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High-Pressure Grinding Rolls in Mineral Comminution Circuits: A Critical Review of Ore Competency, Circuit Integration, Energy Efficiency, Operational Performance, and Techno-Economic Sustainability

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Abstract

High-pressure grinding rolls (HPGR) offer a compression-based alternative or complement to conventional mineral comminution. However, their value depends on ore response and circuit context, not nominal specific energy alone. This critical review examines particle-bed breakage, mineralogical and mechanical applicability, circuit integration, energy normalization, roll wear, downstream liberation, predictive modeling, and techno-economic and environmental trade-offs. The evidence is organized by laboratory, pilot, and industrial scale, with particular attention to differences in feed and product specifications, recirculation, availability, and downstream processing boundaries. The synthesis indicates that improved particle breakage and microcracking do not automatically translate into higher metallurgical recovery, and that equipment-level efficiency cannot establish whole-plant superiority without a common functional basis. The paper proposes a conditional selection framework combining representative ore testing, validated mass–energy balances, downstream response, reliability, and uncertainty analysis. Gaps remain in public industrial datasets, wear-adjusted lifecycle comparisons, and transferability of numerical models across ore types. The review identifies the need for evidence-matched comparisons and explicit validation of source-specific quantitative claims; the methodology reports bibliographic verification status and limitations.

Keywords: High-pressure grinding rolls; Mineral comminution; Ore competency; Energy efficiency; Circuit integration; Techno-economic assessment

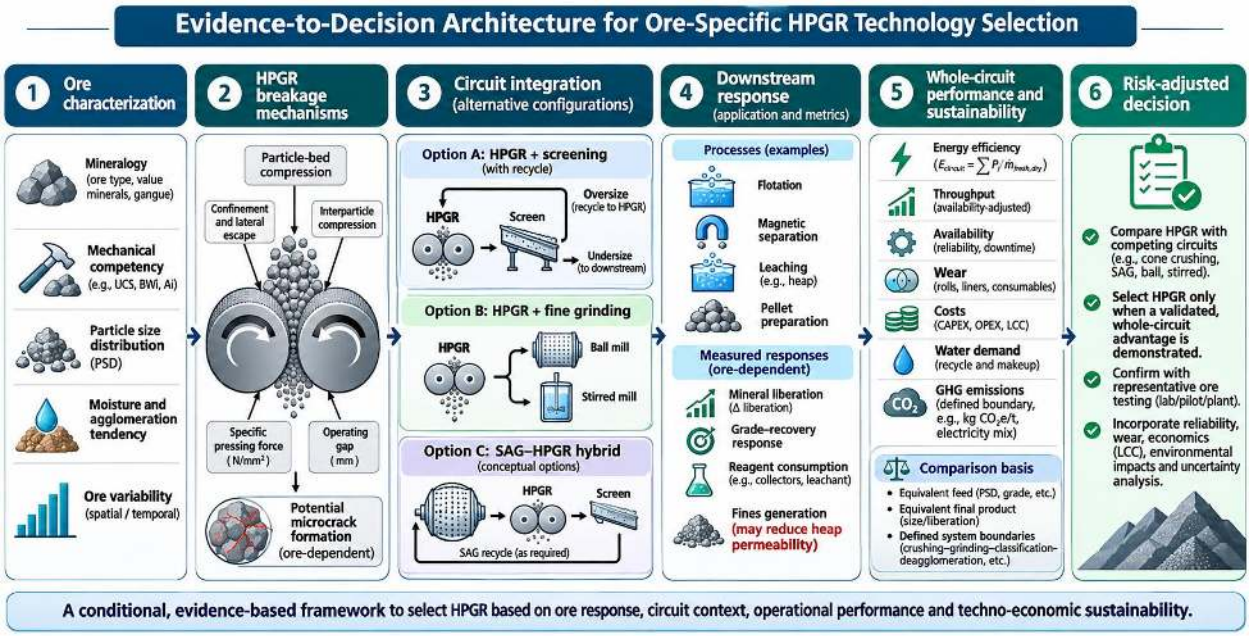
Highlights

• HPGR selection must be based on ore-specific response and the complete comminution circuit.
• Energy comparisons require equivalent feed and product specifications and system boundaries.
• Microcracking is not a sufficient proxy for improved liberation or recovery.
• Wear, availability, uncertainty, and downstream performance govern economic preference.

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Graphical Abstract



1. Introduction

Comminution is a fundamental but energy-intensive step in mineral processing. Selecting a high-pressure grinding rolls (HPGR) configuration solely because compressive particle-bed breakage appears favorable at machine scale can obscure the electrical demand of conveying, classification, deagglomeration, and subsequent grinding. Accordingly, the functional unit for comparing alternative flowsheets should be clearly defined as treatment of a specified ore to a specified downstream-relevant product, under equivalent availability and environmental boundaries. (Morrell, 2022; Morrell, 2010; Napier-Munn, 2015; Starkey et al., 2022).

HPGR technology has evolved from mechanical compression to a family of configurations that differ in confinement, surface geometry, feed presentation, and downstream integration. Published experience covers iron ore concentrates and pellets, sulfide ores, gold-bearing systems, and more specialized mineral feeds; however, evidence from one application cannot be transferred without an explicit argument based on ore properties and flowsheet design. (Rodriguez et al., 2025; Saramak & Saramak, 2024; van der Meer, 2015; Gruendken & Gruendken, 2010).

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The central question of this review is therefore conditional: under what feed, operating, and downstream conditions does HPGR deliver a robust net advantage compared with cone crushing, semi-autogenous grinding (SAG), ball milling, or stirred milling? Figure 1 introduces the governing mechanisms, whereas Table 1 specifies the comparability conditions that underpin subsequent interpretation. Figures 2–4 then link equipment and circuit choices to operational reliability and investment appraisal. (Amelunxen & Meadows, 2011; Rosario, 2017; Saramak, 2012).

Unlike broad HPGR technology and economic reviews (Saramak & Saramak, 2024) or reviews focused on advances in machine design (Rodriguez et al., 2025), the present study develops an ore-specific, whole-circuit, downstream-coupled, and risk-adjusted selection framework. Novelty lies in the comparability and decision structure, not in claiming that compression-induced breakage or energy savings are newly discovered.

2. Review Methodology and Evidence Appraisal

This structured critical narrative review was prepared from an author-supplied thematic bibliography comprising 148 HPGR records and seven additional relevant records (155 before the present revision). The supplied methodological description refers to 24 thematic search expressions and prioritizes 2020–2026 publications, supplemented with older foundational sources. However, the supplied materials did not include the original search strings, database-specific retrieval logs, platform names, or an independently documented final search date. Consequently, these details cannot be reconstructed as historical facts, and this review does not claim systematic-review or PRISMA compliance. Supplementary Table S1 provides 24 reproducible thematic expressions proposed for a documented update; these must not be confused with the unavailable historical search log. We conducted a focused editorial source check on 7 November 2026 for the records explicitly identified in the reviewer report; this does not constitute full verification of the corpus.

Evidence was organized according to its intended inferential role: mechanistic laboratory tests; pilot-scale performance and scale-up; plant observations and operating studies; mechanistic or statistical simulations; and broader comparative or techno-economic analyses. Laboratory observations inform physical plausibility, while industrial evidence is needed to demonstrate stable throughput, wear, energy, and production value. A simulation is

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treated as predictive evidence only to the extent that its calibration domain and independent validation are disclosed. (Alves et al., 2015; Anticoi et al., 2018; Anticoi et al., 2019; Kumar et al., 2023).

Evidence maturity is classified by demonstrated scale and duration, without implying a universal quality score: level 1, mechanistic laboratory experiments; level 2, calibrated simulation; level 3, continuous pilot tests; level 4, industrial short campaigns; and level 5, industrial lifecycle datasets. Model calibration, internal validation, and independent out-of-domain validation are separately identified. The highest relevant evidence level depends on the inference being made.

Table summarises the comparison criteria required to interpret the evidence without conflating machine performance and whole-circuit outcomes.

Table 1. Minimum reporting basis for comparative HPGR studies

Dimension	Required reporting	Common interpretative risk
Ore basis	Mineralogy, moisture, F80, top size, variability	Non-equivalent feeds
Circuit	Open/closed, circulating load, auxiliaries, final P80	Selective equipment boundaries
Performance	Dry t/h, net kW, kWh/t, availability	Nominal versus delivered rates
Downstream	Liberation, recovery, permeability, flotation conditions	Confounding by size distribution
Economics	CAPEX, consumables, wear, utility costs, discount rate	Unreported assumptions

Note. Original analytical framework developed from the scope and literature categories; no empirical values are implied.

This comparison underscores the importance of reporting the basis of calculation, uncertainty, and the operating envelope. Apparent gains under different product specifications cannot be generalized as equipment-level superiority.

3. Fundamentals of HPGR Comminution and Ore–Machine Interactions

In a high-pressure roll press, counter-rotating rolls compress a granular bed. Particle rearrangement, interparticle contact-force networks, densification, and fracture occur simultaneously. Unlike the idealized single-particle compression test, bed breakage depends on packing, loading history, local confinement, and the spatial distribution of stresses. Inferences about microcracks should therefore be separated from quantitative evidence about

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liberation and downstream processing. (Barrios et al., 2020; Brożek & Naziemiec, 2012; Campos et al., 2020; Cleary & Sinnott, 2021).

Mechanistic modeling suggests that the nip geometry and force distribution cannot be reduced to a single machine pressure. Edge effects, lateral escape, roll gap, and feed consistency modify local breakage intensity. Compression may preferentially damage certain phases, but the selective-weakening hypothesis must be tested against mineral textures, size-by-size liberation, and the energy of subsequent unit operations. (Fan et al., 2012; Gu et al., 2025; Rodriguez et al., 2021; Saramak & Naziemiec, 2013; Yu et al., 2026; Zhang et al., 2022).

Distinguish specific pressing force from hydraulic pressure. When the convention is applicable, specific pressing force is reported as $F_{sp} = F_{total}/(D \times L)$ (N/mm²), where F_{total} is the effective applied roll-separating force (N), D is roll diameter (mm), and L is roll working length (mm); the actual manufacturer/test-specific convention must always be identified. Pressure in the hydraulic circuit (bar) is not interchangeable with the local particle-bed stress or Fsp. Measure product PSD before and after a specified deagglomeration protocol, as compressed flakes can affect the result.

Mechanical activation offers a complementary conceptual lens for interpreting compression-induced changes in mineral solids. However, activation, the generation of new fracture surfaces, and demonstrable chemical or metallurgical improvements are distinct endpoints. The potential transfer of activation-based findings to HPGR operation therefore requires measurements of structural changes and a controlled comparison of downstream response rather than extrapolation from applied stress alone (Pereira, 2026c).

The product typically combines compressed agglomerates with fragmented material and may require disintegration or screening before a meaningful size distribution is determined. Comparing directly measured flake size with the product of a conventional crusher without standardizing the deagglomeration procedure risks conflating physical aggregation and genuine particle breakage. (Aminalroaya & Pourghahramani, 2022; Campos et al., 2021; Lieberwirth & Kühnel, 2021).

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The figure provides an original conceptual synthesis of the preceding evidence and identifies the interfaces to test in site-specific studies.

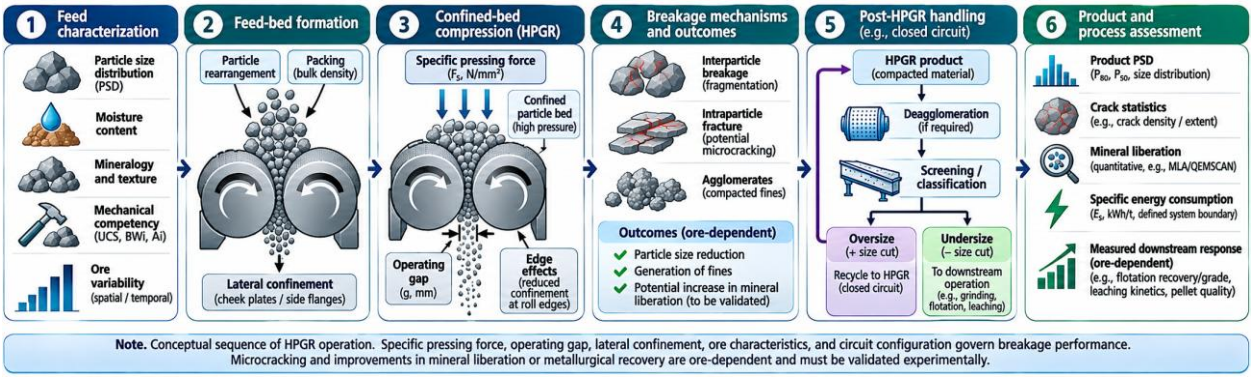


Figure 1. Idealized sequence from feed-bed formation to HPGR product assessment.

Note. Original conceptual figure created for this review, informed by the thematic literature; no quantitative values are reproduced.

Interpret the scheme as an evaluation structure rather than a universal process prescription. The evidence base must establish whether each proposed link is causal, merely correlated, or restricted to a particular ore and circuit. (Barrios & Tavares, 2016; Campos et al., 2020).

4. Ore Characterization and HPGR Applicability

Ore competency is not captured by Bond ball mill work index alone. Mineral assemblage, structural anisotropy, texture, abrasion resistance, size-class composition, and the degree of moisture-sensitive adhesion affect load distribution in a compressed bed. Representative testwork should cover distinct geological domains and anticipated blend envelopes instead of relying on one convenient bulk sample. (Alves et al., 2015; Anticoi et al., 2018; Baawuah et al., 2020; França et al., 2020; Sadangi & Das, 2022).

A representative applicability matrix should span competent and soft ore domains, clay-rich and high-fines cases, coarse-feed excursions, dry- and wet-season moisture, and operational blend scenarios. Bond work index is not a standalone proxy for HPGR response; the test envelope also requires mineral texture, compression-specific tests, abrasion indices, packing response, and feed distribution across roll width.

Feed particle-size distribution controls bed packing and the fraction of particles directly loaded in the nip. Segregation across the roll width can produce variable product and wear

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profiles even at constant nominal set pressure. Piston-press tests and pilot locked-cycle work provide screening information, but they must be linked to scale-specific feed behavior, throughput, and edge confinement before industrial extrapolation. (Izadi-Yazdan Abadi et al., 2025; Kumar et al., 2023; Liu et al., 2024; Pamparana & Klein, 2021; Pamparana et al., 2024; Pamparana et al., 2022).

Moisture and clay content may influence friction, cohesion, bed stability, and screening duty; their effect is not universally monotonic. Any selection threshold requires site-specific testing over the full expected moisture range, including upset conditions and changes in ore handling. (Aminalroaya & Pourghahramani, 2022; Saramak & Kleiv, 2013).

Clay-bearing and chemically heterogeneous mineral feeds warrant a characterization protocol that resolves mineral associations, fine-particle distribution, and moisture-sensitive behavior. Characterization approaches developed for lateritic copper clays illustrate the need for phase-specific observation, but cannot independently establish an HPGR operating envelope (Mano et al., 2015). Similarly, the review of phosphorus removal from iron ore illustrates how mineral occurrence and separation objectives determine the downstream value of size reduction, without providing direct HPGR performance data (Pereira & Papini, 2015).

Table summarises the comparison criteria required to interpret the evidence without conflating machine performance and whole-circuit outcomes.

Table 2. Ore characterization and applicability evidence matrix

Test/observation	Decision role	Qualification
Mineralogical mapping	Breakage and liberation domains	Representative texture and blend
Compressive and impact tests	Contrasting breakage modes	Test scale and stress path
PSD / moisture matrix	Packing and throughput sensitivity	Seasonal and segregation effects
Abrasivity / liner testing	Wear risk screening	Industrial extrapolation uncertain
Pilot HPGR / closed cycle	Product PSD and operating response	Campaign length and recirculation

Note. Original qualitative synthesis. Tests are recommended evidence categories, not interchangeable design guarantees.

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5. HPGR Circuit Configurations and Integration

Flowsheet architecture determines whether an HPGR serves as tertiary crushing, final grinding assistance, or a mineral-processing enabler. Open-circuit and closed-circuit layouts differ in classification efficiency, edge recycle, fines handling, water management, and circulating loads. Consequently, a favorable machine-specific kWh/t result does not resolve the performance of an integrated comminution circuit. (Altun et al., 2011; Jankovic et al., 2016; Jankovic et al., 2015; Ozcan et al., 2015; Gruendken & Gruendken, 2010).

For closed-circuit reporting, circulating load is defined as CL (%) = 100 × (dry recycle mass flow)/(dry fresh-feed mass flow). Report the classifier split and bypass, edge recycle, net product flow, and deagglomeration conditions alongside nominal roll throughput. High roll throughput may coexist with a much lower net fresh-feed rate when circulating load is high.

HPGR can be paired with ball mills, tower mills, or stirred mills, and may form part of hybrid SAG-based circuits. The correct comparison matches functional duty: feed tonnage and mineralogy, product liberation requirement, plant availability, and the energy and material balance of all supporting equipment. A circuit producing a coarser intermediate product is not necessarily a more energy-efficient alternative if finer downstream grinding is needed. (Ballantyne & van der Meer, 2018; Gagnon et al., 2023; Li et al., 2023; Li et al., 2026; Santosh et al., 2023; Wei et al., 2025).

Dry configurations are attractive where water use or wet handling imposes constraints, but they add demands for dust control, dry classification, fines transport, and product moisture management. Evidence from iron ore pellet feed, graphite processing, and magnetite-containing ores demonstrates the need to differentiate pelletizing, liberation, and general-purpose fine-grinding objectives. (Guo et al., 2026; Jankovic et al., 2016; Ma et al., 2021; Oliinyk et al., 2021; van der Meer, 2015; Wen et al., 2026; Xu et al., 2021).

A recent low-carbon comminution review places HPGR within a wider portfolio that includes microwave and electric-pulse pretreatment, (semi-)autogenous milling, stirred milling, and hybrid HPGR–stirred-mill flowsheets. Such comparisons strengthen the case for consistent flowsheet boundaries rather than universally ranking one machine as environmentally superior (Jia et al., 2026).

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Scale-up should be assessed by preserving relevant mechanisms and process interfaces rather than by geometric equipment enlargement alone. This broader mineral-processing principle supports an explicit check that pilot responses remain transferable to an industrial circuit under changes in classification duty, feed variability, recycle, and maintenance constraints; it is not, by itself, evidence of a particular HPGR throughput or energy advantage (Pereira, 2026d).

The figure presents an original conceptual synthesis of the preceding evidence and identifies the interfaces to test in site-specific studies.

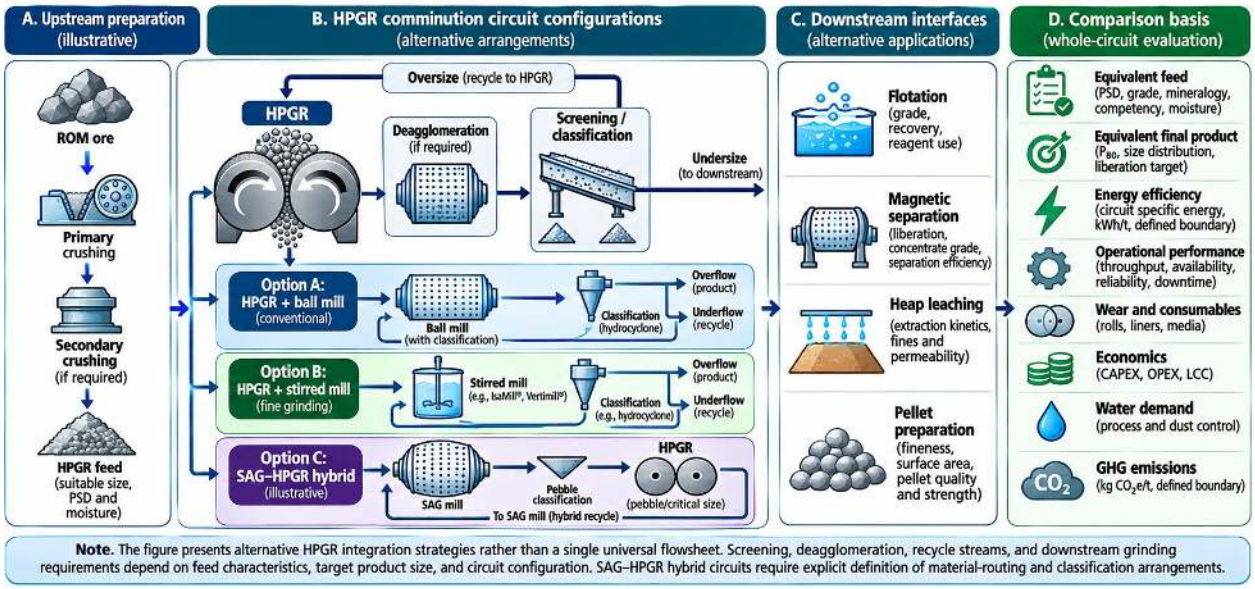


Figure 2. Illustrative hybrid HPGR comminution sequence and downstream interfaces.

Note. Original conceptual figure created for this review, informed by the thematic literature; no quantitative values are reproduced.

Interpret the scheme as an evaluation structure rather than a universal process prescription. The evidence base must establish whether each proposed link is causal, merely correlated, or restricted to a particular ore and circuit. (Gagnon et al., 2023; Jankovic et al., 2015).

6. Energy Efficiency and Comminution Performance

Specific energy is meaningful only with its calculation basis. Net press power, installed motor demand, energy allocated to screens and conveyors, and grinding energy after HPGR are distinct quantities. The review therefore recommends a whole-circuit energy ledger that reports fresh dry throughput, equivalent final product size and liberation, and whether it

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includes standby or low-load power. (Li et al., 2023; Morrell, 2022; Morrell, 2010; Napier-Munn, 2015; Starkey et al., 2022).

A reported percentage improvement is ΔSEC (%) = 100 × (SEC_reference − SEC_HPGR_circuit)/SEC_reference, meaningful only where feed mineralogy, F80, final P80/liberation target, recycle/classification, and measurement boundaries are equivalent. Otherwise, report it as an explicitly case-specific observation. For SEC = P/Q, first-order independent relative uncertainty is approximately $(u_SEC/SEC)^2 \approx (u_P/P)^2 + (u_Q/Q)^2$; correlated errors require covariance terms.

For a matched downstream-suitable dry product, SEC_circuit = (E_HPGR + E_classification + E_conveying + E_deagglomeration + E_downstream_grinding + E_aux)/(m_downstream-suitable,dry), in kWh/t dry product. Energy values must cover identical operating intervals and include relevant standby or ancillary loads. The machine metric is SEC_HPGR = E_roll/(m_fresh, dry), with its roll-drive and dry fresh-feed boundaries stated. If saleable-product output is the decision endpoint, SEC_saleable = E_total/m_saleable, and this denominator must not be conflated with ore tonnes.

Pressure and moisture influence the balance between size reduction, product fineness, and energy. Optimization should include the economic objective and the variability envelope rather than selecting a single nominal maximum-pressure operating point. Industrial-scale studies and comparative cases indicate that interactions among roll setting, operating stability, and classification drive realized performance. (Massinaei & Javanshiri, 2026; Santosh et al., 2023; Saramak & Leśniak, 2024; Wei et al., 2026; Wu et al., 2025; Zheng et al., 2025).

Industrial-scale evidence is especially important for implementing the proposed operating-envelope approach. Massinaei and Javanshiri (2026) reported an iron-ore plant study spanning operating pressure 145–185 bar, roll speed 0.6–1.0 m/s, feed rates of 1,000 and 1,400 t/h, fines fractions of 30% and 42%, moisture contents of 1.8–4%, and both new and worn rolls. These are study-specific ranges, not universal design limits. Their results indicate trade-offs among size reduction, throughput, power demand, feed condition, and wear; a single favorable setpoint does not guarantee lifecycle superiority.

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Size-specific energy frameworks help align different feed and product size distributions, but their input parameters and transferability need validation against the ore under consideration. The common practice of quoting percentage energy savings without specifying the reference circuit, size distribution, and operating window cannot support transferable engineering conclusions. (Akhmetov et al., 2025; Ballantyne & van der Meer, 2018; Li et al., 2023; Morrell, 2010; Santosh et al., 2023).

The table summarises the comparison criteria required to interpret the evidence without conflating machine performance and whole-circuit outcomes.

Table 3. Energy and performance reporting rules

Metric	Basis	Interpretation
HPGR net energy	Measured roll drive kWh / fresh dry t	Machine only
Auxiliary energy	Screening, fans, conveyors, deagglomeration	Additional circuit loads
Total comminution energy	All stages to matched final product	Preferred comparison
Availability-adjusted output	Saleable or downstream-suitable t/year	Economic relevance
Uncertainty interval	Ore variability and power metering	Decision robustness

Note. Original normalization rules for engineering comparisons; no universal savings are asserted.

This comparison underscores the importance of reporting the basis of calculation, uncertainty, and the operating envelope. Apparent gains observed under differing product specifications cannot be generalized as equipment-level superiority.

7. Equipment Design, Wear, Reliability, and Operational Control

HPGR design relies on the interplay of roll geometry, surface wear protection, lateral confinement, pressure control, skew response, and feed presentation. Wear profiles and asymmetry alter both throughput and product distribution; therefore, performance trials obtained immediately after installation should not be assumed representative of the full liner lifecycle. (Chen et al., 2025; Guo et al., 2025; Gu et al., 2025; Kazerani Nejad & Sam, 2017; Penagos et al., 2025; Rashidi & Rajamani, 2020; Saramak et al., 2016; Sesemann et al., 2013).

Where available, wear intensity should be reported as I_W = m_wear-material/m_ore-processed (kg/t); comparable alternatives include mm per 1,000 operating hours, mm/Mt, and total tonnes processed per roll campaign. Availability is A = t_available/t_scheduled, with

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availability-adjusted production Q_annual = q_net × A × t_scheduled. Distinguish scheduled from unplanned downtime; report MTBF, MTTR, roll-replacement duration, and performance changes across the wear lifecycle. These quantities connect technical response directly to delivered annual product and cost.

Studs, flanges, cheek plates, and other confinement designs redistribute material and contact forces differently. Model results on roll surfaces and edge losses help compare design concepts, but their implications for installed availability and maintenance cost require field evidence, including service conditions and replacement downtime. (Guo et al., 2025; Rodriguez et al., 2021; Rodriguez et al., 2024; Tahaei et al., 2025; Onol et al., 2024; Zhang et al., 2025; Zou et al., 2023).

Sensor networks and predictive models may improve fault detection and process control. Still, model deployment should include measurement validation, operating bounds, alarms, and a documented strategy for changes in ore hardness or wear state. Control effectiveness should be evaluated on stable production and whole-circuit outcomes, not prediction accuracy alone. (Campos et al., 2023a; Campos et al., 2023b; Chen et al., 2025; Thivierge et al., 2022; Thivierge et al., 2023; Thivierge et al., 2021; Yang et al., 2026).

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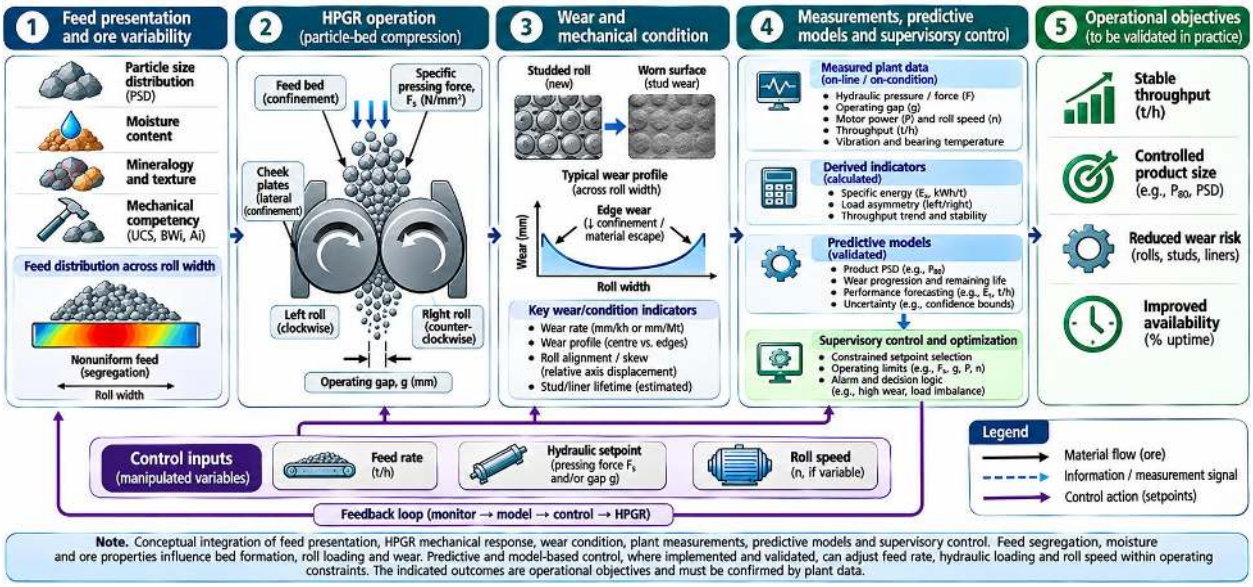


Figure 3. Conceptual coupling of feed distribution, wear, process measurements, and control.
Note. Original conceptual figure created for this review, informed by the thematic literature; no quantitative values are reproduced.

Interpret the scheme as an evaluation structure rather than a universal process prescription. The evidence base must establish whether each proposed link is causal, merely correlated, or restricted to a particular ore and circuit. (Rashidi & Rajamani, 2020; Rodriguez et al., 2024).

8. Effects on Mineral Liberation and Downstream Processing

HPGR-induced microcracks can create new particle boundaries and potentially alter the accessibility of valuable minerals. This physical pathway is plausible, but microcracks do not necessarily translate into improved plant recovery. Comparisons must isolate particle-size effects and include mineralogical liberation measures alongside appropriately controlled flotation, magnetic separation, or leaching tests. (Asakawa et al., 2024; França et al., 2020; Ghorbani et al., 2013; Kodali et al., 2011; Liu et al., 2018; Saramak & Saramak, 2020; Saramak et al., 2017).

For microscopy-based claims, a method-specific two-dimensional crack line-density descriptor may be reported as ρc = L_crack/A_particle. State the size class, imaging resolution, thresholding, crack location and connectivity, and stereological limitations. Automated

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mineralogy (e.g., MLA/QEMSCAN) should independently measure target and gangue liberation by size at matched product PSD. Downstream recovery requires controlled flotation, leaching, or pelletization tests, not inference from cracks alone.

The literature includes studies linking HPGR treatment to copper sulfide liberation, gold leaching, graphite processing, iron ore pellet preparation, and vanadium-bearing feedstocks. These applications show broad process relevance and illustrate that the preferred crushing mechanism depends on the downstream target: extraction kinetics, pellet strength, coarse pre-concentration, or size-by-size recovery may respond differently. (Fan et al., 2012; Gao et al., 2026; Guo et al., 2020; Guo et al., 2026; Ma et al., 2021; Ma et al., 2015; Navaei et al., 2025; Saramak et al., 2014; Tang et al., 2020; Yin & Chen, 2021; Yin et al., 2017; Zhang et al., 2024).

When heap leaching is considered, evaluate crack density alongside percolation, fines generation, agglomeration, and hydraulic performance. Where flotation is involved, the decisive comparison should report liberation and flotation response under common chemistry, grind size, and residence-time conditions. (Devasahayam, 2026; Ghorbani et al., 2013; Nghipulile et al., 2023; Saramak & Saramak, 2020; Tang et al., 2020; Thatipamula & Devasahayam, 2025; Zhong et al., 2023).

Mineralogical evidence is needed to determine whether altered particle-size distribution or fracture patterns improve liberation of the target phases, rather than merely increase fines generation. Automated mineralogy can link liberation to metallurgical recovery and complement HPGR-specific studies, but any claim of recovery enhancement still requires controlled downstream tests (Pereira, 2026b).

The table summarises the comparison criteria needed to interpret the evidence without conflating machine performance and whole-circuit outcomes.

For heap-leaching applications, consider fine-particle agglomeration and its scale-up constraints alongside the HPGR-generated size distribution. Reviews of agglomeration mechanisms and transfer from bench tests to industrial drums help frame test requirements for permeability, stability, and hydraulic response; they do not demonstrate that HPGR always improves heap performance (Pereira, 2026a, 2026f).

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Table 4. Downstream effects: claims requiring independent verification

Potential effect	Suggested measurement	Necessary control
Microcrack generation	Image-based crack statistics	Comparable particle size class
Mineral liberation	Automated mineralogy by size	Matched final PSD
Flotation response	Grade–recovery curves	Reagent chemistry and residence time
Heap leach response	Extraction and permeability	Agglomeration and fine fraction
Pellet quality	Green/dry/fired strength	Binder, moisture and size

Note. This table is a critical test design, not an assertion that HPGR universally improves these outcomes.

This comparison underscores the importance of reporting the basis of calculation, uncertainty, and the operating envelope. Apparent gains under different product specifications cannot be generalized as equipment-level superiority.

9. Modeling, Simulation, Digitalization, and Process Optimization

HPGR models range from empirical relationships to population balance methods (PBM), discrete element method (DEM), particle replacement models, and hybrid particle–machine dynamics. Model fidelity depends on what is represented: force chains and bed rearrangement, breakage probabilities, axial pressure variation, or circuit-scale size distributions. Parameters fitted at one feed and stress state can lose validity following a substantial ore blend or operating change. (Anticoi et al., 2019; Barrios et al., 2020; Barrios & Tavares, 2016; Campos et al., 2019b; Campos et al., 2021; Dundar et al., 2013; Esnault et al., 2015; Guo et al., 2024; Johansson & Evertsson, 2019; Nagata et al., 2020; Rashidi et al., 2017; Rodriguez et al., 2022a; Rodriguez et al., 2022b; Rodriguez et al., 2023; Santosh et al., 2023; Tavares et al., 2021).

A key development is linking plant sensors and data-driven models to physically informed variables. Data-driven prediction can support short-term optimization, but black-box fits may learn correlations that fail when roll conditions, feed humidity, or throughput constraints change. Reported predictive accuracy should be accompanied by external validation, uncertainty bounds, and interpretability relative to measured machine variables. (Campos et al., 2023a; Campos et al., 2023b; Chelgani et al., 2021; Gu et al., 2025; Li et al., 2025; Li et al., 2026; Thivierge et al., 2020; Thivierge et al., 2022; Thivierge et al., 2021ba; Thivierge et al., 2021; Tohry et al., 2021; Wang et al., 2026; Yang et al., 2024; Yang et al., 2026; Yang et al., 2026; Zhang et al., 2026).

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Model comparisons should distinguish goodness of fit on calibration records from holdout validation within one domain and external validation across independent ore, moisture, pressure, throughput, or wear conditions. High R^2 or low RMSE alone is not proof of scale-transferability or operational value.

Independent test datasets are particularly valuable when contrasting models for edge effects, compression force, machine dynamics, and wear evolution. The most decision-useful validation is not merely statistical fit: it establishes whether predicted energy, capacity, wear, and product PSD remain sufficiently accurate to select a circuit or operating policy. (Cleary & Sinnott, 2021; Guo et al., 2024; Gu et al., 2025; Rodriguez et al., 2021; Rodriguez et al., 2022; Rodriguez et al., 2024; Rodriguez et al., 2023; Zhang et al., 2025; Zhang et al., 2022; Zou et al., 2023).

Models intended for technology selection must preserve the link between the mechanism represented and the whole-flowsheet outcomes being predicted. Accordingly, test transferability across scales against independent operating conditions, ore variability, and circuit feedback rather than accepting it from a good local numerical fit alone (Pereira, 2026d).

10. Techno-Economic and Environmental Assessment

Techno-economic assessment should include installed equipment and civil works, material handling, dust suppression, classification, power systems, wear consumables, downtime, and the effect of downstream recovery on revenue. Greenfield and brownfield cases must be distinguished because available footprint, structural constraints, and retrofit interruptions can materially alter the preferred configuration. (Amelunxen & Meadows, 2011; Morrell, 2022; Numbi & Xia, 2015; Rosario, 2017; Saramak & Saramak, 2024; Starkey et al., 2022; Vyhmeister et al., 2019).

Environmental comparisons should use matched lifecycle boundaries and report I_GHG = kg CO_2e per tonne of downstream-suitable product and I_water = m^3 of freshwater withdrawal or consumption per tonne of the same product, with the water definition identified. Inventory boundaries should include energy mix, dust control, consumables, wear components, water recirculation, and downstream impacts where material. A reduction in press drive electricity does not alone demonstrate reduced emissions or freshwater use.

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Minimum quantitative TEA inputs include capacity and schedule, cost year and currency, project location, installed CAPEX and contingency, classification and auxiliary equipment, electricity and water prices, maintenance and labor, wear-part replacement and downtime, downstream recovery, project duration, and discount rate. Wear-linked unit cost can be expressed as C_wear = (C_roll/liner + C_replacement labor + C_downtime)/m_ore processed; the attribution of opportunity cost to outages must be transparent.

Environmental claims require equivalent functional units and boundaries. Reduction in net electrical energy has emissions consequences only after accounting for the electricity supply, changes in product yield, auxiliary services, and the broader process. Dry circuits may conserve process water but can increase demands for dust management; neither outcome establishes environmental superiority without quantified boundaries. (Akhmetov et al., 2025; Napier-Munn, 2015; Saramak, 2021; Saramak & Saramak, 2024; Vyhmeister et al., 2019).

A transparent sensitivity analysis should vary ore competency and moisture, throughput, liner life, availability, electricity price, classification efficiency, and metallurgical response. Treat economic comparisons based solely on vendor design points or unusually favorable operating campaigns as scenarios rather than proven lifecycle performance. (Amelunxen & Meadows, 2011; Rosario, 2017; Saramak, 2012; Saramak & Saramak, 2024; Starkey et al., 2022).

A practical techno-economic comparison should also expose scale-up assumptions, including fines handling, downstream recovery sensitivity, and production losses under uncertain operating conditions. Mechanism-preserving scale-up frameworks provide a useful structure for organizing these assumptions but cannot substitute for site-specific capital, operating, and reliability data (Pereira, 2026d).

11. Critical Synthesis, Technology Selection, and Research Priorities

The accumulated evidence supports a conditional, rather than universal, selection framework. HPGR is most persuasive when representative ore tests show suitable compression response, downstream unit operations benefit from the resulting product, and the full energy–reliability–cost balance remains favorable under realistic variability. Cases with problematic moisture or feed segregation, heavy recirculating loads, or costly liner replacement demand a

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more cautious assessment. (Izadi-Yazdan Abadi et al., 2025; Morrell, 2022; Pamparana et al., 2024; Saramak & Kleiv, 2013; Saramak & Saramak, 2024; Starkey et al., 2022).

Research priorities include longer industrial wear datasets, harmonized energy accounting, factorial ore-variability testing, integration of liberation with metallurgical recovery, and public reporting of uncertainty. Future models should demonstrate transfer from laboratory to industrial scale without relying entirely on refitting to each new feed or machine configuration. (Anticoi et al., 2019; Guo et al., 2024; Rashidi et al., 2017; Rodriguez et al., 2024; Rodriguez et al., 2025; Thivierge et al., 2020; Thivierge et al., 2022; Wei et al., 2026).

The table summarises the comparison criteria required to interpret the evidence without conflating machine performance and whole-circuit outcomes.

Table 5. Conditional technology selection framework

A defensible decision rule compares alternatives across the full ore and operating envelope, with matched downstream product specification and sensitivity to electricity price, feed competency, moisture, classifier efficiency, roll lifetime, availability, and metal recovery. Deterministic sensitivity and scenario analysis are a minimum; use probabilistic uncertainty when data support distributions. Technology preference should withstand plausible adverse cases, not merely maximize expected nominal throughput.

Criterion	HPGR-favourable indicator	Red flag requiring assessment
Ore response	Consistent compression breakage in representative campaigns	High variability, clay or moisture sensitivity
Process integration	Validated matched P80 and downstream benefit	Unaccounted classification/recycle duty
Reliability	Wear and availability within economic envelope	Unproven liner life/feed maldistribution
Economic performance	Robust lifecycle cost under sensitivity tests	Benefit only at nominal design point
Evidence quality	Independent pilot/industrial validation	Extrapolation from unvalidated simulations

Note. Original qualitative decision framework; site-specific thresholds should be determined by testwork.

This comparison underscores the importance of reporting the basis of calculation, uncertainty, and the operating envelope. Apparent gains observed under differing product specifications cannot be generalized as equipment-level superiority.

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The figure provides an original conceptual synthesis of the preceding evidence and identifies the interfaces to test in site-specific studies.

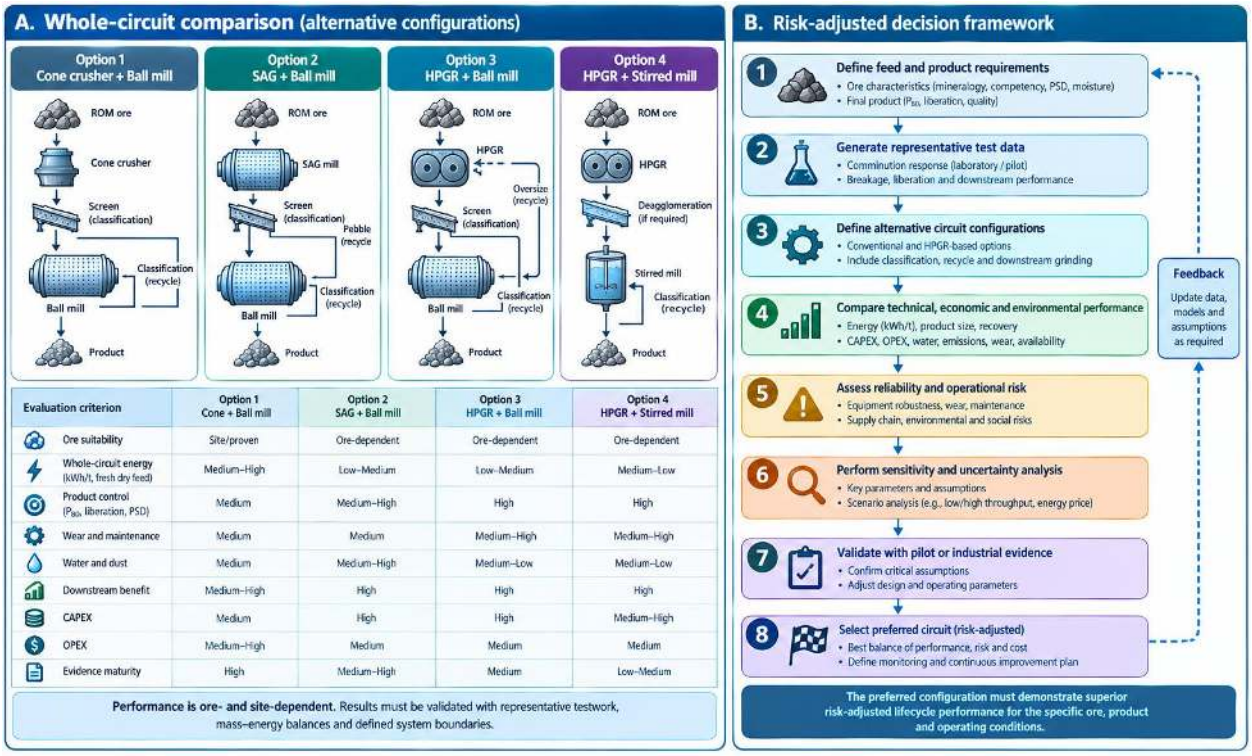


Figure 4. Whole-circuit comparison and risk-adjusted decision framework.
Note. Original conceptual figure created for this review, informed by the thematic literature; no quantitative values are reproduced.

Interpret the scheme as an evaluation structure rather than a universal process prescription. The evidence base must establish whether each proposed link is causal, merely correlated, or restricted to a particular ore and circuit. (Amelunxen & Meadows, 2011; Rosario, 2017).

A further set of practical case studies shows why selection should be framed around explicit process objectives rather than the HPGR label itself. Feed-shape modification, manufactured-sand production, and pellet-feed preparation have different target distributions and downstream constraints from sulfide liberation; their results should not be pooled into a single performance coefficient. (Abazarpoor et al., 2018; Almeida et al., 2023; Athayde & Bagatini, 2018; Campos et al., 2019a; Leite & Leite, 2018; Maphosa & Maphosa, 2012).

Comparative trials also vary in methodology and reporting maturity. Conference presentations, plant case histories, and laboratory equipment evaluations can add context. Still,

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they should be separated from peer-reviewed, reproducible evidence when assigning confidence to energy savings or life-cycle operating costs. (Ferreira & Ferreira, 2025; Lisboa et al., 2025; Mokgomola et al., 2025; Morley, 2010; Saramak & Saramak, 2025; Silva et al., 2015; Uttarwar et al., 2022).

Recent specialist studies on wear-resistant design, multi-physics simulation, and mineral beneficiation offer useful hypothesis-generating observations. Still, their applicability to high-throughput ore circuits depends on test scale and mineralogical similarity rather than publication date. (Weerasekara et al., 2013; Wu et al., 2026; Xue et al., 2024; Xu et al., 2025; Yin et al., 2014; Yu et al., 2024; Zhang et al., 2026; Zhong et al., 2026).

12. Conclusion

HPGR can provide substantial process value as a component of mineral comminution circuits, but the available evidence does not support universal superiority based on equipment-specific energy figures. Appropriate application depends on representative ore characterization, the degree of particle-bed confinement, the integrated classification and grinding circuit, and downstream metallurgical requirements. Controlled liberation and recovery tests should support benefits attributed to microcracking, rather than inferring them from breakage morphology alone. Plant-level comparisons must normalize the feed, final product, throughput, and measurement boundaries, and should include wear-adjusted availability and lifecycle cost. The proposed decision framework therefore treats HPGR selection as a conditional engineering outcome informed by pilot and industrial evidence. Improved public datasets, validated model transfer, and long-term techno-economic and environmental reporting remain priorities.

Declarations

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Data Availability

No new experimental datasets were generated for this narrative review. Literature references are listed below; source-level verification has been completed only for specifically identified records, and an exhaustive source audit is required before a claim of full bibliographic verification can be made.

Author Contributions

Author identity and contributor roles are withheld in this double-masked reviewer manuscript. The final CRediT contribution statement should be restored in the non-anonymized production file after author approval.

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Supplementary Table S1. Reproducible thematic search expressions (proposed update; historical search strings unavailable)

S01. ("high pressure grinding rolls" OR HPGR) AND ("particle bed" OR interparticle) AND breakage

S02. HPGR AND (ore competency OR hardness OR "work index")

S03. HPGR AND (mineralogy OR texture OR anisotropy) AND response

S04. HPGR AND (moisture OR clay OR adhesion) AND performance

S05. HPGR AND ("feed size distribution" OR F80 OR packing)

S06. HPGR AND ("specific pressing force" OR hydraulic pressure OR roll gap)

S07. HPGR AND (edge effects OR flange OR cheek plates)

S08. HPGR AND ("feed segregation" OR skewing OR distribution)

S09. HPGR AND (deagglomeration OR flakes OR "product size")

S10. HPGR AND ("closed circuit" OR screening OR classification)

S11. HPGR AND ("circulating load" OR recycle OR bypass)

S12. HPGR AND ("ball mill" OR "stirred mill" OR SAG) AND circuit

S13. HPGR AND ("specific energy" OR "whole circuit" OR energy efficiency)

S14. HPGR AND (industrial OR plant OR pilot) AND throughput

S15. HPGR AND (wear OR studs OR roll life OR reliability)

S16. HPGR AND (availability OR maintenance OR downtime OR MTBF)

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S17. HPGR AND (microcrack OR fracture OR crack density)

S18. HPGR AND ("mineral liberation" OR MLA OR QEMSCAN)

S19. HPGR AND (flotation OR "grade recovery" OR beneficiation)

S20. HPGR AND ("heap leaching" OR permeability OR agglomeration)

S21. HPGR AND (pelletization OR pellet feed OR green strength)

S22. HPGR AND (DEM OR PBM OR simulation OR scale up)

S23. HPGR AND ("machine learning" OR "predictive control" OR digitalization)

S24. HPGR AND (CAPEX OR OPEX OR techno-economic OR LCA OR "carbon footprint")

Search protocol note. These queries are a reproducible proposal derived from the topics described in the manuscript; they are not represented as the original searches, and database platforms, search date, hit counts, and deduplication should be logged when a complete update is performed.