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When Is Wet Mineral Agglomeration Truly Scaled Up? A Critical Review from Bench Tumbling Tests to Industrial Drums and Granulators

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ABSTRACT **Original Research Article**

Wet mineral agglomeration is routinely described as "scaled up" when a larger drum, disc, or granulator reproduces an acceptable mean granule size, or when laboratory conditions are converted through geometric or Froude-number similarity. That interpretation is too narrow for mineral systems in which feed particle-size distribution, fines content, mineralogy, pore structure, wetting kinetics, binder delivery, collision mechanics, breakage, and downstream bed hydrodynamics are strongly coupled. This structured critical review evaluates scale transfer from bench tumbling tests to pilot and industrial granulators, with emphasis on iron-ore sinter granulation and ore agglomeration for heap leaching. The evidence base comprises 83 sources: 78 contemporary publications from 2020–2026 and five foundational wet-granulation studies retained to anchor mechanistic scale-up concepts. Sources were retrospectively coded by primary evidence family and inferential role rather than treated as interchangeable evidence. The review shows that matching Froude number may preserve selected flow features while failing to preserve particle-to-equipment resolution, mixing and segregation kinetics, residence-time distributions, spray coverage, collision-force distributions, or specific power. Meaningful correspondence is nevertheless possible when feed state, moisture and binder delivery, filling, residence time, product structure, and downstream response are constrained together. True scale transfer is therefore formulated as a non-compensatory multivariable equivalence problem rather than an equipment-sizing exercise. The proposed AGG-SUVF (Agglomeration Scale-Up Validation Framework) uses six gates covering feed equivalence, wetting and binder distribution, kinematic/dynamic similarity, product-state equivalence, downstream functional equivalence, and uncertainty/robustness. It distinguishes insufficient evidence from demonstrated failure and separates conditionally transferable, functionally validated, and robustly scaled processes. The resulting framework defines the minimum evidence needed to make falsifiable scale-up claims while keeping industrial feasibility—throughput, energy, operability, and control authority—as a separate engineering requirement.

Keywords: Wet Mineral Agglomeration, Granulation, Scale-Up, Rotating Drum, Heap Leaching, Population Balance Modeling.

Highlights

- Scale-up should be demonstrated as non-compensatory equivalence of coupled product and downstream function, not inferred from equipment enlargement.
- Froude-number similarity is useful but insufficient without particle-resolution, RTD, wetting, collision, and specific-energy evidence.
- The 83-source evidence map shows strong mechanistic coverage but comparatively scarce direct paired-scale mineral validation.
- AGG-SUVF distinguishes insufficient evidence, failed transfer, conditional transfer, functional validation, and robust scale-up.

Graphical Abstract

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Introduction

Agglomeration and granulation are enabling operations rather than isolated particle-size-enlargement steps. In iron-ore sintering, granulation restructures a blend of ores, return fines, fluxes, and fuel into a permeable green bed whose size distribution, voidage, and mechanical behavior influence gas flow and sintering productivity. In heap leaching, agglomeration binds fines to coarser particles, modifies pore connectivity, reduces segregation, and seeks to maintain liquid and gas pathways under irrigation and self-weight. The scope of this review is therefore wet mineral agglomeration in which liquid-mediated bonding, deformation, breakage, and downstream transport are coupled; dry briquetting and thermal induration are outside the principal evidence boundary. Recent reviews place this operation at the intersection of particle adhesion, raw-material variability, equipment operation, and downstream process performance rather than treating it as a purely geometric enlargement step (Niu et al., 2023; Luo et al., 2026; L. Wang et al., 2021; Pereira, 2026a).

The difficulty is that this coupled function changes its meaning as the scale changes. A bench drum can be made geometrically similar to a larger unit, and the rotation speed can be adjusted to maintain the Froude number, yet the number of particles across the drum diameter, particle travel distance, axial mixing, segregation rate, collision-force distribution, residence-time distribution, liquid spray coverage, and specific power do not necessarily remain invariant. Rotating-drum scale-up studies show that mixing can deteriorate as drum size increases when particle size is held fixed, and that segregation kinetics and force distributions may change even when final patterns appear similar. These observations are especially important for mineral granulation because the feed itself is polydisperse and often contains an ultrafine fraction that controls liquid demand and deformation (Herman et al., 2022; He et al., 2024; Patil et al., 2022).

The opposite problem also occurs: a laboratory unit may reproduce industrial granule attributes under a tightly constrained set of conditions, leading to an apparently successful transfer that is then generalized beyond the tested window. A direct laboratory-commercial comparison in iron-ore sinter granulation reported representative granules when Froude number, space factor, residence time, and moisture were aligned. That result is valuable precisely because it is conditional. It demonstrates that scale correspondence can be achieved, but it also shows why "same Froude number" is not the complete explanation: moisture and material water-holding behavior were part of the correspondence. Industrial relevance therefore depends on preserving a set of coupled states rather than a single operating number (Aladejebi et al., 2023; Adam et al., 2025).

This review adopts that stricter interpretation and asks: when is wet mineral agglomeration truly scaled up? The proposed answer is that a scale-transfer claim is defensible only when the agglomeration function is preserved across scales within predefined acceptance limits and with uncertainty explicitly considered. Equipment similarity is one layer of evidence; it is not the endpoint. The required evidence spans feed state, wetting and binder distribution, agglomeration and breakage mechanisms, equipment kinematics, product structure, downstream response, and robustness to plant-relevant variability. Figure 1 introduces this performance-vector view and shows why the bench-to-pilot-to-industrial path must be evaluated vertically across scales and horizontally through the process chain.

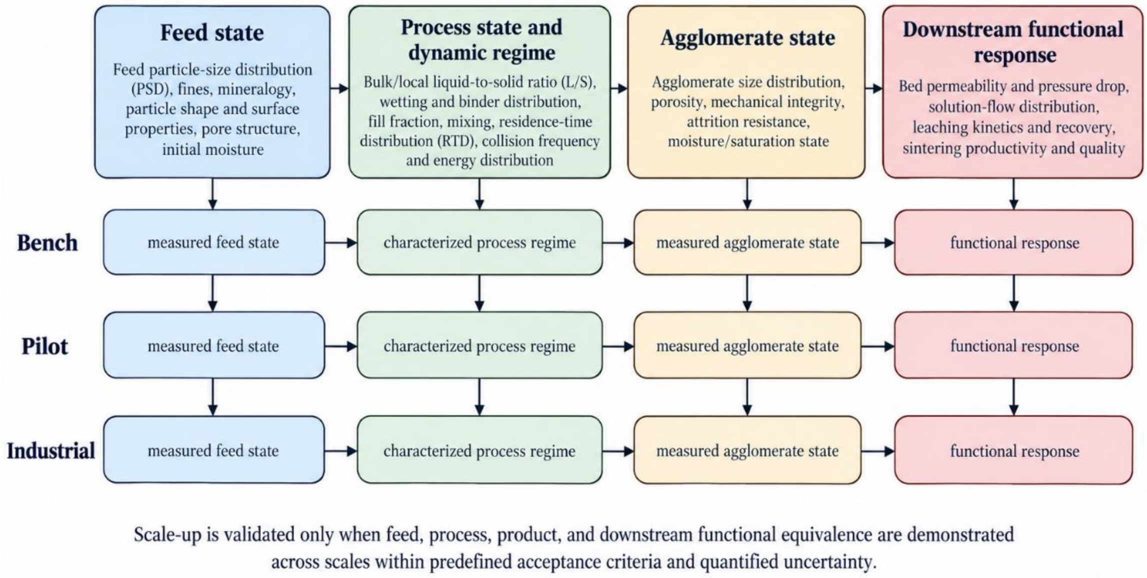

Figure 1. *True scale-up as preservation of a coupled performance vector*

Note. Author-developed conceptual synthesis based on scale-transfer principles discussed by Herman et al. (2022), He et al. (2024), van Staden and Petersen (2021), Niu et al. (2023), and Pereira (2026a). RTD = residence-time distribution; PSD = particle-size distribution.

Figure 1 changes the burden of proof for scale-up. A larger unit is not accepted because it processes more mass or reproduces one average particle size; rather, each scale must be shown to occupy an equivalent feed-process-product-function state within an explicitly defined operating window. This framing is compatible with heap-leach scale-up literature, where the transfer from columns to heaps requires hydrological and kinetic correspondence, and with newer industrial granulation work that connects raw-material preparation to permeability, sintering behavior, or leaching response (van Staden & Petersen, 2021; Guzman et al., 2024; Aladejebi, Mitra, Pinson, et al., 2025; Yi et al., 2025).

Review Methodology, Evidence Coding, and Scope Limitations

This article is a structured critical review built from an evidence base of 83 sources. Seventy-eight sources are contemporary publications from 2020–2026; five foundational studies published before 2020 were retained because they define mechanistic concepts—binder Stokes number, nucleation and growth regimes, and dimensionless spray flux—that remain directly relevant to scale-up reasoning. The original literature collection was not generated through a prospectively registered systematic-search protocol; therefore, the review is not presented as PRISMA-compliant. Rather than obscure that limitation, the review makes its analytical procedure explicit: each retained source was coded retrospectively by primary evidence family, scale-transfer role, application domain, and the type of inference it can legitimately support. The review question was not "which operating condition maximizes granule size?" but "which coupled states and responses must remain equivalent before a scale-transfer claim is justified?"

Eligibility and inferential coding

Sources were retained when they addressed at least one link in the scale-up causal chain: feed properties; wetting or binder delivery; nucleation, growth, coalescence, densification, breakage, or abrasion; drum/disc/high-shear kinematics; residence-time behavior; agglomerate structure or mechanical integrity; downstream permeability, leaching, or sintering response; paired-scale validation; or PBM/DEM/hybrid modeling relevant to transfer across scales. Mineral-specific evidence was given the greatest inferential weight for material behavior and downstream response. Generic rotating-drum studies were used to isolate scale-sensitive flow and segregation physics, while pharmaceutical or formulated-product granulation studies were used only for transferable modeling or dimensional concepts, not for mineral-specific parameter values. Foundational pre-2020 studies were included selectively where a mechanistic construct remains actively used in current granulation science (Ennis et al., 1991; Iveson et al., 2001a, 2001b; Litster et al., 2001; Hapgood et al., 2003).

Quantitative evidence map

For transparency, each source was assigned one primary inferential role so that counts are mutually exclusive rather than inflated by double counting. The 83-source corpus comprises 27 iron-ore sinter-granulation sources, 24 heap-leach or other mineral-agglomeration sources, 8 generic rotating-drum/particle-mechanics sources, and 24 PBM/DEM/hybrid or foundational wet-granulation sources. These counts describe the composition of this curated review corpus; they are not prevalence estimates for the entire literature. The map also reveals an important asymmetry: mechanistic, bench-scale, and modeling evidence is abundant relative to direct paired bench–pilot–industrial validation. The clearest paired mineral examples are therefore treated as high-value but narrow evidence rather than as universal scale laws.

Evidence hierarchy and review limitations

Evidence strength was judged by inferential proximity to the scale-up claim. Direct paired-scale mineral measurements were ranked above single-scale optimization studies for validating transfer, while mechanistic studies were used to explain why transfer might succeed or fail. Cross-sector models were considered structurally informative only when their assumptions were stated and their parameters were recognized as requiring mineral-specific re-identification. Because database-search provenance is incomplete, the review cannot claim exhaustive coverage; instead, it emphasizes transparent evidence roles, falsifiable claims, and explicit scope boundaries. This limitation is revisited in Section 12.6.

Four evidence families were distinguished. First, mineral-specific iron-ore granulation studies provide direct evidence on moisture, ultrafines, intensive mixing, drum and high-shear behavior, bed permeability, and sintering outcomes. Second, copper and other heap-leach agglomeration studies connect binders, curing, agglomerate microstructure, saturation, pore networks, permeability, and leaching response. Third, generic rotating-drum studies isolate scale effects on mixing, segregation, residence time, and particle mechanics. Fourth, PBM/DEM/hybrid and foundational wet-granulation studies provide transferable mathematical or dimensional tools—especially population balances, contact/collision descriptors, dimensionless spray flux, sensitivity analysis, surrogate modeling, and control—but are not treated as direct evidence that mineral-specific parameters can be transferred. Table 1 summarizes the evidence map and the inferential role assigned to each family.

Table 1. Evidence map and inferential roles used to evaluate wet mineral agglomeration scale-up

Evidence family	Primary scale-up question	Strength for this review	Main limitation
Iron-ore sinter granulation (n = 27)	Can feed preparation and granulator operation preserve granule PSD, voidage, strength, permeability, and sintering performance?	Direct mineral evidence across drums, high-shear granulators, ultrafine feeds, and pilot/industrial validation.	Many studies optimize a single ore blend or equipment configuration.
Heap-leach and other mineral agglomeration (n = 24)	Do agglomerates preserve permeability, pore connectivity, strength, curing response, and leaching function under larger beds?	Direct link between agglomerate structure and hydrometallurgical function.	Hydraulic behavior also depends on stacking, lift height, irrigation, and geomechanical loading.
Generic rotating drums/particle mechanics (n = 8)	Which kinematic and segregation variables remain similar as drum size changes?	Separates pure scale effects from mineral chemistry.	Often dry or simplified particle systems; wetting and binder physics may be absent.
PBM/DEM/hybrid + foundational wet-granulation concepts (n = 24)	How can growth, breakage, PSD, uncertainty, and real-time control be represented across scales?	Provides model structures, dimensional descriptors, calibration workflows, sensitivity tools, and coarse-graining strategies.	Cross-sector parameter values are not mineral parameters and require re-identification; foundational concepts do not by themselves validate industrial mineral transfer.

Note. Counts are mutually exclusive assignments by primary inferential role within the 83-source corpus. Author synthesis based on Niu et al. (2023), Larrabure et al. (2024), Singh et al. (2022), Baba et al. (2021), Robertson et al. (2022), and the foundational wet-granulation studies cited in Section 2.1.

Table 1 prevents evidence-category errors. A DEM–PBM paper can justify a coupling strategy, but it does not establish the capillary or breakage parameters of a particular ore. A column-to-heap study can justify the need for hydraulic similarity, but it does not determine optimum drum speed. Conversely, an industrial sinter-plant comparison provides highly relevant scale evidence but may be too blend-specific to establish a universal scale law. The review therefore privileges mechanistic consistency, paired-scale validation, and downstream response over the number of studies reporting a similar trend.

What Counts as True Agglomeration Scale-Up?

Scale ratio, similarity, and validation are different claims

Three claims are frequently conflated. A scale ratio is simply a comparison of geometric or throughput quantities. Dynamic similarity asserts that selected dimensionless or normalized variables are matched. Scale-up validation is more robust: it demonstrates that variables that control the intended process function remain within predefined acceptance margins. For rotating drums, the Froude number is a natural starting point because it compares centrifugal and gravitational accelerations, but Fr is only one member of a similarity set. Preserving it cannot guarantee equal mixing rates, segregation kinetics, particle-force distributions, residence-time structures, spray coverage, or specific energy when particle-to-equipment resolution and internal geometry change (Herman et al., 2022; He et al., 2024; Saghafian Larijani et al., 2026).

$$Fr = \omega^2 R / g$$

Here, ω is angular velocity, R is drum radius, and g is gravitational acceleration. If R increases while the physical particle-size distribution remains fixed, D/d increases even when Fr is held constant. In a polydisperse mineral feed, however, d is not a unique scalar. A defensible report should specify the chosen basis—for example, D/d50—together with distribution-aware values such as D/d10 and D/d90, or a coarse-nucleus ratio when nucleation on large particles is the controlling mechanism. Herman et al. showed that mixing performance can deteriorate with scale when particle diameter is held fixed, whereas greater similarity is observed when the drum-to-particle ratio is maintained. He et al. further showed that final segregation states can look similar while segregation rate, velocity distributions, contact-force distributions, and power per unit mass remain scale-dependent. These results make it unsafe to use a final visual bed pattern or a single Fr match as proof of full-scale equivalence (Herman et al., 2022; He et al., 2024).

The minimum similarity set for wet mineral granulation

For wet mineral systems, a defensible similarity set must include at least: drum or granulator kinematics; a distribution-aware D/d measure; fill or space factor; length-to-diameter ratio where axial transport matters; residence-time distribution rather than mean residence time alone; solids throughput and bed loading; liquid-to-solid ratio and liquid saturation relative to accessible pore volume; wetting and liquid-addition pattern; binder concentration and chemistry; specific power or energy where measurable; and a descriptor of the collision/coalescence/breakage regime. The exact set depends on the application, but variables controlling liquid bridge formation, particle deformation, impact damage, or downstream transport cannot be omitted merely because they are difficult to measure (Mahdavy et al., 2022; Adam et al., 2025; Luo et al., 2026; Urtubia & Suárez, 2020).

The need to separate mean residence time from its distribution is particularly important in continuous drums. Two units can have the same nominal mean residence time but different bypassing, axial dispersion, recirculation, or long-tail hold-up. Those differences change how long different particle classes experience wetting, layering, compression, and abrasion. Similarly, identical bulk moisture can conceal very different local saturation fields if spray coverage, ore water absorption, or fines segregation differs. Thus, scale-up should compare distributions and state heterogeneity where feasible, not only means (Mahdavy et al., 2022; Rudenko et al., 2025; Larrabure et al., 2024).

Beyond Froude number: dimensional groups and coupled time scales

Classical wet-granulation science provides a useful reminder that scale-up is governed by competing time and force scales rather than by geometry alone. Binder Stokes-type numbers compare collisional kinetic energy with viscous dissipation; deformation-based regime maps connect impact conditions with granule deformability and pore saturation; and dimensionless spray flux links liquid flow, powder flux, and droplet size to the likelihood that liquid addition is locally uniform. These descriptors were developed largely outside mineral processing, so their numerical boundaries should not be transferred uncritically to ores. Their value here is conceptual: they identify hidden similarity requirements that a Froude-only rule cannot represent (Ennis et al., 1991; Iveson et al., 2001a, 2001b; Litster et al., 2001; Hapgood et al., 2003).

A practical scale-up program should therefore distinguish quantities that can reasonably be matched from quantities that must instead be monitored and functionally validated. Fr, fill, spray configuration, and nominal liquid-to-solid ratio may be set by design; RTD, local saturation, collision distributions, granule strength, and downstream permeability may only be observable outcomes. The purpose of dimensional analysis is not to create a longer list of numbers to hold constant, but to expose which governing balances are liable to drift as size, throughput, and particle resolution change.

Table 2 translates these principles into a set of scale-up descriptors, preferred evidence, and dangerous surrogates. It does not prescribe universal numerical tolerances: acceptance margins should be defined from measurement uncertainty and downstream sensitivity. Instead, the table separates useful similarity descriptors from single-number surrogates that can create false confidence.

Table 2. Scale-up similarity descriptors, preferred evidence, and common false surrogates

Scale-up dimension	**Preferred evidence**	**Common surrogate**	**Why the surrogate can fail**
Kinematics	Fr plus flow-regime observation and velocity/trajectory data	Fr alone	Equivalent Fr can coexist with different D/d, velocity distributions, and force networks.
Particle resolution	D/d and PSD scaled against equipment geometry	Geometric equipment similarity	Particle size normally does not scale with equipment dimensions in real plants.
Solids hold-up	Fill/space factor and dynamic bed depth	Nominal volume fraction from design	Actual hold-up changes with throughput, slip, recycle, and residence time.
Residence time	RTD, bypass fraction, tailing, and mean time	Mean residence time only	Different RTDs expose particle classes to different growth and breakage histories.
Liquid state	Local liquid-to-solid ratio, moisture distribution, saturation	Bulk moisture wt%	Same bulk moisture can correspond to different water absorption and local saturation.
Binder delivery	Coverage, concentration, droplet distribution, mixing after addition	Total binder dosage	Total dose does not prove uniform contact with fines and nuclei.
Agglomerate mechanics	Strength, abrasion/fines generation, deformation under load	Green mean size	A weak or deformable agglomerate can have the correct size and still fail downstream.
Function	Permeability/flow plus leaching or sintering response	Granulation index alone	Granulation is performed to improve a downstream function, which can diverge at equal size.
Axial geometry	L/D, inclination, internals, and axial transport/RTD diagnostics	Diameter scaling alone	Length and internals control axial dispersion, hold-up, and spray exposure.
Specific energy/power	Specific power input or an experimentally justified energy proxy	Rotational speed alone	Equal speed or Fr can coexist with different force distributions and power per unit mass.
Liquid application	Spray width, droplet size, coverage and, where useful, dimensionless spray flux	Total liquid flow or wt% moisture	Equal dose does not guarantee equal nucleation-zone coverage or wetting time.
Collision/deformation regime	Velocity/contact-force statistics plus a Stokes- or deformation-type descriptor where justified	Mean granule size after tumbling	Different collision histories can produce the same size through different growth–breakage pathways.

Note. Author synthesis based on Herman et al. (2022), He et al. (2024), Mahdavy et al. (2022), Aladejebi et al. (2023), Robertson et al. (2022, 2023), L. Wang et al. (2023), Ennis et al. (1991), Litster et al. (2001), Iveson et al. (2001b), and Hapgood et al. (2003).

Table 2 makes a central critical point: the most convenient scale-up metric is rarely sufficient. Mean granule size, total binder dose, mean residence time, and Froude number compress distributions or coupled balances into scalars. Scale-up failures often emerge in the discarded information—fine-rich zones, poorly wetted particles, long RTD tails, fragile coarse agglomerates, altered collision-energy distributions, or preferential flow paths.

Figure 2 provides a graphical summary of this argument and identifies the similarity variables that should accompany Froude matching when a drum is enlarged.

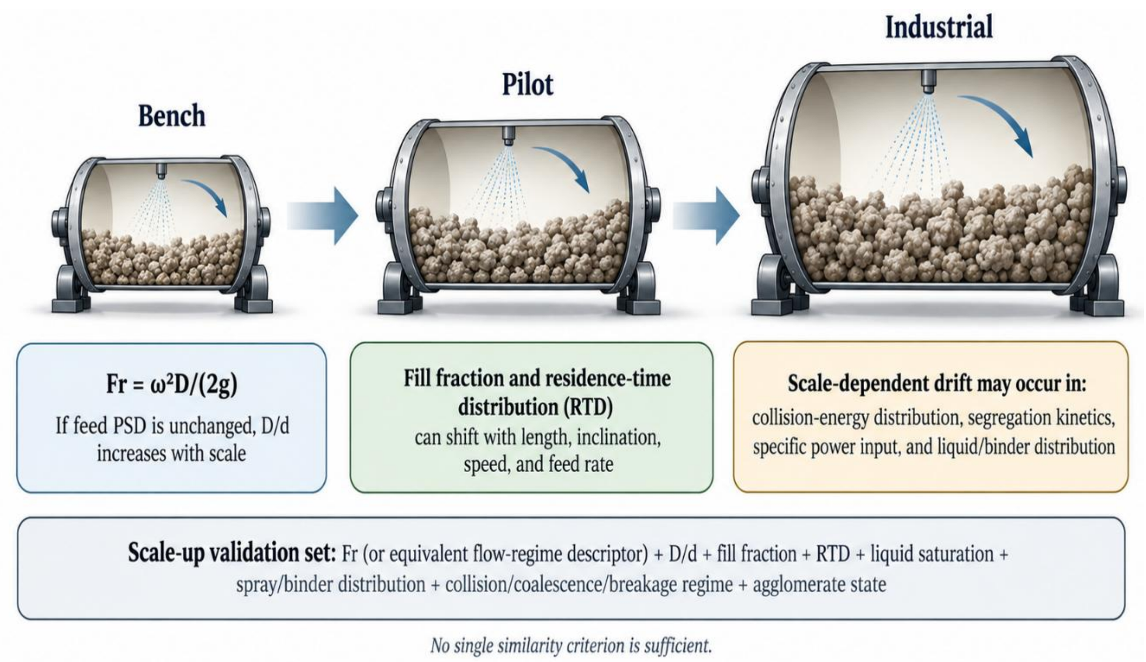

Figure 2. *Limits of geometric and Froude-number similarity during rotating-drum scale-up*

Note. Author-developed conceptual synthesis based on Herman et al. (2022), He et al. (2024), Aladejebi et al. (2023), Mahdavy et al. (2022), and Patil et al. (2022). Fr = Froude number; D/d = drum-diameter-to-particle-size ratio; RTD = residence-time distribution.

Figure 2 should be read as a hierarchy, not as an instruction to match every variable perfectly. Some variables will inevitably change with scale; the engineering task is to determine whether those changes materially alter the product or downstream function. A valid scale-up study therefore combines similarity analysis with response validation rather than replacing response validation with similarity analysis.

Feed PSD, Fines, Mineralogy, Moisture, and Surface Properties

Feed state is part of the scale-up boundary condition

A granulator does not receive "ore" as a single material property. It receives a population of particles with a PSD, shape distribution, mineral assemblage, surface roughness, pore structure, wettability, soluble salts, and pre-existing moisture history. These properties determine where added liquid goes and which particles can become nuclei. Studies on iron-ore mixtures show that changes in specific surface and ultrafine content alter granulation behavior and green-bed properties, while pre-pelletizing or intensive premixing can change the effective feed presented to the main granulation step. The practical implication is that a scale test cannot be considered equivalent if its feed has the same bulk chemistry but a different surface or size state (Oliveira et al., 2020; Han et al., 2023; Takehara et al., 2025; Aladejebi et al., 2025a).

Particle-size distribution influences agglomeration through more than the number of fines. DEM work on wet agglomeration indicates that coarse particles can provide stable nuclei to which fines attach, whereas fine-only systems can form less well-defined macrostructures. In heap-leach systems, the same PSD also governs packing, capillarity, residual moisture, and pore-throat dimensions after stacking. Consequently, a feed PSD that is "similar" by P80 can still be scale-incompatible if its ultrafine tail, coarse-nucleus fraction, or bimodality differs (Moncada et al., 2025; Robertson et al., 2022; L. Wang et al., 2023).

Surface area, pore structure, and water demand

Specific surface area and intra-particle porosity create a hidden liquid-demand term. Porous ores can rapidly absorb water into internal pores, reducing the liquid available for surface bridges, while ultrafines increase external surface area and capillary retention. Laboratory-commercial iron ore work has linked water-holding capacity to intraparticle porosity, and other studies have shown that capillary uptake and preheated water can materially change granulation response. Therefore, fixed moisture addition, expressed only as a mass percent, is not a scale-invariant control variable unless the water absorption and evaporation histories are also comparable (Aladejebi et al., 2023; Rajak et al., 2021; Rudenko et al., 2025).

Mineralogy, comminution history, and binder compatibility

Mineralogy and comminution history affect surface charge, roughness, microcracks, pore accessibility, and binder reaction. HPGR-treated copper ore, for example, can present a microstructure that differs from conventionally crushed material even when nominal size ranges overlap. Geopolymer and polymeric binder studies likewise show that bonding mechanisms depend on mineral surfaces and reaction products, not simply on liquid addition. A scale-up program that uses a convenient surrogate ore or a laboratory feed produced by a different breakage route may therefore reproduce size but misrepresent binder demand, curing behavior, and mechanical integrity (Yin & Chen, 2021; Chen et al., 2020, 2021; Golpayegani & Kiaei, 2023; Oliveira et al., 2024).

Table 3 summarizes the feed descriptors that should be frozen, normalized, or deliberately varied in a scale-up campaign. Table 3 also distinguishes variables that are likely to remain fixed properties of a feed lot from those that can drift because of sampling, segregation, crushing, moisture loss, or storage.

Table 3. Feed-state descriptors that should accompany scale-up comparisons

Descriptor	Why it matters mechanistically	Recommended comparison across scales	Typical scale-up risk
Full PSD, including ultrafines	Controls nuclei/fines balance, surface area, packing, and capillarity.	Report full cumulative PSD plus selected fine and coarse fractions; do not rely only on P80.	Bench sample preparation removes or enriches fines relative to plant feed.
Specific surface and porosity	Controls water absorption and available liquid for bridges.	Measure surface area or a validated proxy and water-holding/absorption behavior.	Equal bulk moisture produces unequal surface saturation.
Particle shape and breakage history	Changes collision, contact area, packing, and pore connectivity.	Document crushing route and shape descriptors where practical.	Laboratory jaw crushing or sieving creates a non-representative feed.
Mineralogy and reactive gangue	Affects wettability, binder reaction, acid consumption, and curing.	Use mineralogical/chemical fingerprinting of test lots.	Surrogate blends reproduce grade but not surface chemistry.
Initial moisture and temperature	Changes wetting kinetics, evaporation, viscosity, and capillary uptake.	Condition feeds to defined ranges and record storage history.	Pilot or plant feed experiences weather exposure absent in bench tests.
Segregation state at feed point	Determines local PSD and local liquid demand entering the granulator.	Sample spatially or temporally at realistic feed rates.	Composite bench sample hides plant-scale segregation.

Note. Author synthesis based on Aladejebi et al. (2023, 2025a), Oliveira et al. (2020), Moncada et al. (2025), Yin and Chen (2021), and Robertson et al. (2022).

Table 3 shows why feed characterization is not a preliminary analytical task separate from scale-up; it is the first validation gate. If the feed state is not equivalent, differences observed between scales cannot be uniquely attributed to equipment size. Conversely, when ore variability is part of the industrial problem, the scale-up test matrix should intentionally include that variability instead of averaging it away.

Figure 3 links the feed descriptors in Table 3 to wetting, growth, product structure, and downstream function. It provides the mechanistic backbone used in the remainder of the review.

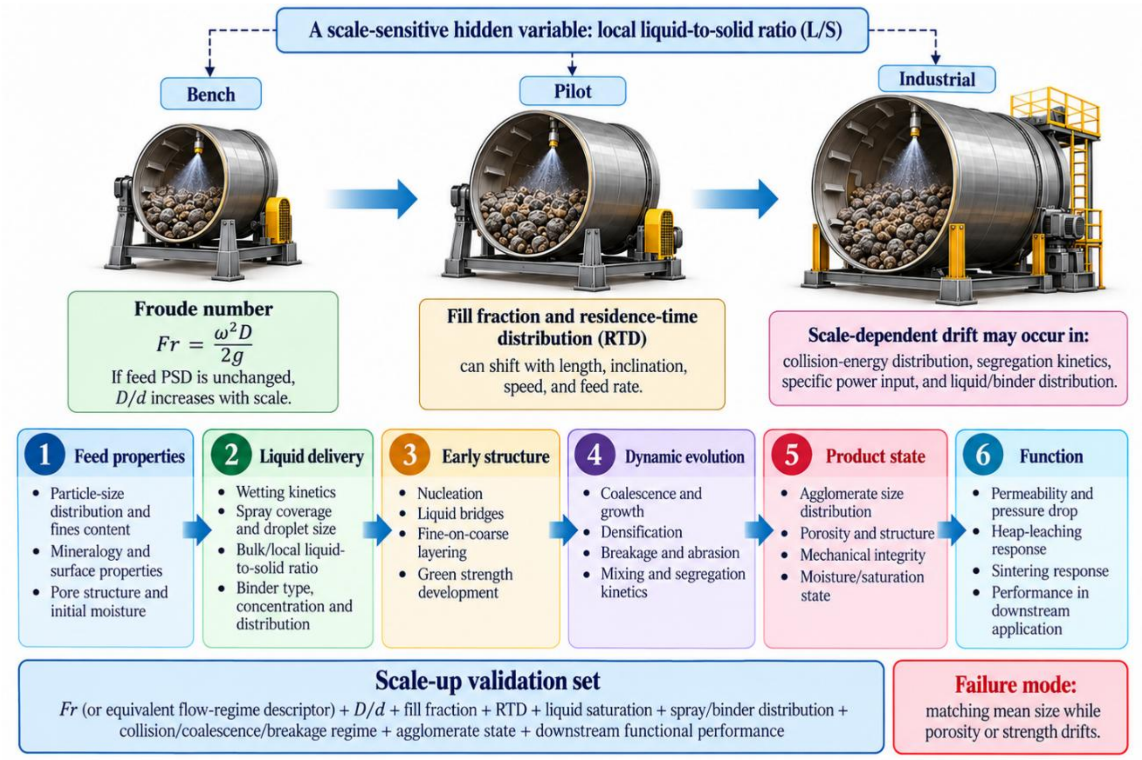

Figure 3. *Mechanistic chain linking feed variability to agglomeration and downstream performance*

Note. Author-developed conceptual synthesis based on Luo et al. (2026), Baba et al. (2021), L. Wang et al. (2021), Robertson et al. (2022), Chen et al. (2021), and Gao et al. (2021).

Figure 3 highlights two scale-sensitive hidden variables: local liquid-to-solid ratio and the history of damage after initial growth. A product can therefore reach the target size by different pathways—stable layering, deformable coalescence, or repeated growth-breakage cycles—and those pathways need not produce the same porosity, strength, or downstream permeability. The numbered boxes in Figure 3 denote mechanistic stages in the causal chain; they are not the AGG-SUVF gates introduced in Section 11.

Wetting, Nucleation, Binder Distribution, and Liquid Saturation

Wetting is a transport process, not a dosage setting

Liquid addition is often recorded as a single mass fraction, but the rate at which liquid reaches and redistributes over the particle population is a separate scale-up problem. Industrial sprays cover a moving, segregating bed; laboratory tests may add liquid by hand, by a narrow nozzle, or during batch tumbling. The same total liquid can therefore produce different local wetting states. Because early liquid bridges determine which contacts survive subsequent collisions, nonuniform wetting during the first seconds of granulation can propagate into the final PSD, porosity, and strength even after bulk moisture appears uniform (Luo et al., 2026; Rajak et al., 2021; Takehara et al., 2025).

Pre-heated water studies reinforce this interpretation by showing that water temperature can improve wetting and granulation indices, while capillary-moisture work emphasizes that liquid uptake into pores competes with surface bridge formation. These effects are not merely laboratory curiosities: larger units can have different liquid residence on free surfaces, different evaporation exposure, and different time between spray contact and high-energy collisions. The scale-up variable is therefore the coupled wetting history, not just final water content (Rajak et al., 2021; Rudenko et al., 2025).

Binder chemistry and spatial distribution

Binders introduce an additional hierarchy of scale dependence. Polymeric binders, geopolymers, cementitious systems, acid solutions, and soluble salts differ in viscosity, reaction kinetics, setting or curing, and sensitivity to mineral surfaces. Geopolymerization studies on fine copper ore demonstrate that binder-mediated agglomeration can produce distinct microstructures, while polymeric binder work shows that chemistry can improve mechanical integrity for difficult-to-oxidize ores or ultrafine iron feeds. These benefits can be lost at scale if the binder is concentrated in a fraction of the feed or if the available mixing time after addition is too short (Chen et al., 2020, 2021; Golpayegani & Kiaei, 2023; Oliveira et al., 2024).

For heap-leach agglomerates, curing further complicates the transfer. Chloride-containing systems and other reactive binders can evolve in strength and pore structure after leaving the drum. Micro-CT and modeling studies show that curing is a spatially heterogeneous process. A bench protocol that measures fresh agglomerates while an industrial pile experiences hours of transport, stacking, compaction, and chemical curing is not testing the same material state. Cure time, temperature, humidity, and load history should therefore be defined as part of the scale-up boundary (Salinas-Farran et al., 2022; Salinas-Farran & Neethling, 2023).

Intra-agglomerate saturation, liquid bridges, and over-wetting

During granulation, liquid saturation is a local agglomerate-state variable: it relates liquid volume to accessible pore volume within the evolving particle assembly and therefore influences bridge formation, deformability, coalescence, and the onset of over-wetting. As saturation increases, capillary bonding can initially strengthen and liquid connectivity can improve, but excessive local saturation can promote plastic deformation, slumping, or loss of gas-filled pore space. The relevant granulation window is therefore bounded on both sides: too little liquid gives weak or incomplete bridges, while excessive liquid can destroy the structure that agglomeration is intended to create. This local state should not be conflated with the later saturation of a stacked heap bed (Urtubia & Suárez, 2020; Salinas-Farran & Neethling, 2023; Pereira, 2026c).

The practical consequence is that liquid addition should be normalized to the feed water demand and the pore capacity, and then verified by a structural or mechanical response. In sinter granulation, relevant responses include granulation index, green-bed voidage, and permeability; in heap-leach agglomeration, fresh and cured agglomerate porosity, strength, and post-handling fines are more direct indicators of the state produced inside or immediately after the granulator. Binder dosage without a saturation and distribution check is therefore an incomplete criterion for scale-up (Aladejebi et al., 2023; Zhou, Lai, et al., 2020; Robertson et al., 2024).

Bed-scale saturation is a downstream hydraulic state

After stacking and irrigation, saturation takes on a different physical meaning: it denotes the liquid-filled fraction of pore space at the bed scale and governs unsaturated hydraulic conductivity, gas continuity, capillary retention, and the risk of local ponding or preferential flow. A heap can therefore contain mechanically acceptable agglomerates yet operate at an unfavorable bed saturation because lift height, irrigation rate, compaction, segregation, or solution chemistry has changed the pore network. AGG-SUVF consequently treats wetting and binder distribution under Gate 1, the resulting agglomerate moisture/saturation state under Gate 3, and the bed-scale hydraulic state under downstream Gate 4, rather than collapsing them into a single moisture variable (Robertson et al., 2022, 2023, 2024; L. Wang et al., 2023).

Agglomerate Growth, Coalescence, Breakage, Abrasion, and Strength Development

Growth pathways are not interchangeable

Granule growth may occur through layering of fines onto coarse nuclei, coalescence of similarly sized wet agglomerates, capture of fines by deformable surfaces, or repeated cycles of collision, densification, breakage, and re-growth. Iron-ore DEM-PBM studies have explicitly represented layering, while high-shear work shows that collision frequency and adhesion can accelerate growth. The resulting granules can have the same external size yet different internal packing and bond topology. Scale-up, therefore, requires evidence that the dominant growth pathway remains comparable, especially when the equipment type changes from low-shear tumbling to intensive or high-shear granulation (Baba et al., 2021; Nakamura et al., 2022; Huang et al., 2025; You et al., 2021).

Population-balance descriptions are useful because they force the analyst to represent competing birth and death processes rather than assuming monotonic size increase. Compartment PBMs and hybrid models developed for wet granulation distinguish induction periods, size-dependent growth, and formulation effects; their specific parameters are not directly transferable to ores, but the modeling lessons are. A scale-up model should include mechanisms for both aggregation and breakage whenever larger equipment changes the collision energy or residence-time exposure (Muthancheri et al., 2021; Muthancheri & Ramachandran, 2021; Ismail et al., 2020).

Breakage and abrasion can reverse apparent scale-up success

Agglomeration performance is sometimes evaluated immediately at the granulator discharge, before transfer, stockpiling, charging, or stacking. That endpoint can overstate scale-up success. Industrial material experiences repeated drops, conveyor transfers, compression, and in-bed loading. If scale enlargement leads to more intense collisions or longer exposure times, an agglomerate population can grow to a target size inside the drum and then generate fines by abrasion downstream. This is why green strength, crushing strength, Young's modulus, attrition resistance, and deformation under load should be considered alongside PSD (Zhou et al., 2020; L. Wang et al., 2024; Robertson et al., 2024).

The balance between strength and porosity is application-specific. Highly dense granules may resist handling but reduce internal permeability or access to reactive surfaces; weakly porous granules may provide favorable initial flow but collapse under load. Microstructural observations during chalcopyrite leaching and copper-ore binder studies show that pores evolve as reactions proceed, so mechanical and transport properties cannot be assumed constant after agglomeration. A robust scale-up test should therefore include both "as-produced" and "after-relevant-history" measurements (Gao et al., 2021; Yin et al., 2021; Salinas-Farran & Neethling, 2023).

Table 4 organizes the principal growth and damage mechanisms by the measurements that can reveal them. Table 4 is intended as a diagnostic matrix: a project need not measure every entry, but it should select at least one observable for each mechanism believed to control the industrial process.

Table 4. Mechanistic observables for growth, coalescence, and damage during scale-up

Mechanism	Scale-sensitive driver	Useful observable	Interpretive warning
Nucleation / fine capture	Local wetting, coarse-nucleus availability, fines fraction	Nucleus fraction, fine-on-coarse attachment, early PSD change	A final PSD cannot reveal whether nucleation was spatially uniform.
Layering growth	Collision frequency, liquid bridges, available fines	Layer thickness or size-class transfer; DEM/PBM growth rate	Growth can appear similar while internal porosity differs.
Coalescence	Surface liquid, deformability, collision velocity	Coalescence frequency; coarse-tail development	Excess coalescence can produce oversized weak agglomerates.
Densification	Repeated compression and shear	Bulk/granule porosity; deformation under load	Higher strength may be achieved by sacrificing permeability.
Breakage	Collision energy, residence-time exposure, dry zones	Breakage kernel, fines generation, post-drum PSD	Breakage may be masked by simultaneous re-agglomeration.
Abrasion	Surface bond strength, transfer history	Attrition index; dust/fines after handling simulation	Discharge PSD alone can overestimate industrial integrity.

Note. Author synthesis based on Baba et al. (2021), Nakamura et al. (2022), Huang et al. (2025), Zhou et al. (2020), and L. Wang et al. (2024).

Table 4 also clarifies why a single growth kernel is unlikely to remain valid across a wide range of scales without revalidation. The relative importance of coalescence, layering, and breakage can shift as collision statistics and liquid distribution shift. Mechanistic scale-up therefore requires either direct paired-scale measurements or a model whose kernels are constrained by such measurements.

Drum, Disc, and High-Shear Granulators: Geometry, Speed, Filling, and Residence Time

Rotating drums: similarity with scale-dependent exceptions

Rotating drums remain attractive for mineral granulation because they are mechanically simple, tolerant of high throughputs, and capable of combining mixing and granulation. Their apparent simplicity can encourage overly simple scale laws. Drum diameter and length change the available cascading path, the axial distance over which solids and liquid redistribute, and the number of particle layers through the bed. Rotation speed changes flow regime and collision history; inclination and throughput change RTD; fill changes both bed depth and exposure to sprays. The operating variables therefore interact rather than forming independent tuning knobs (Adam et al., 2025; Mahdavy et al., 2022; Y. Wang et al., 2023).

DEM and numerical work provide a useful decomposition of these interactions. Particle mixing and granulation simulations in iron ore drums show that collision and adhesion statistics depend on the operating state, and that baffles can alter stabilization time, collision fluctuations, and water exchange. Nucleus shape has a smaller influence on the overall flow pattern than on the local number of attached fines, whereas certain baffle configurations can enhance attachment. These results illustrate why internal drum details must be included in scale definitions: a “same diameter ratio” comparison with different baffle architecture is not geometrically or dynamically equivalent in the relevant sense (Y. Wang et al., 2023, 2024; Shi et al., 2022).

High-shear granulation and equipment switching

High-shear granulators deliberately intensify mixing and collision frequency. Iron ore studies report strong particle adhesion and rapid growth under horizontal high-shear conditions, and comparisons with conventional drums show that equipment type can affect axial mixing, water/calcium distribution, granule uniformity, bed permeability, and subsequent sintering indicators. This is a critical scale-up issue because changing equipment family is not merely “scaling” a drum; it changes the mechanism and should be treated as process redesign followed by functional validation (You et al., 2021; You, Guo, Li, Zheng, Li, & Lü, 2022; You, Guo, Li, Zheng, Li, Yu, & Lv, 2022; You, Guo, Zheng, et al., 2022).

Process intensification can be advantageous when ultrafines or difficult blends exceed the mixing capability of a conventional drum. Reviews of modern sinter practice and experimental work with pre-pelletizing or intensive mixing point toward multi-stage strategies in which feed conditioning, nucleation, and final growth are intentionally separated. Such flowsheets can improve granulation, but they remove the basis for simple one-equipment scale-up. Each stage introduces its own residence time, liquid distribution, and recycle interactions (Aladejebi et al., 2025b; Han et al., 2023; Takehara et al., 2025).

Disc pelletizers and product-shaping objectives

Disc pelletizers impose a different solids circulation pattern and are often used when a narrower, more spherical pellet product is desired. Work on carbon-core iron ore pellets demonstrates the ability of disc systems to form layered structures around nuclei. For scale-up purposes, the relevant comparison variables include disc angle, speed, bed circulation, feed location, liquid addition location, and product discharge trajectory. A disc-to-drum change should not be justified by equal residence time or mean size alone because the internal circulation and selection of growing pellets differ fundamentally (Iwase et al., 2023; Lv et al., 2021).

Continuous operation, recycle, and transients

Industrial granulators operate in circuits, not as isolated steady-state vessels. Feed-rate disturbances, recycle variations, water-pressure changes, and changes in ore moisture cause the process to pass through transient states. Dynamic models of rotary-drum granulation loops show how recycle and process holdup can amplify or damp disturbances. Digitalization studies in continuously formulated product manufacturing likewise demonstrate the importance of integrating sensing, process models, and control rather than assuming a fixed operating point. For mineral scale-up, this means a pilot campaign should include controlled disturbances, not only steady-state optimization (Vesjolaja et al., 2020; Ntamo et al., 2022).

The combined evidence supports a multi-variable view of similarity. Figure 2, introduced earlier, captures the geometric aspect; the industrial design problem adds liquid-distribution hardware, feed distribution, recycle, and control capability. Consequently, the “same drum” at a different scale is a system-level claim and should be validated as such.

Agglomerate PSD, Structure, Mechanical Integrity, and Downstream Transport State

Product PSD is necessary but not sufficient

Granule PSD is the most common product descriptor because it is easy to measure and directly reflects growth and breakage. Yet PSD does not uniquely specify internal porosity, inter-agglomerate packing, binder distribution, or strength. Two products with nearly identical d50 values or granulation indices can produce different bed voidage because particle shape and deformability differ. The scale-up target should therefore be a product-state vector rather than a single size statistic (Niu et al., 2023; Aladejebi et al., 2023; Zhou et al., 2020).

Porosity and pore-network connectivity

Pore structure is especially important in heap leaching. Three-dimensional characterization of packed beds containing crushed particles and agglomerates shows that intra-particle and inter-particle pores jointly determine connected pathways, stagnant regions, tortuosity, and preferential flow. Agglomeration can improve connected pore structure by incorporating fines into larger units, but excessive densification can create small throats or isolated pores. Thus, “more agglomeration” is not always “better permeability”; the spatial organization of pores matters (L. Wang et al., 2023; Gao et al., 2021).

The Robertson series provides a complementary engineering view. PSD and fine content influence hydraulic radius, residual moisture, compressibility, and saturated or unsaturated flow. Low-permeability ores may operate near saturation because fines increase moisture hold-up and reduce air-filled pathways; suitable agglomeration can move the bed away from that condition by binding fines and resisting slumping. These findings make hydraulic behavior an essential downstream validation metric for heap-leach agglomeration (Robertson et al., 2022, 2023, 2024).

Permeability, hydraulic conductivity, and unsaturated flow in heap leaching

Hydraulic terminology must be used carefully because intrinsic permeability, saturated hydraulic conductivity, unsaturated hydraulic conductivity, and gas permeability are not interchangeable. Intrinsic permeability is a property of the pore geometry; hydraulic conductivity additionally depends on fluid properties; and unsaturated conductivity varies strongly with liquid saturation and connectivity. Gas permeability introduces a separate phase-continuity constraint. Accordingly, a heap-leach scale-up claim should identify the measured quantity and test condition—such as saturated or unsaturated state, confining load, irrigation rate, and solution chemistry—rather than reporting a generic “permeability” value. The Robertson studies show why this distinction matters: fines content, compressibility, residual moisture, and saturation jointly control solution and air flow through crushed ore (Robertson et al., 2022, 2023, 2024).

Green-bed permeability and downstream performance in sintering

In iron-ore sintering, the equivalent functional metric is green-bed permeability and its consequences for flame-front movement, productivity, yield, and sinter quality. Drying treatment after granulation, intensive granulation, and ultrafine-feed management can alter permeability even when nominal granule size remains acceptable. The strongest scale-up evidence therefore couples granule characterization to the subsequent sinter response rather than ending the experiment at the granulator outlet (Zhou, Lai, et al., 2020; Aladejebi et al., 2025a; You, Guo, Zheng, et al., 2022).

Table 5 defines a practical performance vector for mineral agglomeration. Table 5 intentionally avoids fixed, universally accepted limits. Instead, it recommends that each project define tolerance bands from measurement precision and the sensitivity of downstream performance to each variable.

Table 5. Recommended performance vector for scale-up validation

Vector component	Example metric	Why it belongs in the vector	Acceptance principle
Feed state	Full PSD; fines fraction; water-holding capacity; initial moisture	Defines whether scale comparisons start from equivalent material states.	Equivalent distribution or a deliberate variability envelope.
Liquid/binder state	Bulk and spatial moisture; binder concentration; saturation proxy	Determines nucleation, coalescence, curing, and deformation.	Within project-defined distribution and chemistry bands.
Kinematic state	Fr; fill; D/d; RTD; collision/velocity proxy	Defines how particles experience mixing, growth, and breakage.	Similarity in relevant regime, not necessarily exact equality of every variable.
Granule PSD	d10/d50/d90; span; target-size fraction; fines and oversize	Captures net balance of nucleation, growth, and breakage.	Multiquantile equivalence rather than mean size only.
Structure	Granule porosity; bed voidage; pore connectivity/tortuosity proxy	Controls liquid/gas transport and deformation.	Preserve functionally relevant structure within uncertainty.
Mechanical integrity	Green/crushing strength; Young's modulus or deformation under load where relevant; attrition/abrasion index; fines generated after handling	Determines whether agglomerates survive transfer, stacking, compression, and subsequent processing without excessive degradation.	Mechanical properties and post-handling fines must remain within predefined, application-specific acceptance margins.
Downstream function	Permeability/hydraulic conductivity; leach recovery or sinter productivity	Tests whether agglomeration achieved its engineering purpose.	Must remain within the project's functional acceptance band.

Note. Author synthesis based on Niu et al. (2023), Robertson et al. (2022, 2023, 2024), L. Wang et al. (2023), Zhou et al. (2020), and Aladejebi et al. (2023).

Table 5 converts scale-up into a multivariate but non-compensatory equivalence problem. The vector components may be prioritized according to the dominant failure modes of a project, but a favorable result in an easy-to-measure variable should not numerically compensate for failure in a critical downstream variable. An excellent PSD match cannot compensate for the loss of heap hydraulic performance, and increased granule strength cannot compensate for a sinter bed with permeability outside the operating window. AGG-SUVF therefore uses gate logic rather than a weighted-average score.

Bench → Pilot → Industrial Granulation: What Evidence Is Enough?

Bench tests establish mechanisms and sensitivity, not industrial truth

Bench tumbling tests are indispensable because they permit controlled variation of moisture, binder dosage, PSD, speed, time, and feed composition. Their weakness is that they compress industrial heterogeneity into a small, often batch, sample. Bench results are therefore strongest when used to identify mechanism, sensitivity, and feasible operating windows. They become weak when used to declare industrial equivalence without evidence on continuous residence time, liquid delivery, segregation, and downstream loading (Pereira, 2026a; Larrabure et al., 2024; Pereira, 2026e).

Paired laboratory-commercial evidence: a high-value but narrow form of validation

The laboratory-commercial sinter-granulation comparison by Aladejebi et al. is unusually valuable because both scales were explicitly aligned in Froude number, space factor, residence time, and moisture, and granule and green-bed properties were compared. The finding that laboratory granules could represent commercial granules under the tested conditions is exactly the type of paired evidence scale-up studies need. At the same time, it should not be generalized to all ores or moisture windows, because the correspondence depends on material water-holding behavior and the tested blend. This is "conditionally validated transfer," not a universal scale law (Aladejebi et al., 2023).

Pilot scale must reproduce industrial sources of heterogeneity

Pilot equipment earns its role by introducing phenomena absent from bench tests: continuous feed, realistic spray width, axial mixing, recirculation, realistic solids hold-up, industrial residence-time distribution, and sufficient material depth to evaluate handling or downstream bed behavior.

Pilot-scale industrial validation of composite agglomeration strategies, including work integrating difficult secondary materials into sinter feed, shows the importance of linking multiscale consolidation mechanisms to pilot or industrial outcomes rather than relying on a small-drum endpoint alone (Yi et al., 2025; Aladejebi et al., 2025b).

Heap-leach scale-up adds bed hydrodynamics and geomechanics

For heap-leach agglomeration, scale-up continues after the drum. Agglomerates are conveyed, stacked, irrigated, compressed by overburden, and exposed to evolving solution chemistry. Fundamentally, heap-scale upscaling relates laboratory or column behavior to densification, tortuosity, irrigation geometry, and spatially heterogeneous flow, while three-dimensional pore-network studies and saturated/unsaturated flow measurements show that nominal test dimensions do not guarantee representative transport. The implication for agglomeration is direct: a granule population is only functionally transferred if it survives the hydrological and mechanical environment of the bed it is intended to create (van Staden & Petersen, 2021; Larrabure et al., 2024; Robertson et al., 2022, 2023, 2024; L. Wang et al., 2023). Within the curated corpus, complementary reviews of tall-column representativeness, heap-leach pilot-plant design, and bed hydrodynamics provide additional context for this transport-and-loading boundary (Pereira, 2026b, 2026d, 2026f).

Leaching scale-up models provide an additional bridge. Reactor-to-column-to-heap modeling of chalcopyrite systems illustrates how reaction and transport representations can be propagated across scales only when changing geometry and transport environments are represented explicitly. Agglomeration should be treated analogously: a bench-growth model must be embedded in a broader handling-and-transport context before it can support industrial prediction (Winarko et al., 2023; van Staden & Petersen, 2021).

Functional scale-up is necessary but not sufficient for industrial feasibility

AGG-SUVF validates agglomeration transfer but is not a substitute for a feasibility study. A process may maintain product quality yet remain impractical because of throughput, energy demand, spray capacity, recycle load, water or binder supply, maintenance requirements, equipment constraints, or limited control authority. These factors should be reported as an industrialization overlay after scale-transfer validation. The distinction is deliberate: economic or operational infeasibility does not invalidate the physical transfer analysis, but physical transfer alone does not justify commercial deployment.

Figure 4 summarizes the resulting evidence ladder. Figure 4 is intentionally asymmetric: moving upward requires new types of evidence rather than merely more repetitions at the same scale.

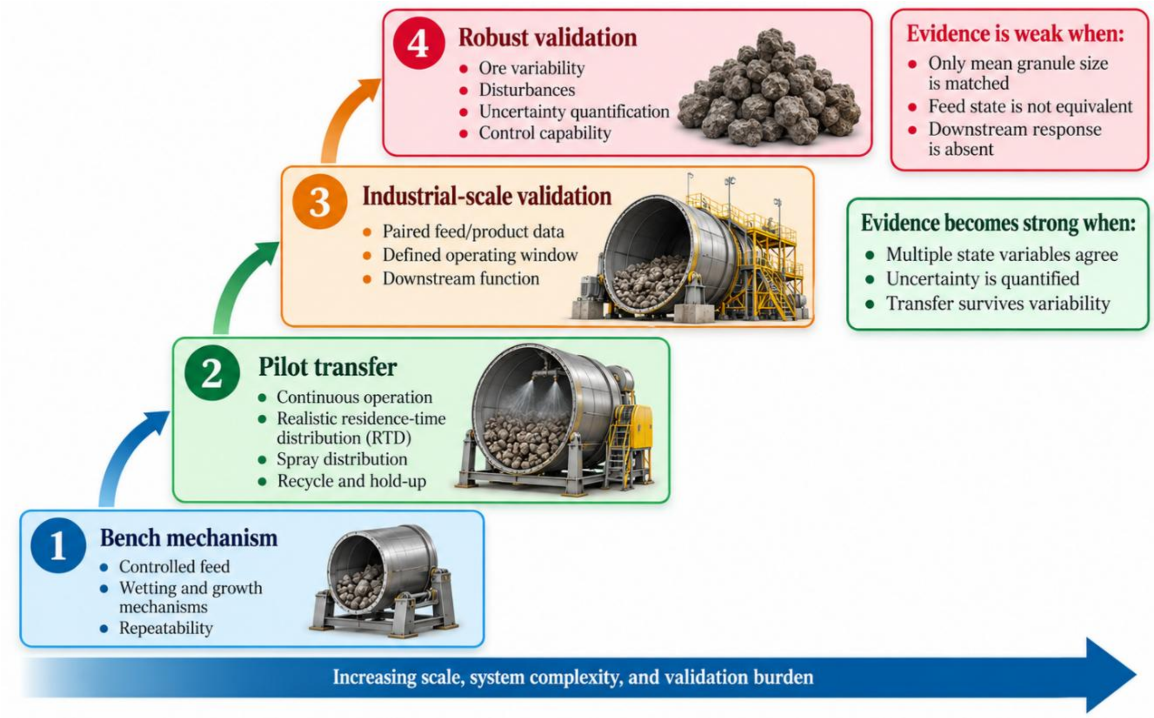

Figure 4. *Bench-to-pilot-to-industrial evidence ladder for agglomeration scale-up*

Note. Author-developed conceptual synthesis based on Aladejebi et al. (2023), Yi et al. (2025), Larrabure et al. (2024), van Staden and Petersen (2021), and Robertson et al. (2022, 2023, 2024).

Figure 4 also provides a practical criterion for publication. A study reporting only bench data can still make a strong contribution if it frames its claims as mechanistic or predictive and quantifies uncertainty. What it should not do is label a laboratory optimum as an "industrial scale-up rule" without paired-scale validation. Conversely, industrial correspondence is much more persuasive when the study reports both the variables that were preserved and those that changed.

Population-Balance, DEM, Hybrid Modeling, and Uncertainty in Scale-Up

PBM and DEM answer different parts of the scale-up problem

Population balance models (PBMs) efficiently track the evolution of particle populations through aggregation, growth, and breakage kernels. Discrete element methods (DEM) resolve particle motion, contact, and collision statistics but become computationally expensive as particle count increases. Coupled DEM-PBM approaches are therefore particularly attractive for granulation scale-up: DEM can inform local collision and adhesion behavior, while PBM propagates the population response. Iron-ore layering work demonstrates the feasibility of this coupling in a directly relevant mineral system (Baba et al., 2021; Nakamura et al., 2022).

Newer frameworks address the computational barrier through adaptive scaling, coarse graining, multi-stage coupling, and hybrid surrogate representations. These developments are critical for industrial drums, where a direct particle-by-particle simulation at real particle count is usually infeasible. Upscaled DEM for wet drum granulation and recent coarse-grained DEM-PBM frameworks indicate a path toward retaining physically meaningful coalescence and breakage behavior while reducing computational cost. The methodological advance is significant, but scale-up credibility still depends on validation against measurements at more than one scale (De et al., 2026; Saghafian Larijani et al., 2026; Wu, Liu, Chen, et al., 2026; Wu, Liu, Zhou, et al., 2026).

Calibration, identifiability, and sensitivity are scale-up requirements

A model can fit a granule PSD for the wrong mechanistic reasons. Calibration must therefore be accompanied by sensitivity analysis and, where possible, independent validation of porosity, growth rate, or other internal states. Studies in high-shear and twin-screw wet granulation provide mature examples of model-driven workflows, global sensitivity-based calibration, and two-dimensional PBMs that track more than size alone. For mineral applications, these approaches are transferable as methodology, not as parameter values (Bellinghausen et al., 2022; Yeardley et al., 2021; Barrera Jiménez et al., 2023; Bala et al., 2024).

Mechanistic twin-screw and compartment PBMs also show how spatial compartments or process zones can be used when a single perfectly mixed population is unrealistic. This is directly relevant to long industrial drums with staged liquid addition or axial gradients. Again, the appropriate mineral model must be re-identified using mineral feed data because binder rheology, particle stiffness, surface roughness, and breakage behavior differ from formulated pharmaceutical systems (Ismail et al., 2020; Wang, Morrissey, et al., 2021; Muthancheri et al., 2021).

Hybrid models and real-time control

Hybrid modeling extends the scale-up problem from prediction to control. DEM-ANN-PBM and other hybrid architectures can map expensive mechanistic simulations into rapid surrogates, while recent PBM-machine-learning work demonstrates the use of a learned surrogate inside model predictive control. Fluid-bed granulation studies further show how hybrid models can reduce the number of experiments required during development. These concepts are attractive for mineral granulators because industrial feed variability can move the process away from the design point faster than operators can re-tune fixed water or speed settings (Dosta & Chan, 2022; Dosta et al., 2024; Mast et al., 2026; Ramachandran et al., 2026).

Physics-constrained kernels and model credibility

Scale-up requires models that extrapolate, not only interpolate. Sparse identification of physically plausible aggregation kernels is one route to limiting overfitting, while multi-stage DEM-PBM frameworks enable testing of competing coalescence mechanisms. The model should also propagate parameter uncertainty to predicted products and downstream metrics. A useful credibility test is whether a model calibrated at one scale predicts a second scale without re-tuning every kernel; if extensive re-tuning is required, the model may be a scale-specific correlator rather than a scale-up model (Tölle et al., 2026; Wu, Liu, Zhou, et al., 2026; Singh et al., 2022).

The strongest modeling workflow is therefore hierarchical: calibrate contact or wetting submodels on focused experiments; validate population growth and breakage at bench scale; test transfer to pilot scale; and only then use the model to explore industrial geometry or control. Data digitalization can support this hierarchy by connecting process historians, online measurements, and model states, but digital infrastructure does not substitute for mechanistic observability (Ntamo et al., 2022; Ramachandran et al., 2026).

AGG-SUVF: a validation framework for declaring scale-up

Rationale and definition

The literature reviewed above supports a stricter decision framework than the conventional sequence "bench optimization → larger equipment → industrial design." This review proposes AGG-SUVF, the Agglomeration Scale-Up

Validation Framework, as a six-gate protocol. AGG-SUVF is not a new constitutive model and does not replace ore-specific design correlations. Its purpose is to organize the evidence required before a scale-transfer claim is made and to prevent a single matched metric from masking failures elsewhere in the process chain.

The framework is deliberately falsifiable: a scale-up claim fails if any critical gate fails, unlike scorecards in which strong performance in one dimension can offset deficiencies elsewhere. For example, matching Froude number and d50 cannot compensate for lost hydraulic conductivity, nor can high crushing strength offset poor green-bed permeability. Figure 5 shows the six gates and the associated decision logic.

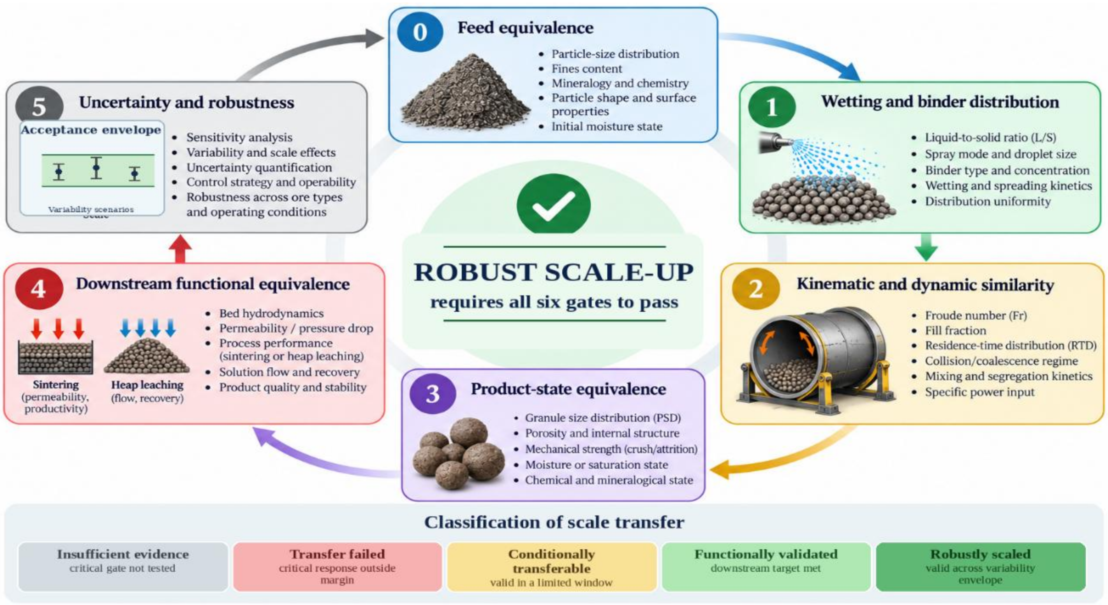

Figure 5. *AGG-SUVF: Agglomeration Scale-Up Validation Framework*

Note. Framework proposed in this review; author-developed conceptual synthesis based on scale-transfer, hydrodynamic, and model-validation principles in Herman et al. (2022), He et al. (2024), van Staden and Petersen (2021), Larrabure et al. (2024), and Ramachandran et al. (2026).

Figure 5 treats uncertainty and robustness as the final gate rather than as an optional statistical appendix. Importantly, the decision logic distinguishes an untested gate from a tested gate that fails its acceptance criterion. Insufficient evidence means the claim ceiling cannot advance because a critical gate was not evaluated; transfer failure means the gate was evaluated and the response fell outside the predefined acceptance margin. A process that matches at one nominal feed and one operating point may be conditionally transferable, but robust scale-up requires that the relevant Gates 0–5 remain satisfied over the expected ore variability and disturbance envelope.

Gate 0 — feed equivalence

Gate 0 verifies that the comparison begins from comparable feed states. At a minimum, the test should report the full PSD, including ultrafines, initial moisture, a descriptor of water demand or surface area, and mineralogical or chemical fingerprints relevant to binder behavior. If the industrial objective is explicitly to accommodate variable feeds, Gate 0 should instead define a variability envelope and ensure that all scales sample the same envelope. Failure at Gate 0 invalidates causal attribution of subsequent differences to equipment scale (Aladejebi et al., 2025a; Oliveira et al., 2020; Moncada et al., 2025).

Gate 1 — wetting and binder-distribution equivalence

Gate 1 verifies that liquid and binder reach the particle population in an equivalent way. Total dosage is reported, but so are nozzle arrangement, addition time, concentration, local moisture variability, and a saturation- or water-demand-normalized descriptor. Reactive binders require cure time and temperature to be accounted for in the gate. The gate is especially important when scaling spray width or moving from batch addition to continuous addition (Rudenko et al., 2025; Chen et al., 2021; Salinas-Farran et al., 2022).

Gate 2 — kinematic and dynamic similarity

Gate 2 evaluates the variables that determine particle motion and exposure: Froude number, a distribution-aware D/d descriptor, fill, length-to-diameter ratio, where relevant, residence-time distribution, throughput, internal geometry, specific power or energy, where measurable, and at least one velocity, collision, or segregation diagnostic, where feasible. Exact equality of every descriptor is not required if functional equivalence can be demonstrated, but material deviations must be documented and mechanistically interpreted. This gate prevents scale-up from being reduced to a rotation-speed calculation (Herman et al., 2022; He et al., 2024; Mahdavy et al., 2022; Y. Wang et al., 2024).

Gate 3 — product-state equivalence

Gate 3 compares the multivariable granule state. At minimum, this should include several PSD quantiles or target-size fractions together with structural and mechanical measures such as granule porosity, bed voidage, crushing strength, or attrition. For heap-leach agglomerates, a post-handling or post-load condition should be included. For sinter granulation, green-granule strength, granule structure, and green-bed voidage may complement PSD; green-bed permeability and subsequent sintering response are evaluated under Gate 4 because they are downstream functional responses (Zhou et al., 2020; Aladejebi et al., 2023; L. Wang et al., 2024).

Gate 4 — downstream functional equivalence

Gate 4 asks whether agglomeration still performs its engineering function. In heap leaching, the metric must be physically specified—for example intrinsic permeability, saturated or unsaturated hydraulic conductivity under stated load and irrigation conditions, gas permeability, solution-distribution response, and ultimately leaching kinetics or recovery. In sintering, relevant responses include green-bed permeability, sintering speed, yield, tumbler strength, or productivity. This gate is the most important distinction between "granule scale-up" and "process scale-up." (Robertson et al., 2023, 2024; L. Wang et al., 2023; Aladejebi, Mitra, Pinson, et al., 2025; You, Guo, Zheng, et al., 2022)

Gate 5 — uncertainty, variability, and robustness

Gate 5 evaluates uncertainty, variability, and robustness of the transfer. Replicate variability, sampling uncertainty, model-parameter uncertainty, and ore variability should be propagated to the metrics used in Gates 0–4. Sensitivity analysis can identify which uncertain variables most threaten transfer, and hybrid models can be used for scenario exploration only after predictive error is established. A process is "robustly scaled" when its functional acceptance criteria remain satisfied over the expected industrial variability envelope rather than only at the nominal design point. Robustness therefore concerns tolerance to variability; it must not be portrayed as confidence that automatically increases with equipment size (Yeardley et al., 2021; Bala et al., 2024; Ramachandran et al., 2026; Tölle et al., 2026).

Table 6 converts AGG-SUVF into a minimum-evidence protocol. It can be used as a design-of-test checklist or as a manuscript-reporting checklist when authors make scale-up claims. The classification is deliberately non-compensatory: the claim level is limited by the lowest critical gate for which adequate evidence exists.

Table 6. AGG-SUVF gates, minimum evidence, and claim ceilings

Gate	Minimum evidence	Failure or evidence gap	Highest claim supported if passed
0. Feed	Full PSD/fines; moisture; surface/water-demand proxy; relevant chemistry/mineralogy	Critical feed descriptor unreported, or systematic feed-state difference between scales.	Feed basis suitable for mechanistic comparison.
1. Wetting/binder	Dosage, concentration, addition pattern, moisture distribution or saturation proxy, cure history if relevant	Local wetting/curing state unreported or materially different despite equal total dose.	Wetting/binder transfer conditionally supported.
2. Kinematics	Fr, D/d, fill, RTD, throughput, internals, and at least one flow/collision/segregation diagnostic where feasible	Matched Fr but RTD, particle-resolution, segregation, force, or energy regime unreported or materially different.	Dynamic similarity supported for the tested regime.
3. Product state	PSD distribution plus structural/mechanical properties after relevant handling	Correct mean size but fines, porosity, strength, attrition, or post-handling state unreported or outside tolerance.	Product-state equivalence supported.
4. Downstream function	Permeability/flow and application-specific leaching or sintering metric	Downstream metric unreported, or response shifts outside the predefined functional margin.	Functionally validated scale transfer.
5. Robustness	Replicates, confidence bands, ore variability, disturbance tests, model predictive error where used	Transfer assessed only at one nominal point, or uncertainty/variability overlaps the failure region.	Robustly scaled within the stated operating envelope.

Note. AGG-SUVF is proposed in this review. The evidence logic is based on the combined lessons of Aladejebi et al. (2023), Herman et al. (2022), He et al. (2024), Robertson et al. (2022, 2023, 2024), Larrabure et al. (2024), and Yeardley et al. (2021).

Table 6 provides a vocabulary for qualified claims. “Insufficient evidence” means that one or more critical gates were not tested or were reported too incompletely to support a claim. “Transfer failed” means that a critical gate was tested and did not meet its acceptance criterion. “Conditionally transferable” means that mechanistic and product correspondence was demonstrated over a limited feed and operating window. “Functionally validated” adds downstream equivalence. “Robustly scaled” adds the ability to survive expected variability and to quantify uncertainty. These labels prevent an untested condition from being confused with a demonstrated failure and reduce the tendency to present a successful demonstration as a universal design rule.

Statistical equivalence and non-compensatory decision rules

Equivalence should be defined before comparing scales. For a scalar metric j, the project should specify an acceptance margin $\pm\Delta j$ from downstream sensitivity, process risk, and measurement capability rather than selecting a margin after seeing the data. Scale transfer is supported when the confidence interval for the between-scale difference lies inside that margin; multiplicative variables may instead use predefined ratio limits. For distributional variables such as PSD or RTD, equivalence should be assessed with multiple quantiles and, where justified, a distribution-distance metric rather than a mean alone. The statistical objective is therefore not to prove that two scales are exactly identical, but to show that any difference is small enough to be functionally irrelevant within quantified uncertainty.

Gate decisions are non-compensatory. A project may identify some metrics as informative and others as critical, but a failed critical metric cannot be offset by a good result elsewhere. Where evidence is missing, the gate is recorded as not demonstrated rather than failed. This distinction is essential for both publication and design decisions because “absence of evidence” and “evidence of nonequivalence” imply different next experiments.

Retrospective application of AGG-SUVF to representative evidence

To test whether AGG-SUVF discriminates among different evidential situations, Table 7 applies the framework retrospectively to representative studies already used in this review. The exercise is intentionally conservative: a gate is marked “demonstrated” only when the evidence role described in the cited study directly addresses that gate; “partial” indicates useful but incomplete evidence; “NR” indicates that the gate was not reported for the scale-transfer purpose; and “NA” indicates that the gate is outside the study’s intended evidence role. The table is not a re-analysis of raw data and therefore does not assign numerical equivalence margins.

Table 7. Retrospective AGG-SUVF evidence profiles for representative studies

Study/evidence role	G0 Feed	G1 Wetting	G2 Dynamics	G3 Product	G4 Function	G5 Robustness/claim ceiling
Aladejebi et al. (2023), laboratory–commercial sinter granulation	D	P	D	D	P	NR — conditionally transferable
Yi et al. (2025), pilot-scale industrial validation of composite agglomeration	P	P	P	D	D	P — functionally supported; robustness not fully established
Herman et al. (2022), rotating-drum scale study	D	NA	D	NA	NA	P — mechanistic scale-similarity evidence only
He et al. (2024), rotating-drum segregation/flow scale study	D	NA	D	NA	NA	P — mechanistic scale-similarity evidence only
Wang et al. (2024), lab-scale copper agglomeration with bonding/leaching/mechanics	D	D	NR	D	D	P — bench functional evidence; no scale-transfer validation

Note. D = demonstrated for the study’s evidence role; P = partial; NR = not reported for scale-transfer validation; NA = not applicable to the study’s intended evidence role. The coding is a critical synthesis of the evidence as used in this review, not a substitute for re-analysis of the original datasets.

Table 7 demonstrates the practical value of the framework. Aladejebi et al. (2023) supplies unusually strong paired-scale evidence but does not establish robustness across broad ore variability; Yi et al. (2025) reaches further into downstream industrial validation but remains application-specific; Herman et al. (2022) and He et al. (2024) provide strong mechanistic evidence on dynamic similarity without constituting mineral agglomeration validation by themselves; and Wang et al. (2024) provides strong bench functional evidence without a scale-transfer comparison. AGG-SUVF therefore prevents these distinct contributions from being collapsed into the same category of “scale-up evidence.”

Research Gaps, Validation Priorities, and Limitations

Paired-scale datasets remain the largest evidence gap

The most important research gap is not another isolated optimization study, but rather paired datasets in which the same feed or a deliberately matched variability envelope is tested at bench, pilot, and industrial scales, with synchronized measurements of feed state, wetting, operating variables, product structure, and downstream function. The Aladejebi laboratory–commercial comparison and recent pilot-industrial validation studies show the value of such designs, but comparable mineral datasets remain rare. Without them, scale laws are difficult to distinguish from material-specific correlations (Aladejebi et al., 2023; Yi et al., 2025).

Liquid-distribution observability is inadequate

Industrial granulators generally know how much liquid was added but not how uniformly it was distributed within the moving bed. Future work should combine fast moisture sensing, tracer methods, spray characterization, DEM-based coverage estimates, and downstream spatial sampling. This gap is particularly serious for ultrafine feeds and reactive binders, where a small wetting nonuniformity can create strong local differences in agglomerate deformability and curing (Rudenko et al., 2025; Oliveira et al., 2024; Salinas-Farran & Neethling, 2023).

Mineral-specific growth and breakage kernels need cross-scale validation

DEM-PBM developments are advancing faster than the experimental databases needed to constrain their kernels. Future mineral studies should report not only final PSD but time-resolved size evolution, breakage after controlled handling, and at least one structural metric. Coarse-graining and adaptive DEM are promising for industrial geometry, but they should be validated against the same observables used to claim physical fidelity. Kernel sparsity and physics constraints should be preferred over unconstrained fitting when the objective is extrapolation (De et al., 2026; Wu, Liu, Chen, et al., 2026; Wu, Liu, Zhou, et al., 2026; Tölle et al., 2026).

The feed-variability problem should be treated geometallurgically

Scale-up studies usually compare equipment sizes while holding one or more blends fixed. Industrial plants face the reverse problem: equipment is fixed while ore properties change. Future research should therefore define agglomeration response domains in terms of fines, specific surface, water-holding capacity, mineralogy, and binder demand, then test whether the selected operating strategy preserves the performance vector across that domain. Such a framework would connect ore characterization to control and would be more operationally useful than a single optimal moisture or speed (Aladejebi et al., 2025a, 2025b; Niu et al., 2023; Luo et al., 2026).

Digital scale-up should be judged by prediction under disturbance

Model-assisted control is a promising endpoint for scale-up science because it can compensate for feed drift rather than assuming perfect similarity. However, digital-twin claims should be evaluated by out-of-sample prediction and disturbance rejection, not by goodness of fit at the calibration point. PBM-ML surrogates, model-predictive control, and hybrid development workflows provide useful templates for this transition. Mineral implementations should account for sensor error, ore variability, actuator limits, and the propagation of uncertainty from model kernels to downstream performance (Dosta et al., 2024; Mast et al., 2026; Ramachandran et al., 2026; Ntamo et al., 2022).

The research agenda can therefore be summarized as a shift from “scale correlation” to “scale validation”: paired-scale datasets, direct observation of wetting and RTD, mineral-specific mechanistic kernels, downstream function tests, and uncertainty-aware control. The next generation of scale-up studies should be designed so that a failed transfer is scientifically informative rather than treated as an experimental inconvenience.

Limitations of this review and framework

This review has four principal limitations. First, its evidence base was curated rather than generated through a prospectively logged systematic-search workflow, so the quantitative evidence map describes this corpus and should not be interpreted as a bibliometric census. Second, direct mineral evidence is concentrated in iron-ore sinter granulation and heap-leach agglomeration; disc pelletizing and other mineral-agglomeration families receive less coverage. Third, several mechanistic and modeling concepts are imported from pharmaceutical or formulated-product wet granulation and are used only at the level of method or dimensionless reasoning; their parameter values and regime boundaries require mineral-specific validation. Fourth, paired bench–pilot–industrial datasets remain scarce, so AGG-SUVF should be viewed as a falsifiable validation framework that now requires prospective testing rather than as an already universal design standard.

These limitations do not invalidate the central synthesis; they define its claim boundary. The framework is strongest as a reporting and experimental-design discipline: it identifies which evidence is missing, which gate has failed, and which additional measurement is required before a stronger transfer claim can be made.

Conclusions

Wet mineral agglomeration is truly scaled up only when the engineering function created by agglomeration is preserved across scale within predefined acceptance limits. Equipment enlargement, geometric similarity, and constant Froude number can support that objective, but none is sufficient evidence by itself. The decisive variables form a coupled chain from feed state through liquid and binder distribution, particle motion, growth and breakage, product structure, handling history, and downstream transport and process performance.

The practical consequence is that scale-up should be evaluated with a non-compensatory performance vector rather than a single granulation index or mean size. Feed PSD and water demand, distribution-aware particle-to-equipment ratios, residence-time distribution, wetting and saturation state, binder coverage, granule PSD, porosity, mechanical integrity, and application-specific hydraulic or sintering response should be selected according to the dominant failure modes. Acceptance margins must be project-specific, defined before comparison, and wide enough to incorporate measurement uncertainty without masking functionally important differences. Functional scale transfer is also distinct from industrial feasibility: throughput, specific energy, equipment loading, reagent delivery, operability, and control authority require a subsequent engineering assessment.

AGG-SUVF formalizes this logic through six gates: feed equivalence; wetting and binder-distribution equivalence; kinematic and dynamic similarity; product-state equivalence; downstream functional equivalence; and uncertainty/robustness. The framework distinguishes insufficient evidence from demonstrated transfer failure and separates conditionally transferable, functionally validated, and robustly scaled processes. Its central principle is that scale-up is not proven by what was kept constant, but by demonstrating that the required function remains inside an accepted operating envelope despite the variables that inevitably change with scale.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. The evidence-role coding and AGG-SUVF synthesis presented in this review were derived from the cited literature; all literature-based quantitative values remain traceable to the original sources.

Author Contributions

Conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation: Antonio Clareti Pereira.

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