishing returns and adverse effects occur. This non-linear behavior is often overlooked in design practices.

Reagent use in agglomeration impacts metal recovery and process efficiency. Binder, especially sulfuric acid, improves permeability and leaching but raises costs and can cause secondary issues like precipitation and pore blockage. Table 6 compares reagent consumption and recovery for various strategies, showing the trade-offs.

Table 6. Comparative analysis of reagent consumption and recovery gains for different agglomeration strategies. Adapted from Agatzini-Leonardou et al. (2021), Aghazadeh et al. (2025), and Araya et al. (2020).

Agglomeration Strategy	Binder Type	Dosage (kg/t)	Additional Reagent Consumption (%)	Recovery Gain (%)	Net Process Impact	Key Limitations
No agglomeration	None	0	0	Baseline	Low cost, poor hydraulic performance	High channeling; low recovery
Low acid addition	H_2SO_4	5–10	+5–10%	+5–10%	Improved initial kinetics	Limited structural stability
Optimal acid agglomeration	H_2SO_4	10–40	+10–25%	+10–20%	Best balance between cost and recovery	Sensitive to ore variability
High acid addition	H_2SO_4	>40–60	+25–50%	+5–10% (diminishing returns)	Increased cost; marginal benefit	Precipitation and poreclogging
Cement-based agglomeration	Cement	2–10	+5–15%	+8–15%	Improved mechanical stability	Reduced permeability if overdosed
Mixed binder system	Acid + cement	10–30 (combined)	+15–30%	+15–25%	High recovery and stability	Complex optimization
Polymeric binder system	Polymer	0.5–5	+10–20% (high cost basis)	+10–20%	Enhanced stability, especially for fines	High cost limits application
Geopolymer-based system	Geopolymer	5–20	+15–25%	+15–25%	Strong structure; stable bioleaching	Risk of permeability reduction

Table 6 highlights that while increased acid consumption may improve short-term kinetics, long-term efficiency depends on maintaining permeability and avoiding precipitation-driven clogging.

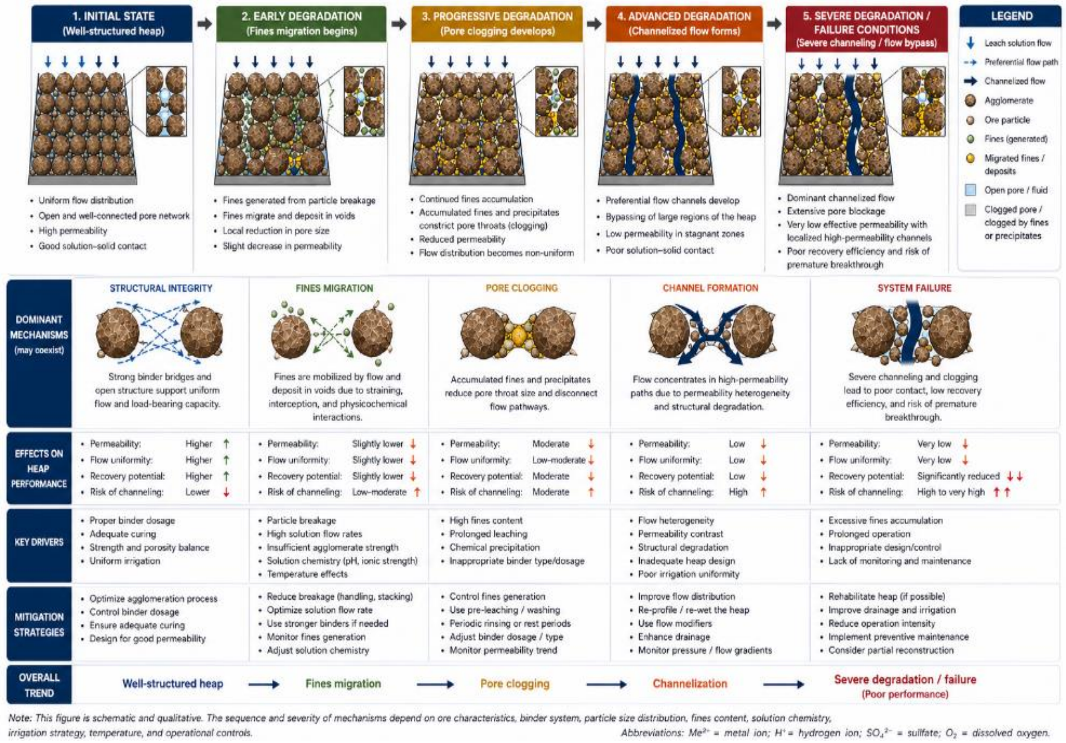
This trade-off links chemical consumption to hydraulic performance, reinforcing the need for integrated optimization rather than isolated parameter tuning. These interactions become even more critical when considering failure mechanisms at scale.

Failure Mechanisms and Scale-Up Limitations

Agglomerated systems are inherently unstable over long operational periods due to mechanical, chemical, and hydraulic degradation processes. The most common failure mechanisms include agglomerate disintegration, fines migration, pore clogging, and structural collapse. These processes are driven by cyclic wetting, chemical reactions, and mechanical loading within the heap (Ghadiri et al., 2020; Shumilova et al., 2021).

Fines migration is particularly critical, as liberated particles accumulate in pore spaces, progressively reducing permeability. This effect can lead to localized flow channeling, where solution bypasses large regions of the heap, reducing effective contact area and metal recovery (Robertson et al., 2024).

Agglomerated heaps degrade structurally during operation through mechanical, hydraulic, and chemical processes like fines migration, pore clogging, and flow path development, leading to permeability and flow changes over time (Robertson et al., 2024; Ghadiri et al., 2020). Figure 9 illustrates this transition from a well-structured system to channeling and flow bypass.



	STRUCTURAL INTEGRITY	FINES MIGRATION	PORE CLOGGING	CHANNEL FORMATION	SYSTEM FAILURE
DOMINANT MECHANISMS (may coexist)	Strong binder bridges and open structure support uniform flow and load-bearing capacity.	Fines are mobilized by flow and deposit in voids due to straining, interception, and physicochemical interactions.	Accumulated fines and precipitates reduce pore throat size and disconnect flow pathways.	Flow concentrates in high-permeability paths due to permeability heterogeneity and structural degradation.	Severe channeling and clogging lead to poor contact, low recovery efficiency, and risk of premature breakthrough.
EFFECTS ON HEAP PERFORMANCE	• Permeability: Higher ↑ • Flow uniformity: Higher ↑ • Recovery potential: Higher ↑ • Risk of channeling: Lower ↓	• Permeability: Slightly lower ↓ • Flow uniformity: Slightly lower ↓ • Recovery potential: Slightly lower ↓ • Risk of channeling: Low-moderate ↑	• Permeability: Moderate ↓ • Flow uniformity: Low-moderate ↓ • Recovery potential: Moderate ↓ • Risk of channeling: Moderate ↑	• Permeability: Low ↓ • Flow uniformity: Low ↓ • Recovery potential: Low ↓ • Risk of channeling: High ↑	• Permeability: Very low ↓ • Flow uniformity: Very low ↓ • Recovery potential: Significantly reduced ↓↓ • Risk of channeling: High to very high ↑↑
KEY DRIVERS	• Proper binder dosage • Adequate curing • Strength and porosity balance • Uniform irrigation	• Particle breakage • High solution flow rates • Insufficient agglomerate strength • Solution chemistry (pH, ionic strength) • Temperature effects	• High fines content • Prolonged leaching • Chemical precipitation • Inappropriate binder type/dosage	• Flow heterogeneity • Permeability contrast • Structural degradation • Inadequate heap design • Poor irrigation uniformity	• Excessive fines accumulation • Prolonged operation • Inappropriate design/control • Lack of monitoring and maintenance
MITIGATION STRATEGIES	• Optimize agglomeration process • Control binder dosage • Ensure adequate curing • Design for good permeability	• Reduce breakage (handling, stacking) • Optimize solution flow rate • Use stronger binders if needed • Monitor fines generation • Adjust solution chemistry	• Control fines generation • Use pre-leaching / washing • Periodic rinsing or rest periods • Adjust binder dosage / type • Monitor permeability trend	• Improve flow distribution • Re-profile / re-wet the heap • Use flow modifiers • Enhance drainage • Monitor pressure / flow gradients	• Rehabilitate heap (if possible) • Improve drainage and irrigation • Reduce operation intensity • Implement preventive maintenance • Consider partial reconstruction
OVERALL TREND	Well-structured heap →	Fines migration →	Pore clogging →	Channelization →	Severe degradation / failure (Poor performance)

Note: This figure is schematic and qualitative. The sequence and severity of mechanisms depend on ore characteristics, binder system, particle size distribution, fines content, solution chemistry, irrigation strategy, temperature, and operational controls.

Abbreviations: Me^{2+} = metal ion; H^+ = hydrogen ion; SO_4^{2-} = sulfate; O_2 = dissolved oxygen.

Figure 9. Evolution of failure mechanisms in agglomerated heaps, including fines migration, pore clogging, and channelized flow development. Adapted from Robertson et al. (2024), Ghadiri et al. (2020), and Wang et al. (2022).

Figure 9 shows how uniform systems develop into heterogeneous structures with main flow paths.

Scale-up adds complexity. Lab and column tests are under controlled conditions with limited height and short durations. Industrial heaps, however, operate at 5–10 m or more for months to years, creating different stress, temperature, and chemical gradients (van Staden & Petersen, 2021; Pereira, 2026b).

A key limitation in assessing agglomeration is the difference between laboratory, pilot, and industrial conditions. Scale variances affect stress, flow, residence time, and chemical gradients, influencing agglomerate stability and failure. Table 7 compares these conditions and their effects on performance and degradation.

Table 7. Comparison of laboratory, pilot, and industrial conditions affecting agglomeration performance and failure mechanisms. Adapted from van Staden and Petersen (2021), Pereira (2026b), and Robertson et al. (2024).

Parameter	Laboratory Scale	Pilot Scale	Industrial Scale	Impact on Agglomeration Performance
Column/heap height	0.3–1.0 m	1–5 m	5–10+ m	Higher stress at industrial scale promotes compaction and degradation
Test duration	Days–weeks	Weeks–months	Months–years	Long-term effects (fines migration, clogging) only visible at larger scales
Stress conditions	Low (negligible overburden)	Moderate	High (overburden pressure)	Increased particle breakage and agglomerate collapse
Flow distribution	Uniform (controlled)	Semi-uniform	Highly heterogeneous	Channeling develops at larger scales
Irrigation control	Precisely controlled	Controlled	Variable (field conditions)	Uneven wetting affects agglomerate stability
Temperature variation	Minimal	Moderate	Significant (diurnal/seasonal)	Affects reaction rates and binder behavior
Chemical gradients	Limited	Moderate	Strong (pH, Eh, concentration)	Drives precipitation and structural changes
Permeability evolution	Often constant	Gradual decline	Strong decline over time	Not captured in short-term tests
Fines generation	Minimal	Moderate	Significant	Leads to pore clogging and channeling
Failure mechanisms observed	Rare	Partial	Fully developed	Only industrial scale captures full degradation sequence
Representativeness	Low	Moderate	High	Laboratory data often overestimates performance

Table 7 shows that stress conditions in industrial heaps can be an order of magnitude higher than in laboratory tests, accelerating agglomerate degradation and altering flow behavior. These discrepancies explain why laboratory results often overestimate heap performance.

These limitations highlight the need for scale-aware methodologies that integrate mechanical, chemical, and hydraulic factors. The final section synthesizes these insights into design principles and identifies critical gaps in current practice.

Integration with Heap Design, Best Practices, and Critical Synthesis

Agglomeration cannot be treated as an isolated operation; it must be integrated into the overall design and operation of heap leaching systems. Key interactions include irrigation strategy, stacking method, and compaction, all of which influence the evolution of permeability and flow distribution (Petersen & van Staden, 2025; Dreier, 2025).

Irrigation rates of 5–15 L/m²·h must match permeability to avoid ponding or channeling. Stacking methods impact compaction and stress, affecting agglomerate stability. Poor integration of these factors can negate agglomeration benefits, causing quick performance decline (Guzman et al., 2024; Cook & Scott, 2025).

Agglomeration's effects depend on hydraulic behavior, transport, and heap performance. Key design factors like irrigation, compaction, and heap shape interact with agglomerate structure, forming a complex system that changes over time (Petersen & van Staden, 2025; Guzman et al., 2024). Figure 10 shows a framework linking agglomeration, hydraulics, and heap design, emphasizing their interdependence and influence on performance.

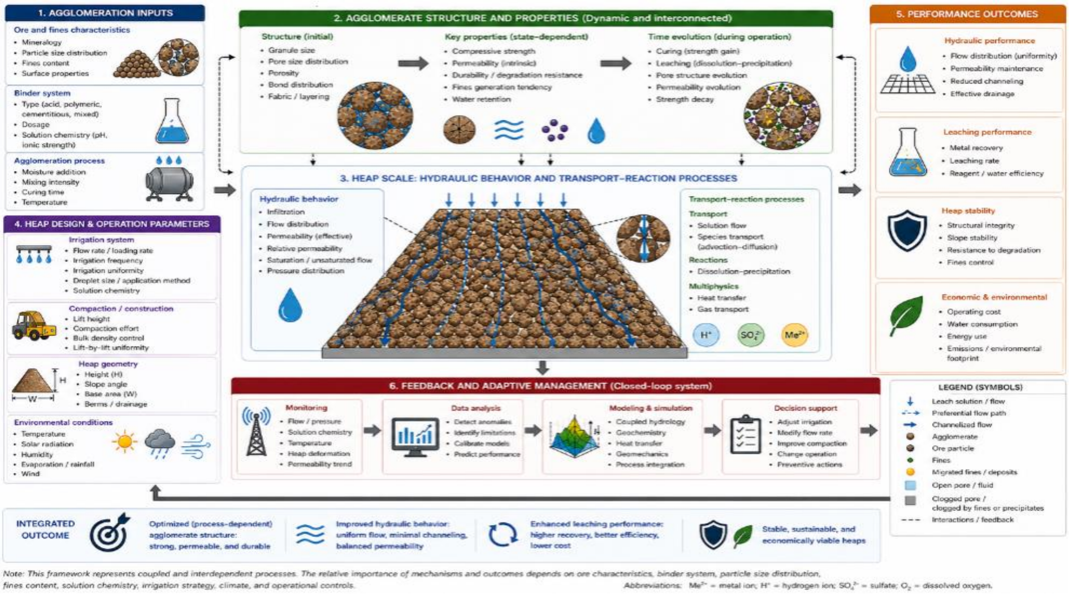


Figure 10. Integrated framework linking agglomeration, hydraulic behavior, and heap design parameters, including irrigation, compaction, and transport processes. Adapted from Petersen and van Staden (2025), Guzman et al. (2024), and Pereira (2026b).

Figure 10 shows how agglomeration and heap design depend on each other. Combining them requires controlling key parameters for stability and hydraulic performance, balancing strength, permeability, and reagent use within recommended ranges. Table 8 details best practices, ranges, and effects.

Table 8. Best practices for agglomeration and heap design, including operating ranges for moisture, binder dosage, curing time, and irrigation rates. Adapted from Cook and Scott (2025), Guzman et al. (2024), and Pereira (2026a).

Parameter	Recommended Range	Operational Objective	Effect on Performance	Risks if Deviated
Moisture content (agglomeration)	8–12 wt.%	Promote capillary bonding and uniform granule formation	Optimal agglomerate strength and permeability	Low → weak bonding; High → segregation and collapse
Binder dosage (acid)	10–40 kg/t	Ensure sufficient cohesion and chemical activation	Balanced permeability and recovery	Low → instability; High → pore clogging and excess consumption
Binder dosage (cement/lime)	2–10 kg/t	Improve mechanical stability	Increased strength and resistance to degradation	Excess → reduced porosity and flow restriction
Curing time	24–72 h	Allow bond development and structural stabilization	Improved durability and permeability control	Insufficient → weak agglomerates; Excess → operational delays
Agglomerate size	5–25 mm	Balance permeability and diffusion path length	Uniform flow and efficient leaching	Too small → clogging; Too large → diffusion limitation
Heap permeability (initial)	10^{-11} – 10^{-9} m^2	Ensure adequate fluid flow	High contact efficiency and recovery	Too low → channeling; Too high → poor distribution control
Irrigation rate	5–15 L/m^2·h	Maintain uniform wetting without ponding	Stable leaching kinetics and transport	Low → incomplete wetting; High → channeling and erosion
Lift eight (heap stacking)	4–8 m per lift	Control stress and compaction	Maintains structural integrity	Excess → agglomerate breakdown
Compaction control	Moderate (controlled stacking)	Maintain pore connectivity	Balanced permeability and stability	Over-compaction → permeability loss
Solution chemistry (pH, Eh)	System-dependent (e.g., pH <2 for Cu)	Optimize leaching reactions	Improved kinetics and recovery	Poor control → precipitation and clogging
Monitoring frequency	Continuous (flow, pH, recovery)	Detect performance deviations	Early identification of failure mechanisms	Lack of monitoring → delayed corrective actions

Table 8 consolidates recommended operating ranges, emphasizing the need for tight control of key parameters. For example, optimal moisture content typically lies between 8% and 12%, while curing times of at least 24 hours are required for stable agglomerates in most systems.

From a critical perspective, the literature consistently underestimates the role of time-dependent processes and over-relies on short-term laboratory data. Agglomeration is often evaluated based on initial conditions, ignoring the dynamic evolution of structure, permeability, and chemical composition during leaching.

The central conclusion of this review is that agglomeration is a controlling variable for heap leaching performance. Its effects extend beyond initial granule formation, governing hydraulic behavior, transport processes, and long-term system evolution. Future research must focus on integrated, multi-scale approaches that capture these interactions, rather than on simplified, isolated evaluations.

Conclusions

Agglomeration in heap leaching has traditionally been treated as a preparatory operation to improve particle-size distribution and initial permeability. This review demonstrates that such a perspective is fundamentally incomplete. Agglomeration is not a secondary step but a controlling variable that governs hydraulic behavior, transport processes, and long-term system evolution.

A central finding is that agglomerate performance cannot be adequately assessed using static metrics such as initial strength or short-term permeability. These parameters fail to capture the dynamic nature of agglomerated systems, which evolve continuously under chemical, hydraulic, and mechanical influences. Processes such as fines migration, binder dissolution, and precipitation-driven pore clogging progressively alter the internal structure of the heap, often leading to significant declines in permeability and recovery over time.

The literature reveals a persistent disconnect between laboratory evaluation and industrial performance. Most studies rely on short-duration tests conducted under controlled conditions, which systematically overestimate agglomerate stability and leaching efficiency. These approaches neglect key scale-dependent factors, including stress gradients, heterogeneous flow distribution, and long-term chemical interactions. As a result, direct extrapolation from laboratory data to industrial heaps remains unreliable.

Another critical issue is the lack of integration between agglomeration and overall heap design. Parameters such as binder dosage, moisture content, curing time, irrigation rate, and stacking method are often optimized independently, despite their strong interdependence. This fragmented approach limits process optimization and increases the risk of operational failure.

From a process perspective, agglomeration introduces unavoidable trade-offs. Increasing binder addition improves structural stability and permeability but increases reagent consumption and may induce secondary effects, such as pore blockage. Optimal performance is therefore achieved within narrow operating windows, which are highly sensitive to ore characteristics and operating conditions.

Future research must move beyond isolated studies and adopt integrated, multi-scale approaches that explicitly couple agglomeration, transport, and reaction phenomena. This includes the development of time-dependent models, improved experimental protocols that replicate industrial conditions, and systematic validation at pilot and full scale. Advanced characterization techniques, such as X-ray tomography and pore network modeling, offer significant potential for improving mechanistic understanding.

In conclusion, agglomeration should be recognized as a fundamental design variable in heap leaching systems. Its role extends beyond initial conditioning, directly controlling the evolution of permeability, flow distribution, and reaction kinetics. Failure to account for its dynamic and scale-dependent behavior remains a primary source of error in process design and performance prediction.

Declarations

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Conflicts of Interest / Competing Interests

The author declares no conflict of interest.

Availability of Data and Materials

No new data were generated or analyzed in this study. All information is derived from published literature and is properly cited.

Code Availability

Not applicable.

Authors’ Contributions

The author solely conceived the study, performed the literature review, developed the analysis, and wrote the manuscript.

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