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Dry Vertical Roller Mill Circuit Configurations, Pneumatic Classification and Integration into Mineral Processing Plants: A Critical Review

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Abstract

Dry vertical roller mills (VRMs) combine bed compression, material conveying and size classification in a compact comminution platform. Yet, equipment-level energy or fineness claims cannot establish superior plant-wide performance. This critical review examines the choice of open versus closed circuits, integrated versus external pneumatic classification, feed preparation, gas–solid recirculation, dust collection, product logistics and interfaces with high-pressure grinding rolls (HPGR), ball mills and downstream separation. A source-based working bibliography of 147 published records was organized into direct VRM evidence and complementary evidence from classification, dry grinding, dust filtration, control and adjacent sectors. The appraisal uses explicit boundaries for electrical and thermal energy, solids and air streams, recirculation, bypass and product specifications. Direct comparisons remain constrained by dissimilar feeds, unreported classifier partition curves and incomplete auxiliary-power accounting. External classifiers may enable independent tuning and product flexibility, whereas integrated classifiers may reduce transfer points; neither configuration can be preferred unconditionally without material-specific tests and system-wide balances. The proposed evaluation framework emphasizes measured throughput, product size distributions, liberation, moisture, wear, emissions, and operational stability alongside uncertainty and technology readiness. The result is a decision-oriented evidence synthesis rather than a pooled quantitative estimate of VRM savings.

Keywords: vertical roller mill; dry comminution; pneumatic classification; circuit integration; mass and energy balances; mineral processing

Highlights

- Circuit boundaries determine whether reported VRM energy advantages are comparable.
- Classifier choice should be based on partition behavior, bypass and product requirements.
- Airflow, dust filtration and product logistics are integral to circuit performance.
- A staged validation protocol links bench tests, pilot trials and industrial adoption.

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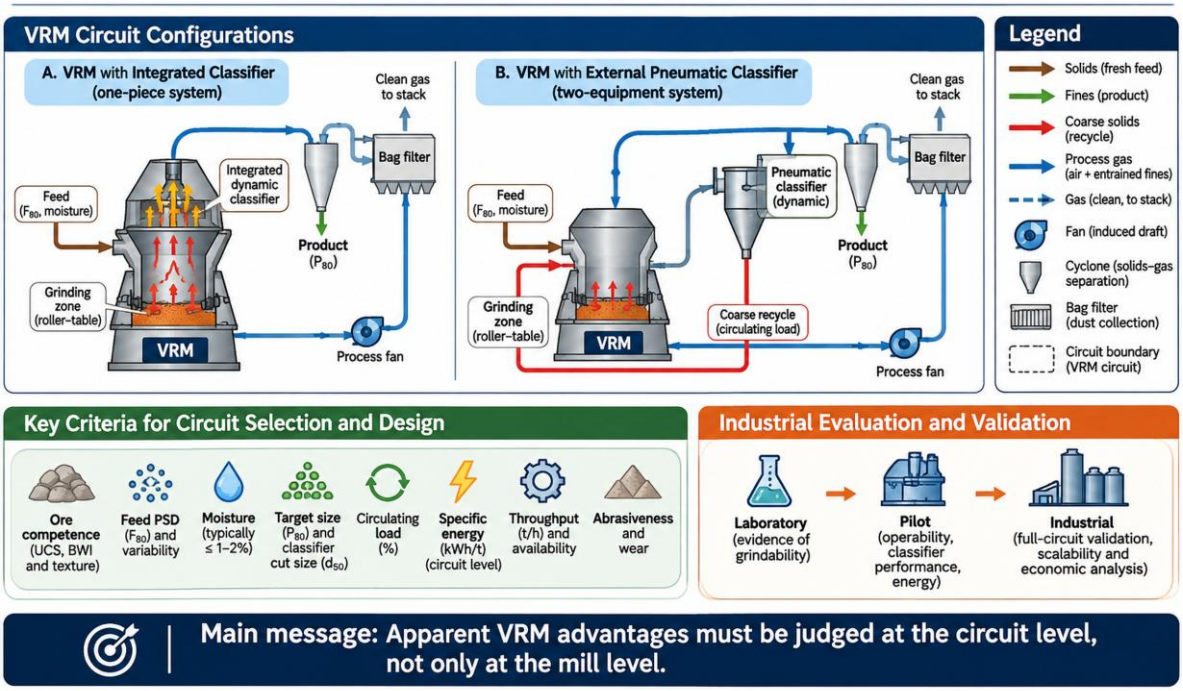
Graphical Abstract



1. Introduction and rationale

Mineral comminution must be evaluated in terms of energy demand, water use, particle-size specification, and mineral liberation. A dry vertical roller mill (VRM) combines bed-compression grinding with pneumatic solids transport and, frequently, integral classification. Its merits cannot be determined solely from the mill motor: air movement, drying, coarse return, dust recovery, and product handling can change both the energy balance and the operating constraints. Direct mineral VRM investigations (Altun et al., 2015; Altun et al., 2017) provide a starting point, while the broader air-classification literature supports specific comparisons only after acknowledging feed and equipment differences.

Three questions structure the review: when might an external classifier offer a circuit-level benefit relative to an integral separator; how should ore properties, feed size, moisture, and target product quality determine design; and what measured process boundaries allow defensible comparisons? Table 1 defines evidence levels, Table 2 lists the required balance streams, and Table 3 identifies equipment and controls. The graphical abstract and Figures 1–4 are included as conceptual illustrations; their instrument labels, stream connections, and design assumptions require independent engineering verification before publication. Figures

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1–2 distinguish integrated from external classification, Figure 3 summarizes gas–solid circulation and partitioning, and Figure 4 compares integration alternatives.

2. Critical review methodology and evidence grading

This manuscript is a structured critical review of a supplied 147-record working bibliography, assembled from focused searches emphasizing 2020–2026 and extending to earlier relevant publications. The source set was not obtained through a fully reproducible database export and should not be called a systematic review or PRISMA-compliant selection. We mapped its bibliographic entries to direct VRM evidence and transferable circuit-interface studies; independent source verification remains incomplete.

Evidence was categorized provisionally as D1 (direct mineral VRM experiments or operation), D2 (VRM modeling and control), C1 (direct mineral classification or dry-circuit evidence), and C2 (mechanistically transferable evidence from other applications). The distinction is methodological rather than a validated quality score: bibliographic metadata and abstracts alone do not support quantitative cross-study comparisons. Industrial claims require examination of methods and full texts.

Reject any comparative result from quantitative synthesis unless the material basis, product specification, and auxiliary equipment are declared. A useful hierarchy is replicated plant measurement above calibrated pilot experiments, then validated mechanistic simulation, then model-only prediction, followed by supplier claims. Disagreement across these categories should be reported, not averaged away. The frequent occurrence of CFD–DEM studies is valuable for mechanism identification but does not independently establish industrial wear rates, uptime, or costs.

Table 1 distinguishes direct VRM operating evidence from calibrated models and transferable unit-operation studies. This hierarchy restricts which conclusions can legitimately be drawn from each source category.

Table 1. Evidence grading and permitted interpretations

Tier	Source type	Permitted claim	Principal limitation
D1	Industrial or pilot VRM measurements	Conditional performance for disclosed feed and boundary	Single-ore or site-specific behavior

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Tier	Source type	Permitted claim	Principal limitation
D2	Calibrated VRM simulations and control models	Mechanism or prediction within calibration domain	Scale transfer and sensor drift
C1	Mineral air classifier or dry circuit tests	Classifier and circuit-design analogies	Different mill and air network
C2	Adjacent-sector or unit-operation studies	Mechanistic transfer hypotheses	Unknown mineralogical transferability
X	Reviews and process-context studies	Design context and research prioritization	Not VRM performance evidence

The hierarchy in Table 1 prevents transferring performance estimates from cement classifiers or simulated flows directly to mineral-ore VRM operations without matching material and circuit conditions.

3. Circuit boundaries and process objectives

A circuit definition begins at the feed battery limit and ends at a product whose PSD, chemistry, liberation, moisture, and temperature are acceptable to the next operation. On the solid side, the boundary includes receiving, precrushing (if required), drying, grinding, classifier rejects, product discharge, and collected filter dust. On the gas side, it includes intake and recirculated gas, make-up and leakage air, heaters, mill sweep, classifier, cyclones or filters, fan discharge and stack. Electrical energy accounting must cover the main drive, fans, separator rotor, mechanical feeders, conveyors, dust-filter cleaning and ancillary services, while thermal accounting must identify fuel and sensible heat. A stated value in kWh/t is uninterpretable until its numerator and product-mass denominator are defined.

The minimum mass-balance closure includes fresh dry-feed solids, classifier returns, captured fines, final product, purge, and losses; moisture evaporated requires a separate water balance. F80 and P80 are necessary but insufficient descriptors because classification depends on the full distributions and fines bypass, while subsequent flotation or leaching may respond to mineral-specific liberation or surface states. Mineralogy-based process-selection sources are useful here but cannot be used as measurements of VRM circuit performance (Pereira, 2026a, 2026b; Rocha et al., 2025).

A thermal boundary is particularly important when comparing an integral drying arrangement with a separately heated external classifier. If heat is recovered or supplied by

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another process, the comparison must explicitly state whether that heat is free, allocated, or charged as fuel. A nominal "dry" circuit may still require water management for dust suppression, cleaning, and downstream conditioning. Thus, water avoidance is a flowsheet attribute, not a property that can be inferred solely from mill technology.

Table 2 specifies the minimum stream measurements needed to compare alternative VRM circuits on a consistent solids, gas, water, and energy basis. Unmeasured returns or auxiliary loads can invalidate apparent efficiency differences.

Table 2. Stream-wise mass, energy and design data needed for a VRM comparison

Stream/interface	**Required measurements**	**Why indispensable**
Fresh feed	Wet/dry rate; component and size PSD; moisture; T	Reproducible ore and water basis
Mill discharge	Solids and entrained-gas rates; PSD; T	Grinding duty and circulating balance
Classifier coarse return	Rate and size-dependent partition	Circulating load and bypass
Finished fine product	Dry rate; PSD; liberation; residual moisture	Functional product specification
Air intake/recycle	Flow; T; absolute pressure; humidity; dust	Fan and dryer boundaries
Dust collector and stack	Captured solids; pressure drop; emissions	Recovery, compliance and ancillary power
Power and heat inputs	Drive/rotor/fan power; fuel; air heater duty	Full delivered-product specific energy

Collect the measurements in Table 2 at compatible battery limits; otherwise, the reported kWh/t may omit fan, dryer, filter, or reject-handling duties.

4. Open-circuit versus closed-circuit operation

In nominal open-circuit grinding, solids traverse the mill without an intentional coarse-product return to the grinding zone. By contrast, closed circuits contain a size-selective recycle that can limit overgrinding and permit independent adjustment of final fineness. Terminology becomes ambiguous in an air-swept VRM because internal bed turnover and rejects can occur even when no external coarse-return line is drawn. A rigorous classification should therefore specify whether recirculation is internal, pneumatic, or externally conveyed, and whether a sharp partition function is measured. Figure 1 summarizes the relevant circuit concept.

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Figure 1 illustrates the integrated-classifier VRM, highlighting the internal coarse-particle return and the separate gas–solid collection train.

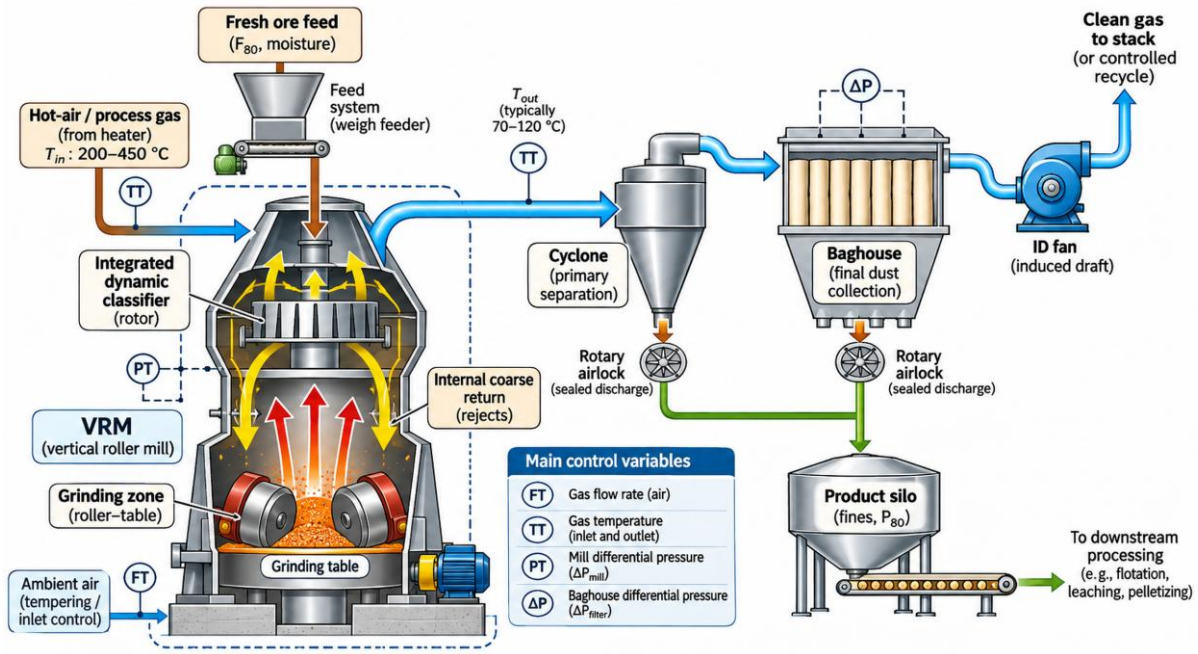

Figure 1. Dry vertical roller mill circuit with an integrated dynamic classifier, internal coarse-particle return, cyclone–baghouse solids recovery, and product handling.

Note. AI-assisted conceptual illustration prepared for this review, based on the technical synthesis in the manuscript; not adapted or reproduced from a published figure. Not to scale; process configuration requires project-specific engineering validation.

Figure 1 provides an illustrative boundary for integrated classification. The collected solids and gas streams must be reconciled separately when comparing circuit performance.

Pilot overflow-mode modeling demonstrates why classification and residence-time definitions cannot be treated as interchangeable (Altun & Benzer, 2021). In direct pilot-scale ore studies, operating pressure and classifier speed were varied while product rate and particle size were assessed (Altun et al., 2017). By contrast, predictive work using piston-die breakage characterization and pilot VRM tests across eight ores provides a more explicit framework for material dependence (Altun et al., 2021). These studies address complementary questions—circuit dynamics, operating sensitivity, and grindability prediction—and should not be pooled as if all report equivalent whole-circuit energy boundaries. Residence-time data for cement clinker remain methodological analogies (Barani et al., 2022), not direct mineral-ore calibration.

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An apparently efficient closed circuit may lose its advantage through a high reject load, excessive separator pressure drop, or unstable solids return. Conversely, an open or overflow arrangement may be appropriate where broad PSD is acceptable and secondary classification occurs downstream. Circuit design must test these alternatives under identical feed and P80 targets; there is no universal ranking of their energy or liberation outcomes.

5. Integrated classifier versus external air classifier

An integrated classifier shares enclosure, airflow, and often control interactions with the grinding unit. Its compactness can reduce ductwork and transfer points, but mill sweep and separator operating windows may be coupled. An external classifier provides additional degrees of freedom in rotor speed, air velocity, and feed dispersion, potentially enabling multiple products or reconfiguration. These benefits are conditional: extra ductwork, lift, cyclones and fans can erase gains in classifier sharpness. Neither layout should be selected based on nominal cut size alone. Figure 2 summarizes the relevant circuit concept.

Figure 2 illustrates the alternative with an independent pneumatic classifier and external coarse-solids recycle, which introduces additional transport and pressure-loss interfaces.

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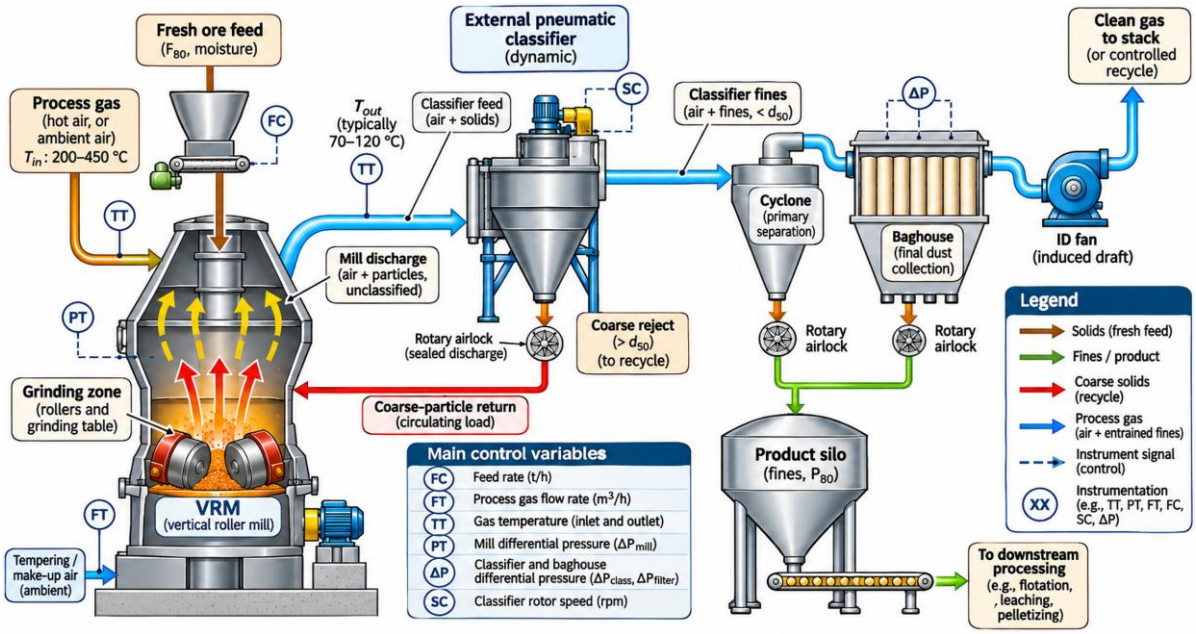

Figure 2. Dry vertical roller mill circuit with an independent pneumatic classifier, external coarse-particle return, cyclone–baghouse collection, and induced-draft gas handling.

Note. AI-assisted conceptual illustration prepared for this review, based on the technical synthesis in the manuscript; not adapted or reproduced from a published figure. Not to scale; process configuration requires project-specific engineering validation.

Figure 2 differs from Figure 1 in the location and transport requirements of classifier rejects; full-circuit comparisons must include extra conveying and pressure losses.

An external classifier must be assessed with a measured size-dependent partition (Tromp) function, including the selected direction of partition, d_{50}, sharpness, and fine-particle bypass to the coarse return. Coarse contamination of fines is a different misplacement mechanism and must not be assigned the same bypass parameter without definition. Rotor speed and gas velocity alone are insufficient descriptors: inlet dispersion, solids loading, particle density, shape, and agglomeration alter separation. Mineral-plant testing of an air separator (Ansari et al., 2025) and industrial quartz-classifier modeling (Ho et al., 2025) inform these interfaces but do not directly compare a matched integrated-versus-external VRM circuit. An equivalent comparison requires feed, coarse, and fine PSDs, dry mass rates, gas pressure losses, and fan power.

CFD and particle-tracking studies are especially useful for identifying short-circuit flow, poorly distributed inlets, and zones of agglomerate dispersion. However, single-phase flow fields alone cannot certify a partition curve. A technically credible comparison requires

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physical sampling of feed and coarse and fine outlets, an independently determined partition function, and repeated observations across moisture and loading variation. Claims of improved classification without these data are qualitative hypotheses.

6. Feed preparation, screening and precrushing

Grinding suitability begins with top size, F80, hard-mineral content, clay content and moisture. A feed with a nominally acceptable P80 may still contain sporadic oversize fragments that destabilize the bed, damage the feeder or demand excessive grinding force. Ore competence is not a single scalar property: mineral associations, breakage anisotropy, and size-dependent texture can affect the response to compression and its downstream liberation. Assess pre-crushing and scalping as coupled components of the final product specification rather than as independent equipment optimizations.

Moisture interacts with bed cohesion, air classification, powder adhesion, and filter performance. Where thermal drying is required, the assessment must distinguish water removal upstream of the mill from in-mill evaporation. The engineering choice depends on moisture variability, residence time, the useful heat-source temperature, and materials constraints. Fragmentation and preconditioning studies (including mineral-texture screening for HPGR) can support test planning, but do not quantify the required VRM grindability or classifier performance in isolation (Pereira, 2026d).

An industrial test campaign should include representative lithological composites, feed-tail variation, and moisture states, not a single blended sample. For each condition, report screen analysis, mineral liberation, operating stability, and any oversize bypass. Distinguish a finer P80 from improved downstream separation response: more grinding may generate slimes or surface changes that reduce recovery even when the bulk PSD becomes narrower.

7. Air and solid circulation, recycles and bypass

In an air-swept circuit, the gas network is both a transport system and a classification control variable. Airflow changes influence entrainment of fines, separation velocity, mill pressure drop, internal temperatures and fan power. The true circulating load cannot be safely inferred from a nominal separator setting; estimate it from measured solid-stream rates or

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balanced PSDs with uncertainty intervals. Unmetered bypasses can arise through short-circuit inlet flows, separator leakage, or coarse entrainment to fine product, and can be concealed in otherwise plausible overall mass balances. Figure 3 summarizes the relevant circuit concept.

Figure 3 distinguishes internal circulating load from classifier particle misplacement and locates the main gas-handling and control interfaces.

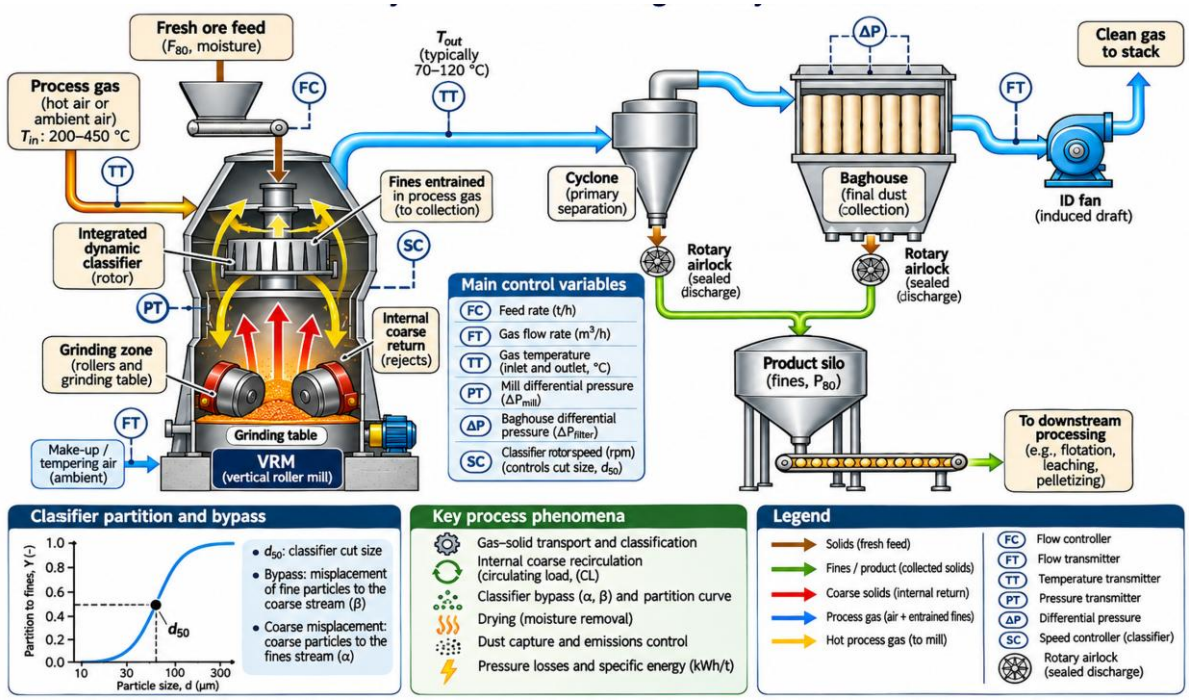

Figure 3. Gas–solid circulation, internal coarse-particle recirculation, classifier partitioning, and control interfaces in a dry VRM circuit.

Note. AI-assisted conceptual illustration prepared for this review, based on the technical synthesis in the manuscript; not adapted or reproduced from a published figure. Not to scale; process configuration requires project-specific engineering validation.

Figure 3 distinguishes the classifier misplacement phenomena from the recirculating mass load. Partition-curve conventions must be defined before assigning numerical bypass values.

Mechanistic simulations have illuminated millstone segregation, particle trajectories, and classifier vortices. However, extrapolation across equipment scales remains uncertain because particle–particle coupling, near-wall effects, and cohesive fines are difficult to characterize. CFD–DEM predictions are therefore most persuasive when checked against local pressure, velocity, and stream-composition measurements. The separation between gas

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recirculation and solids return is crucial: lowering gas flow to save fan energy may change both dust loading and product fineness.

A reliable circuit PFD should label every recycle, purge, bypass, bleed, and leak path; airflow set points should be supported by temperature and moisture constraints, not only by the classifier cut size. The design should explicitly estimate fan power under clean and dirty filter conditions, recognizing that filter pressure drop is dynamic and may control attainable airflow.

8. Dust collection, baghouses and emissions handling

Dust collection is not a secondary utility in dry comminution. Cyclones, fabric filters, transfer-point enclosures and stack fans govern product recovery, pressure drop, occupational exposure and compliance risk. Fine powder captured in the main baghouse may be part of the commercial product, a separately classified fraction, or a purge, depending on chemistry and downstream acceptability. It should never be silently counted as both product and loss.

Pulse-jet filter regeneration illustrates the interdependence of electricity, compressed air, and particulate emissions. Experimental and modeling investigations by Bächler and colleagues consider energy use, transient emissions, and leak detection in pulse-cleaned systems (Bächler et al., 2022, 2023, 2024). These data are relevant to monitoring methods and engineering trade-offs but are not emission factors specific to a VRM grinding a defined ore. Comparable constraints apply to cyclones whose nominal collection efficiency can vary with the actual gas–particle distribution and local vortex structure.

Baghouse design should disclose inlet mass loading and particle-size distribution, filtration velocity, pressure-drop design range, pulse pressure and consumption, filter-media specification, hopper discharge and maintenance isolation. For hazardous or chemically sensitive ores, evaluate requirements for containment, ignition prevention, and material compatibility separately; do not infer a universal collection percentage from a generic unit catalog. Site-specific permitting and exposure criteria remain outside the present evidence corpus.

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9. Product handling, storage and transport

The product of a pneumatic milling circuit is not necessarily stable or saleable immediately after the classifier. The process boundary may require gas–solids separation, cooling, storage, silo de-aeration, enclosed conveying, sampling and dust-return provisions. Powder properties may change with residual moisture, temperature, fineness and segregation. These changes can affect hopper flow, discharge accuracy, transport stability and downstream conditioning.

A design based only on bulk P80 can overlook fine-fraction re-entrainment, differential settling and high-density mineral segregation. Mineralogical analyses and downstream extraction studies in the supplied bibliography support attention to product composition and particle-size fractions. However, their transfer to dry VRM handling must be treated as contextual. Operationally, the finished-product sampling point should be after the final dust-recovery and transport boundary if those steps materially alter its PSD.

Product silos and transfer systems should be represented in the PFD, assigned independent dust collection or ventilation interfaces as needed, and included in fan and conveying power. Specify bulk-density, moisture-sorption, and flowability tests before selecting hopper angles, screw feeders, or pneumatic transport velocity. Poor downstream operability can be a true throughput bottleneck even when the VRM itself meets its design rate.

10. Integration with HPGR, ball mills and downstream circuits

The benchmark must match feed mineralogy and size distribution, accepted product specification, and the full electrical and thermal circuit boundary. HPGR compression and VRM bed grinding share particle-bed loading features but differ in feed presentation, transport, and classification. Jankovic et al. (2015) experimentally compared two HPGR-based dry-circuit options on a specified aggregate feed; their reported power difference belongs to those HPGR options and cannot be transferred numerically to a VRM. Heinicke et al. (2022) provide another HPGR–air-classification integration example, whereas variable-Tromp closed-circuit ball-mill modeling offers a transferable balance method rather than

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direct VRM operating evidence (Muanpaopong et al., 2023). Figure 4 therefore shows testable concepts, not a technology ranking.

Figure 4 compares the conceptual interfaces for HPGR precomminution, VRM pregrinding before ball milling, and a standalone VRM with external classification.

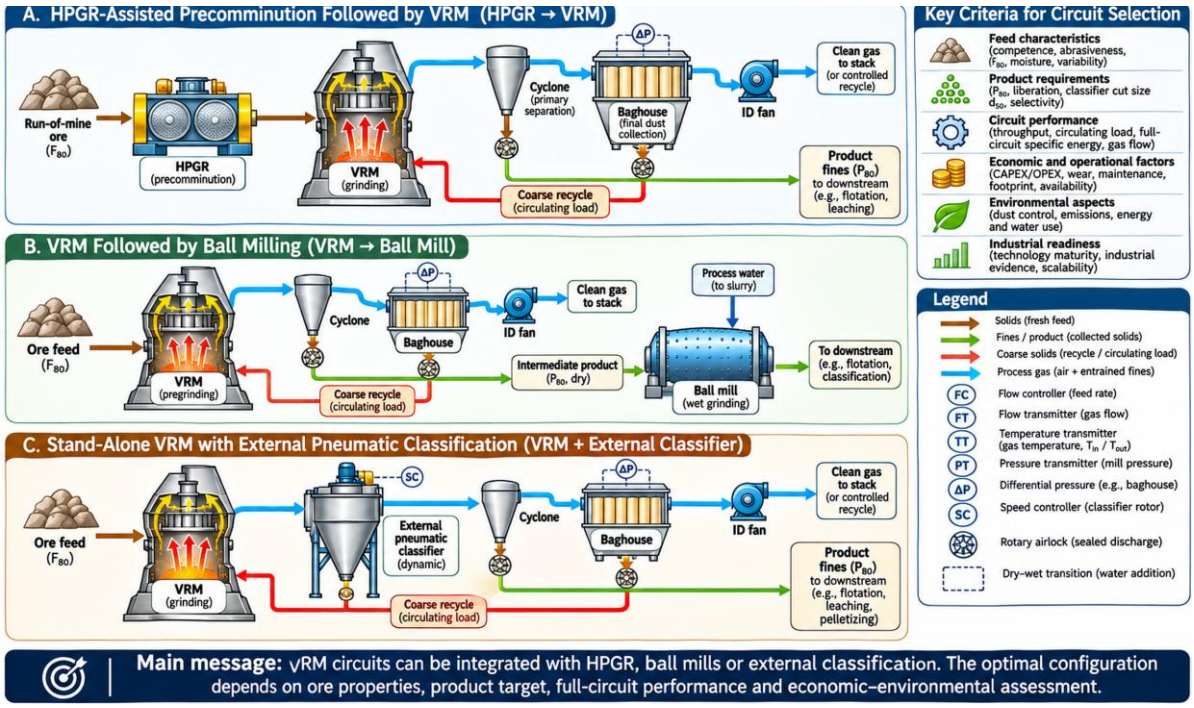

Figure 4. Conceptual dry VRM integration alternatives involving HPGR precomminution, subsequent ball milling, and external pneumatic classification.

Note. AI-assisted conceptual illustration prepared for this review, based on the technical synthesis in the manuscript; not adapted or reproduced from a published figure. Not to scale; process configuration requires project-specific engineering validation.

Figure 4 illustrates alternative flowsheet concepts, not a performance ranking; compatibility depends on ore behavior, process boundaries, water addition, and measured auxiliary loads.

Hybrid arrangements worth testing include HPGR precomminution ahead of a VRM, VRM pregrinding ahead of fine ball milling, and a VRM with downstream external classification. Each has distinctive process risks: oversized bypass from the upstream step, overloading of classification returns, unnecessary fines production, and mismatched subsequent flotation or leaching. A complete comparison should report circuit availability, screen/classifier consumables, wear, conditioning requirements, and total specific energy at matched liberation targets.

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The most actionable sequence is an ore-specific laboratory assessment, short integrated pilot campaigns over multiple feed and moisture states, and a confidence-bound full-scale mass and energy balance. Where downstream mineral recovery is the economic objective, selection should be based on recovered-value productivity rather than solely on tonnes of dry product per hour. The supplied case studies on downstream mineral response are therefore relevant context, not a substitute for parallel VRM-versus-alternative pilot trials.

11. Instrumentation, process control and debottlenecking

VRM operation is a multivariable control problem. Fresh feed, bed level or differential pressure, grinding force, classifier rotor speed, gas flow, mill vibration, reject rate and thermal inputs are coupled through residence time and particle transport. A controller that maintains constant main-drive loading can still deliver variable PSD if moisture or feed breakage behavior changes. Instrumentation should therefore observe process outcomes—preferably product PSD or reliable proxies—in addition to actuator states.

Data-driven models reported for cement VRM pressure, grinding force and drive power demonstrate potential for soft sensing and explanatory diagnostics. However, their reported accuracy should not be transported to a mineral VRM without recalibration. Models must be evaluated under temporal cross-validation, realistic feed shifts and sensor-failure scenarios, not merely random splits of near-duplicate steady-state plant records. Interpretability methods can identify associated variables but do not establish that changing a variable will cause the observed response.

A practical debottlenecking procedure isolates the current constraint: feeder capacity; bed instability; classifier capacity; fan flow at maximum pressure drop; baghouse filtration; product transport; or downstream acceptance. The test protocol should include step tests around stable operating points and repeated balanced surveys. Evaluate changes to separator speed or gas flow for their effects on both fineness and whole-circuit electricity.

Table 3 links commissioning measurements and actuators to the operational decisions they support. Assess the interfaces jointly, since changes in airflow or separator speed can affect both product fineness and auxiliary electricity.

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Table 3. Equipment and control interfaces for circuit commissioning

System	Measurements/actuators	Critical decision
Grinding module	Feed rate; force; vibration; main-drive kW	Bed stability and true grinding duty
Pneumatic classifier	Rotor speed; airflow; stream PSD; bypass	Cut size and misplaced material
Gas circuit	Flow; T; humidity; pressure; fan kW	Transport, drying and energy
Baghouse	Differential pressure; pulse air; stack dust	Operating envelope and emissions
Product dispatch	Rate; moisture; PSD; silo level	Accepted finished-product throughput
Plant historian	Time-synchronized ore and energy data	Comparable surveys and uncertainty

The interfaces in Table 3 show why commissioning requires synchronized stream surveys and control-system trends; equipment set points alone do not establish final-product quality.

12. Critical synthesis and implications

The evidence supports a conditional, not categorical, assessment of dry VRM circuits. Integrated classification can reduce physical interfaces, whereas external air classification can provide independent process tuning and potentially more transparent coarse-return management. Both propositions remain engineering hypotheses until confirmed for the feed, product, and operating envelope under consideration. Current gaps include limited head-to-head comparisons at equal mineralogy and P80, incomplete reporting of fan and filter electricity, and insufficient measurement of fines bypass and wear during variable-feed operation.

The review recommends a sequential selection protocol: define downstream quality and throughput; establish representative material variability; choose physically feasible circuit alternatives; test classifier partition curves independently; close solid, moisture and gas balances; calculate delivered-product energy with every auxiliary; quantify emissions and operating constraints; then conduct sensitivity analysis on moisture, feed hardness and product fineness. Carry uncertainty bounds and the distinction between observation and simulation into economic modeling.

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Environmental and techno-economic claims require parallel treatment of water, fuel, electricity source, filter media, replacement components and uptime. Dry operation may reduce water demand but may increase the importance of fine-particle containment, air movement and thermal drying. The sustainable option is consequently context-specific, depending on utilities and the downstream value chain. Additional direct mineral-ore VRM trials comparing integrated and external classifiers would be particularly valuable because they could test competing design choices within a single controlled experimental framework.

Table 4 summarizes the conditional rationale, unresolved uncertainties, and validation requirements of the principal configurations. These alternatives are engineering hypotheses, not a ranking of proven industrial performance.

Table 4. Configuration selection: conditional benefits, evidence gaps and validation tests

Alternative	Potential engineering rationale	Key uncertainty	Required validation
Integrated air-swept VRM	Compact equipment and fewer transfers	Coupled mill/rotor/gas operating window	Pilot full-circuit power and Tromp curve
VRM + external air classifier	Independent classification and flexible coarse return	Duct, fan and transfer energy penalty	Matched-product survey including all auxiliaries
VRM with pre-crushing	Control feed top size and bed stability	Oversize bypass and extra handling	Multiple feed lithologies and size distributions
HPGR + air classifier	Dry precomminution and independent separation	Different breakage mechanism and liberation	Ore-specific downstream recovery comparison
Ball mill + air classifier	Established fine-grind alternative	Different wear and energy distribution	Comparable boundary and product quality

Table 4 therefore directs the selection process toward comparative trials and balanced process measurements rather than nominal equipment efficiencies.

12.1. What the direct VRM literature establishes

Direct VRM evidence is most useful when the mill operating mode, feed characteristics, material balance, and product specification are disclosed together. Altun and Benzer (2021) examined pilot-scale overflow operation; Altun, Benzer, Aydogan, and Gerold (2017) considered operational parameters; and Altun, Gerold, Benzer, Altun, and Aydogan (2015) investigated a copper-ore pilot plant. These studies inform the structure of test campaigns but do not, by themselves, establish a general advantage for external

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classification. Material-dependent energy prediction (Altun, Benzer, Gerold, & Schmitz, 2021) reinforces that an apparently favorable motor-power comparison may change with the feed and chosen duty.

12.2. When external classification is worth testing

External classification has a credible engineering rationale when an integral separator cannot achieve the required cut size and bypass simultaneously at a stable mill gas flow. The benefit must nevertheless be tested at equal product specifications: the external classifier introduces fan pressure loss, ducting, conveying, and a reject stream that may raise grinding load. Industrial mineral-separator characterization (Ansari et al., 2025) and rotor-classifier investigations (Jia et al., 2021; Mou et al., 2021) illustrate methods for examining separation behavior; they do not constitute direct head-to-head VRM plant trials. The decision variable should be overall circuit performance, not isolated classifier sharpness.

12.3. Integration with competing technologies

A dry HPGR–air-classifier arrangement provides a particularly relevant alternative boundary, rather than a surrogate VRM dataset (Jankovic et al., 2015). Mineral liberation and energy comparisons among comminution technologies must be interpreted alongside ore-specific material response (Baawuah et al., 2020). For HPGR–VRM hybrids, the major unresolved question is whether any reduction in VRM grinding duty outweighs the added handling, screening, and recycle demand. A decision should therefore compare a common ore composite, identical liberation targets, matched moisture, and measured total electrical and thermal utility requirements.

12.4. Emissions and auxiliary-system trade-offs

For dry circuits, filtration is part of the energy and materials accounting rather than a remote environmental attachment. Work on pulse-jet filters separates cleaning energy from particle emissions (Bächler, Meyer, & Dittler, 2023; Bächler, Meyer, & Dittler, 2024), but the results concern filter performance and cannot be converted into VRM-specific emission factors without corresponding dust characteristics. Where product fines are collected in the baghouse, filter availability directly affects saleable throughput. This is a compelling reason to include both filter pressure drop and compressed-air demand in circuit comparisons.

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12.5. Evidence gaps and recommended validation sequence

The available bibliography is broad but strongly heterogeneous: separate air-classifier, cement-mill, filtration, and HPGR studies are more numerous than matched mineral-ore comparisons of VRMs with integral and external classification. A decisive campaign would characterize lithology-dependent compression breakage, top-size excursions, moisture, and abrasiveness; operate both circuit configurations on comparable feed; close dry-solids and water balances with measured reject rates; and measure the complete classifier partition, product PSD/liberation, fan and mill power, thermal duty, filter pressure loss, availability, and product-handling losses. Replicate tests across feed changes should report uncertainty rather than a single claimed saving. No universal energy benefit is justified by the evidence as currently verified.

13. Conclusions

Dry VRM selection should be made on the performance of the complete mineral-processing circuit rather than a mill-only power rating. No universal superiority of integrated or external pneumatic classification can be inferred from the heterogeneous published record. Decisive evidence requires an ore-specific partition curve linked to an independently closed mass balance, matched final PSD and liberation, and a full electrical and thermal boundary including the fan, classifier, and dust-control system. Feed variability and recirculation must be treated as design conditions, not disturbances to be ignored.

The compiled 147-record bibliography covers relevant mechanisms and equipment interfaces, but its size does not demonstrate equivalent depth of direct mineral VRM operating evidence. Until all entries have been independently checked and reconciled with substantive citations, the bibliography must remain provisional. The strongest immediate research priority is matched-condition industrial testing of integral and external classification, with measured auxiliary energy, recycle, product quality, and emissions.

Declarations

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Conflict of Interest

The author declares no conflict of interest.

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Data Availability

No new experimental datasets were generated. All quantitative values discussed in the review are traceable to the cited literature.

Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

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