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Mineral Beneficiation Using Attrition Scrubbing: Mechanisms, Applications and Process Optimization

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ABSTRACT

Original Research Article

Attrition scrubbing is a common mechanical beneficiation method that promotes strong particle–particle interactions in water-based suspensions. It helps remove surface coatings, clays, oxide films, weathered layers, and loosely attached impurities from mineral particles. Unlike traditional grinding, attrition scrubbing primarily cleans surfaces rather than reducing particle size, thereby improving mineral liberation and boosting downstream separation processes such as flotation, leaching, gravity separation, and magnetic separation. This review carefully explores the basic mechanisms behind attrition scrubbing, including interparticle abrasion, hydrodynamic shear, and effects of slurry rheology, and assesses its industrial use across various mineral systems such as silica sands, phosphate ores, iron ores, heavy mineral sands, lithium pegmatites, rare earth minerals, and recycled industrial materials. Special focus is given to operational factors like pulp density, impeller design, residence time, energy input, and particle size distribution, as these significantly affect scrubbing effectiveness and cost efficiency. The review also discusses limitations related to energy use, equipment wear, and the creation of very fine particles that can hinder downstream processing. Emerging advances in process optimization, such as staged scrubbing, hybrid washing–attrition systems, and integration with modern beneficiation circuits, are highlighted to demonstrate potential for improved cleaning performance with lower energy consumption. Finally, the review highlights key research gaps in scale-up, numerical modeling of surface-cleaning mechanisms, and the lack of standardized performance metrics, providing a foundation for future improvements in the design and optimization of attrition-based mineral beneficiation systems.

Keywords: Attrition Scrubbing, Mineral Beneficiation, Surface Cleaning, Slurry Rheology, Particle–Particle Abrasion, Process Optimization.

Highlights

- Attrition scrubbing enhances mineral beneficiation by removing surface coatings and weathered layers without significant particle size reduction.
- Process efficiency is strongly controlled by slurry density, particle interactions, residence time, and energy input.
- Industrial applications include silica sand cleaning, phosphate beneficiation, iron ore upgrading, and rare earth mineral processing.
- Current research gaps include scale-up modeling, energy efficiency optimization, and standardized performance metrics.

Graphical Abstract

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Introduction

Beneficiation of complex mineral resources requires pretreatment to improve mineral surfaces prior to separation. Surface coatings such as clay minerals, iron oxides, and weathering products reduce efficiency by masking reactive surfaces and altering interfacial properties (Rao et al., 2023; Mweene et al., 2024).

Surface contamination mechanisms such as organic adsorption, oxide films, and particle attachment are well studied in mineral and environmental systems, illustrating complex particle–surface interactions (Guan et al., 2020; Jin et al., 2022; Vidal et al., 2021).

Attrition scrubbing is a common mechanical surface-cleaning method in mineral processing, using particle–particle abrasion and hydrodynamic shear in high-solids slurry to remove coatings and slimes (Abdullah, 2020; Hussein & El-Midany, 2022). Unlike grinding, which reduces particle size to promote mineral liberation, attrition scrubbing primarily removes surface coatings without significantly altering particle size (Behera & Dwari, 2026; Wang et al., 2021).

Surface cleaning before beneficiation is crucial and has shown benefits in mineral systems like silica sand, phosphate, lithium clay, and recycling. However, benefits vary by ore, and while improved cleanliness often is assumed to enhance performance, direct quantitative Links between scrubbing and recovery are limited. Confusion arises from the overlap between attrition scrubbing and mechanical activation. Mechanical activation applies high energy to modify solids by defect generation, amorphization, or refinement, aiming to increase mineral reactivity (Pereira, 2026b). Attrition scrubbing, however, is a beneficiation pretreatment focused on surface cleaning and slime removal.

Despite widespread industrial use, the details of attrition scrubbing remain poorly documented, with limited data on energy, wear, and economics. Literature often reports cleaning efficiency without showing effects on downstream processing, making it hard to assess its true contribution in beneficiation across ore types. (Beeks & Keller, 2020)

This review uses a structured method to differentiate mechanistic evidence from application claims and identify descriptive rather than quantitative literature.

Mechanical operations on mineral particles include grinding for size reduction, attrition scrubbing to remove surface coatings, and mechanical activation to alter structure. Figure 1 illustrates these differences and effects.

Figure 1. Conceptual comparison between grinding, attrition scrubbing, and mechanical activation. Adapted from Wills and Finch (2016); Wang et al. (2021); Sahoo et al. (2021); and Pereira (2026a).

Figure 1 shows that these operations mainly differ in energy use and purpose. Grinding fractures particles to reduce size and free mineral phases. Attrition scrubbing involves fewer fractures but encourages particle interactions changes. Mechanical activation uses high-energy impacts to change internal structures and boost reactivity.

The distinction matters as their roles in mineral processing differ: attrition scrubbing conditions surfaces before beneficiation, while grinding and activation enhance liberation or reactions.

Methodology

A structured review evaluated evidence, applications, and outcomes of attrition scrubbing in mineral beneficiation, guided by PRISMA principles (Page et al., 2021), tailored to mineral processing literature.

Relevant publications were identified in databases such as Scopus, Web of Science, and Google Scholar using keywords including attrition scrubbing, scrubber, mineral beneficiation, scrubbing flotation, and surface cleaning. Additional terms included studies on clay removal, slime detachment, and mineral surface conditioning prior to flotation or magnetic separation.

The literature covered peer-reviewed articles, conference proceedings, theses, and reports on attrition scrubbing in mineral processing, including primary ore beneficiation and emerging, such as recycling industrial materials and batteries (Widijatmoko et al., 2020; Bedekovic & Tenjer, 2021; Chen & Tien, 2023). It also reviewed slurry hydrodynamics, flotation, and mineral surface interactions for understanding scrubbing mechanisms (Han et al., 2020; Zeng et al., 2023).

To facilitate comparison across studies, the literature was categorized into three main themes:

- fundamental mechanisms of attrition scrubbing
- mineralogical controls affecting surface cleaning
- industrial applications and process optimization

Each publication was examined by ore type, experimental scale, and reported performance indicators.

A major issue is the inconsistent reporting of operational parameters and performance metrics. Many studies report qualitative improvements but omit key variables such as energy use, equipment wear, and circuit economics. This hampers cross-study comparisons and limits understanding of industrial relevance.

Techno-economic assessments in mineral processing are often case-specific and not transferable across ore types, limiting generalization of performance improvements (Uysal, 2022).

Despite limitations, studies reveal key patterns for attrition scrubbing. Next, examine the physical mechanisms of surface cleaning during these operations.

A literature survey identified studies on attrition scrubbing, operational parameters, and mineral beneficiation applications, using a multi-step screening process to distinguish mechanistic from application reports. It focused on parameters, mineralogy, and metallurgical performance, summarized in Figure 2.

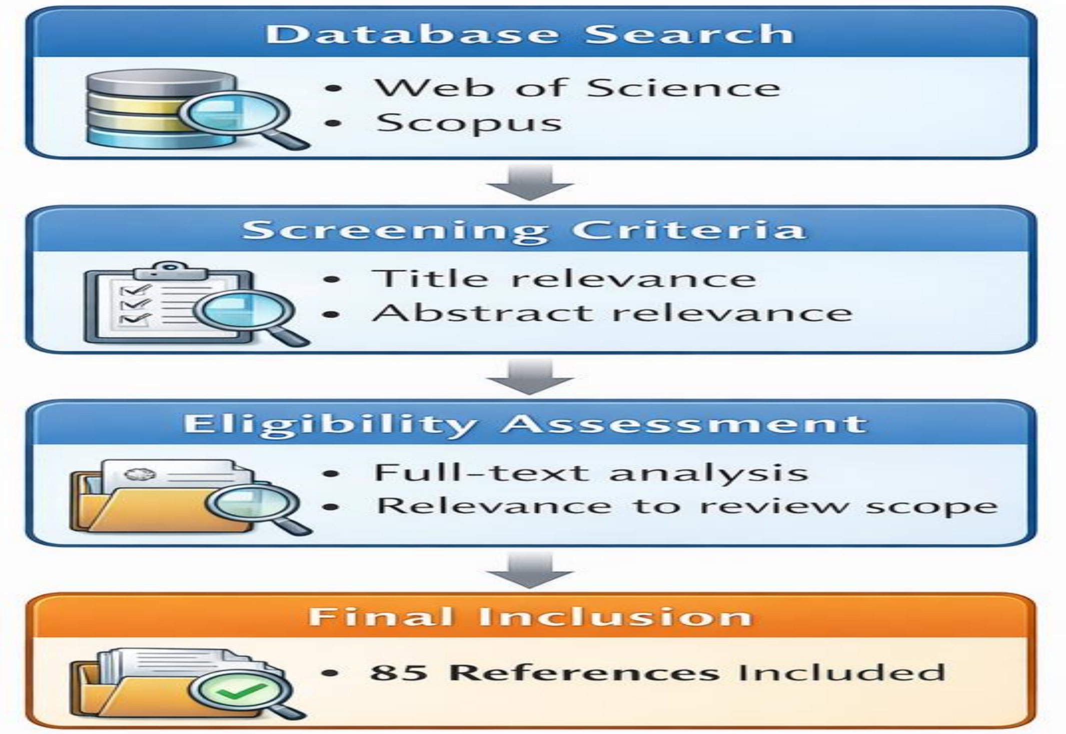

Figure 2. Literature selection workflow used in this review. Adapted from Page et al. (2021); Wills and Finch (2016); Wang et al. (2021); and Behera and Dwari (2026).

Fundamentals of Attrition Mechanisms

Attrition scrubbing is a surface-conditioning process using mechanical interactions in high-solids slurries to remove loosely attached coatings and fines. Unlike grinding, which reduces particle size and liberates minerals, attrition scrubbing mainly cleans surfaces while maintaining the overall particle size.

Despite widespread use, the mechanisms behind coating removal are not well understood. Most studies focus on surface cleanliness, with few linking operating conditions to the stresses needed for detachment.

Physical Mechanisms

Attrition scrubbing operates through a combination of particle–particle abrasion and hydrodynamic shear generated within a dense slurry environment (Abdullah, 2020; Wang et al., 2022). These mechanisms act simultaneously but are rarely isolated experimentally.

Particle–particle abrasion occurs through repeated collisions between mineral grains at high solids concentration. It effectively removes weakly bonded clay coatings and slimes. Higher solids increase collision frequency, but the link between collision intensity and cleaning efficiency is not well understood.

Hydrodynamic shear, caused by turbulence from the impeller in the attrition scrubber, acts at the particle–fluid interface to detach surface films, especially in systems with fine clay minerals like kaolinite and montmorillonite (Sahoo et al., 2021). Its effectiveness depends on slurry rheology and turbulence, which are rarely characterized in detail.

Turbulence enhances if excessive.

Though these mechanisms are often cited, their specific impacts are unclear. Most studies involved in coating removal (Cho et al., 2021; Chiu & Gani, 2024). As a result, predictive models for attrition scrubbing are limited.

As illustrated in Figure 3, attrition scrubbing involves the combined action of particle collisions, shear forces, and turbulence-induced dispersion. The dominance of each mechanism depends on slurry conditions and mineralogical characteristics rather than on a single operating parameter.

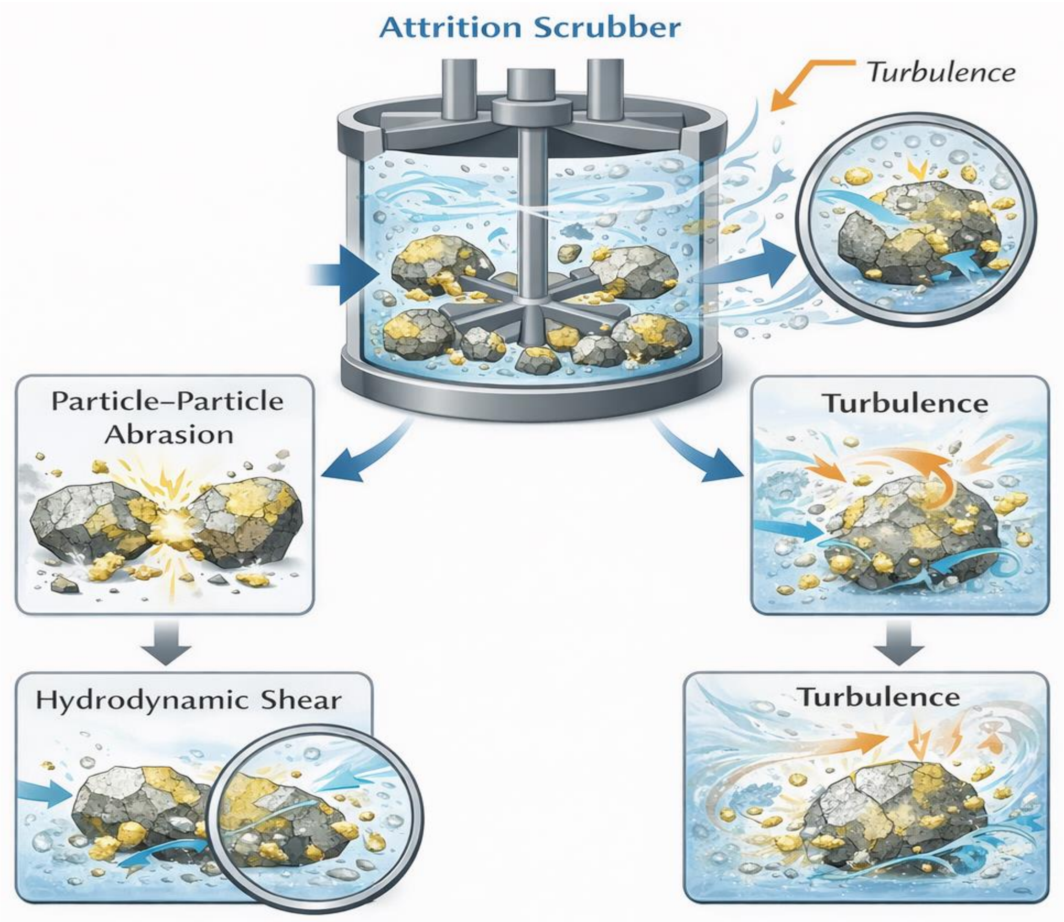

Figure 3. Mechanisms of attrition scrubbing in mineral processing. Adapted from Wills and Finch (2016); Abdullah (2020); Wang et al. (2021); Wang et al. (2022); and Behera and Dwari (2026).

Figure 3 shows that attrition scrubbing involves particles, fluid dynamics, and turbulence. Collisions cause abrasion; shear detaches coatings, and turbulence increases collisions and disperses slimes.

Each mechanism's contribution depends on slurry density, agitation, particle size, and mineralogy, but these are rarely quantified separately, limiting scrubbing models.

Operational Parameters

Attrition scrubbing effectiveness depends on variables such as solids concentration, residence time, impeller speed, and energy input, which influence particle interactions in the slurry.

Solids concentration affects collision frequency—higher values enhance cleaning but xcessively high values increase slurry viscosity, reducing mixing efficiency. Thus, the optimal range is system-dependent.

Residence time affects particle exposure to abrasion and shear. Too short leads to incomplete cleaning, too long causes fines. This trade-off is rarely quantified.

Impeller speed controls turbulence intensity and shear forces. Increasing rotational speed enhances cleaning efficiency but also increases energy consumption and accelerates equipment wear. The relationship between impeller speed and cleaning performance is often reported qualitatively rather than quantitatively.

Specific energy consumption (kWh/t) provides a useful metric for comparing operating conditions; however, it is rarely linked to downstream metallurgical performance. Most studies report energy input independently of recovery or grade improvement, limiting process optimization.

Typical operating ranges are summarized in Table 1. These values provide general guidance but should not be interpreted as universally applicable, since optimal conditions depend strongly on mineralogy and coating characteristics.

Importantly, increasing scrubbing intensity does not guarantee improved beneficiation performance. Excessive abrasion may generate ultrafine particles, which can reduce flotation selectivity, increase entrainment, or lead to losses during classification (Hussein & El-Midany, 2022).

Process optimization balances cleaning efficiency, fines, and costs.

Attrition scrubbing depends on variables like solids concentration, residence time, and agitation, which affect particle collisions and shear forces. Energy input impacts cost and cleaning, with parameters summarized in Table 1.

Table 1. Typical operating ranges reported for attrition scrubbing in mineral beneficiation. Adapted from Wills and Finch (2016); Abdullah (2020); Wang et al. (2021); Sahoo et al. (2021); and Behera and Dwari (2026).

Parameter	Typical Range	Effect on Process
Solids concentration	50–75 wt%	Higher collision frequency
Residence time	2–10 min	Controls cleaning intensity
Impeller speed	300–1200 rpm	Controls turbulence intensity
Specific energy consumption	0.5–10 kWh/t	Determines process cost

Table 1 shows that attrition scrubbing occurs at high solids to enhance particle interactions, causing surface abrasion. Residence time and impeller speed control mechanical intensity, while specific energy indicates cleaning costs.

Increasing scrubbing intensity does not always improve metallurgical performance. Excessive residence time or agitation can produce ultrafine particles and slimes, thereby hindering downstream processes such as flotation. Optimization should balance cleaning efficiency, fines, and costs.

Distinction Between Attrition Scrubbing and Mechanical Activation

Although attrition scrubbing and mechanical activation both use mechanical energy on particulates, they differ in purpose, intensity, and results.

Attrition scrubbing is a surface-cleaning process that removes loose coatings, clay films, and slimes via particle abrasion and shear. It works at moderate energy levels and minimally alters mineral internal structure (Abdullah, 2020; Wang et al., 2021; Wang et al., 2022).

Mechanical activation is a high-energy process that modifies solids, promotes defects, induces lattice distortion, and induces partial amorphization, thereby increasing surface reactivity and improving dissolution or reduction (Pereira, 2026b).

The distinction is critical for interpreting process outcomes. In beneficiation circuits, attrition scrubbing acts as a pretreatment step that improves surface condition prior to separation. Mechanical activation, in contrast, is a process-intensification strategy aimed at modifying reaction pathways.

Confusion often arises in high-intensity milling studies, where surface cleaning and structural modification occur simultaneously (El-Mofty et al., 2023), yet their roles in process design remain distinct.

As summarized in Table 2, the two processes differ in energy demand and Dominant attrition scrubbing focuses on surface cleaning and beneficiation, while mechanical activation aims to boost reactivity in downstream chemical processes.

Table 2. Comparison between attrition scrubbing and mechanical activation. Adapted from Baláž (2008); Wills and Finch (2016); Wang et al. (2021); and Pereira (2026b).

Aspect	Attrition scrubbing	Mechanical activation
Main objective	Surface cleaning	Structural modification
Dominant mechanism	Particle–particle abrasion and hydrodynamic shear	High-energy impact and fracture
Structural effects	Minimal	Defect formation and amorphization
Particle size reduction	Limited	Often significant
Typical energy level	Moderate	High
Role in flowsheet	Beneficiation pretreatment	Reaction intensification

Table 2 shows that attrition scrubbing and mechanical activation differ mainly in energy used and effects. Attrition scrubbing, a surface-conditioning step, removes coatings and slimes via particle abrasion without altering internal structure. Mechanical activation uses high-energy collisions to create lattice defects, amorphization, and increased surface free energy.

This distinction is important because the two processes serve different roles: attrition scrubbing is a beneficiation pretreatment, while mechanical activation enhances chemical reactivity in hydrometallurgical or pyrometallurgical systems.

The effectiveness of attrition scrubbing depends on the ore's mineralogy, which affects the nature and adhesion of surface coatings. Understanding these factors is key to predicting ore responses to scrubbing.

Different ores respond variably to attrition scrubbing based on mineralogy. This section analyzes how mineralogy influences cleaning effectiveness and beneficiation outcomes.

Mineralogical Controls

An ore's response to attrition scrubbing depends on mineralogy, not equipment. Surface coatings and adhesion influence contaminant removal. Similar-sized ores may respond differently under the same conditions. Clay coatings like kaolinite and smectite form thin films on mineral grains, hindering flotation and magnetic separation (Arthur et al., 2025; Mweene et al., 2024). Attrition scrubbing can remove these layers, depending on clay dispersion and coating adhesion.

Iron oxides, such as hematite and goethite, cause surface contamination by adhering minerals. In silica sand beneficiation, attrition scrubbing removes these coatings prior to magnetic separation or flotation to reduce the iron content (Othman et al., 2023; Ibrahim et al., 2021). However, scrubbing is less effective when iron phases are discrete inclusions instead of surface films.

Thin silica films and weathering products cover mineral surfaces, impacting surface charge, reagent adsorption, and wettability during flotation (Liu et al., 2023). Attrition scrubbing can remove these layers, depending on cementation. Adhered slimes are ultrafine particles attached to larger grains, decreasing beneficiation by raising pulp viscosity, promoting entrainment, and masking mineral surfaces (Gerber & Grobler, 2023). Attrition scrubbing disperses these fines, detaching them to expose clean mineral surfaces.

Despite mineralogical controls' importance, many studies report surface cleaning success without detailing coating thickness, mineral composition, or adhesion strength, making removal mechanisms inferred and complicating performance comparisons across ore systems (Guo et al., 2024; Jadeppa et al., 2024; Ismail et al., 2020)..

Attrition scrubbing's effectiveness depends on mineralogical traits on that affect coating adhesion to mineral grains. Certain ores have coatings hide clay, iron oxide, or weathering products that hinder reagent adsorption, reduce magnetic response, or obscure reactive surfaces. Removing these coatings is a primary goal of attrition scrubbing in beneficiation. Figure 4 illustrates the key mineralogical factors influencing ore response.

Figure 4. Mineralogical factors controlling attrition scrubbing efficiency. Adapted from Wills and Finch (2016); Sahoo et al. (2021); Wang et al. (2022); Gerber and Grobler (2023); and Mweene et al. (2024).

As shown in Figure 4, attrition scrubbing efficiency depends on the surface coatings on mineral particles. Clay minerals like kaolinite, smectite, and montmorillonite have weakly bonded layers that particle abrasion can remove. Conversely, iron oxide films or silica weathering layers adhere more strongly and require greater mechanical force for removal.

Adhered slimes complicate beneficiation by changing slurry rheology and promoting entrainment during flotation. Although mineralogical factors are critical, many studies only note improved surface cleanliness without quantifying coating thickness, adhesion, or mineral distribution. This limits the ability to predict scrubbing performance across ore types.

The effectiveness of attrition scrubbing depends on mineral particles' surface coating and bond strength. Coatings react differently: clay is weak and easily removed, whereas iron oxide and silica are more adhesive and require greater scrubbing force. Table 3 summarizes coating types and responses.

Table 3. Common surface coatings in mineral ores and their expected response to attrition scrubbing. Adapted from Wills and Finch (2016); Sahoo et al. (2021); Wang et al. (2022); Gerber and Grobler (2023); and Mweene et al. (2024).

Coating type	Typical minerals	Adhesion strength	Expected response to attrition scrubbing
Clay coatings	Kaolinite, montmorillonite	Weak to moderate	Usually removable
Iron oxide films	Hematite, goethite	Moderate	Partially removable
Silica weathering films	Secondary silica	Moderate to strong	Variable
Adhered slimes	Ultrafine gangue particles	Weak	Readily removable

As shown in Table 3, the response of mineral particles to attrition depends on the adhesion of surface coatings. Clay coatings and slimes are usually removed by abrasion and shear in the scrubber. However, iron oxide films and silica weathering layers bond more strongly, limiting scrubbing unless higher mechanical intensity or longer durations are applied.

Mineralogical characterization of surface coatings is crucial for assessing the benefits of attrition scrubbing, as it prevents attributing improvements to scrubbing intensity rather than to the natural ease of coating removal in some ore systems.

Because mineralogical conditions vary widely, the benefits of attrition scrubbing can't be generalized. The next section explores how these factors affect its application across mineral commodities.

Applications for Mineral Processing

Attrition scrubbing is used in mineral beneficiation circuits to remove surface coatings or slimes that hinder separation. Its success varies by commodity and ore type, influenced by mineralogy, particle size, and coating adhesion. Therefore, reported improvements are not universally applicable.

Iron Ore

In iron ore beneficiation, attrition scrubbing removes clay coatings and slimes from ore particles before magnetic separation or pelletization (Sahoo et al., 2021; Rao et al., 2023). These coatings can mask magnetic response or increase gangue entrainment during classification.

Attrition scrubbing disperses clay particles and removes surface coatings, enhancing magnetic separation efficiency and iron concentrate grade. The extent of improvement depends on the clay type and degree of weathering (El-Wekil et al., 2024).. Many studies show improved concentrate grade but lack data on energy use or costs of the scrubbing stage.

Phosphate Ores

Attrition scrubbing in phosphate beneficiation removes clay coatings from apatite before flotation (Ahmed et al., 2025; Rizk, 2022). Clay minerals can reduce flotation efficiency by increasing pulp viscosity and hindering reagent adsorption.

Pre-scrubbing disperses clay and reveals cleaner apatite surfaces. Studies show it improves phosphate recovery and concentrate grade (Aarab et al., 2023; Farid et al., 2025).

The improvement depends on ore mineralogy; phosphate deposits with cemented clay phases or fine intergrowths may respond poorly to mechanical scrubbing (Aleksandrova et al., 2022).

Bauxite

In bauxite beneficiation, attrition scrubbing disaggregates clay-rich matrices and removes impurities before processing (Datta & Nandi, 2021). It enhances the separation of bauxite minerals and clay during classification or washing.

Nevertheless, the effectiveness of attrition scrubbing in bauxite systems depends on ore texture. Highly cemented lateritic ores may require additional size reduction before clay dispersion (Tinesha et al., 2025).

Alluvial Gold Deposits

Attrition scrubbing helps treat alluvial deposits by dispersing clay and releasing trapped gold particles for gravity separation (Phengsaart et al., 2023).

In these systems, scrubbing is usually a pretreatment before classification or gravity concentration. However, excessive scrubbing can create ultrafine particles, increasing later losses.

Industrial Silica Sands

Attrition scrubbing purifies silica sand for glass, foundry, and high-purity applications by removing iron oxide coatings and surface contaminants prior to magnetic separation or flotation (Othman et al., 2023; Ibrahim et al., 2025b).

The process works best when iron is on surface films rather than within the quartz matrix. When iron minerals are embedded in the grain, attrition scrubbing alone cannot greatly reduce impurities (Fawzy et al. 2022).

Although attrition scrubbing is used in many mineral systems, literature mainly highlights concentrate grade or recovery, with little focus on overall circuit performance. Operational factors like energy use, wear, and water demand are seldom reported (Elshwehy et al. 2025).

Attrition scrubbing is used in mineral beneficiation to remove surface coatings or slimes that hinder separation. It's especially useful in ores containing clay minerals, weathering products, or fine particles, which can reduce the efficiency of flotation, magnetic separation, or gravity concentration. While the mechanism stays the same, the process goal varies by mineral and method. Figure 5 highlights key sectors employing attrition scrubbing.

Figure 5. Major industrial applications of attrition scrubbing in mineral processing. Adapted from Wills and Finch (2016); Sahoo et al. (2021); Rao et al. (2023); Othman et al. (2023); and Ibrahim et al. (2025a).

As shown in Figure 5, attrition scrubbing has various roles in mineral processing. In iron ore, it removes slimes before magnetic separation; in phosphate processing, it detaches clay from apatite before flotation; and in bauxite beneficiation, it disperses clay-rich matrices and enhances classification.

Attrition scrubbing is common in industrial silica sands to remove iron oxide coatings for high-purity quartz and in alluvial deposits to release fine particles trapped in clay, aiding gravity separation.

Despite its widespread applications, the effectiveness of attrition scrubbing depends on mineralogy and circuit setup.

Attrition scrubbing is used in mineral beneficiation to remove surface coatings, disperse clay, or release fine particles hindering separation. Table 4 summarizes common applications and their downstream processes.

Table 4. Main mineral commodities where attrition scrubbing is applied and the primary purpose of the operation. Adapted from Wills and Finch (2016); Sahoo et al. (2021); Rao et al. (2023); Othman et al. (2023); and Ibrahim et al. (2025a).

Ore Type	Primary Objective	Typical Downstream Process
Iron ore	Removal of slimes	Magnetic separation
Phosphate ore	Clay removal	Flotation
Bauxite	Clay dispersion	Classification
Alluvial deposits	Release of fine particles	Gravity separation
Silica sand	Removal of iron coatings	Magnetic separation/flotation

Table 4 shows that attrition scrubbing varies across circuits, primarily by removing coatings or particles that hinder separation. In iron ore, it eliminates slimes, reducing magnetic separation efficiency. In phosphate beneficiation, it removes clay from apatite to improve flotation.

In bauxite processing, attrition scrubbing disperses clay aggregates, aiding classification and washing. In alluvial deposits, it releases fine clay particles, improving separation. The impact on metallurgical performance varies by circuit type and is rarely accounted for in full-circuit economics.

Studies show that mineral beneficiation improves liberation. Benefits vary by mineralogy, coating strength, and circuit. Table 5 summarizes these improvements and limitations across ore types.

Table 5. Reported beneficiation improvements following attrition scrubbing. Adapted from Wills and Finch (2016); Sahoo et al. (2021); Phengsaart et al. (2023); Othman et al. (2023); and Ibrahim et al. (2025b).

Ore Type	Reported Improvement	Main Limitation
Iron ore	Improved magnetic separation	Limited data on energy consumption
Phosphate	Increased flotation recovery	Mineralogical variability
Bauxite	Better clay dispersion	Requires prior disaggregation
Alluvial gold	Liberation of fine particles	Risk of ultrafine losses
Silica sand	Reduced iron contamination	Ineffective for locked inclusions

As shown in Table 5, attrition scrubbing enhances separation by removing surface coatings and fine particles. In iron ore, it improves magnetic separation; in phosphate processing, it boosts flotation by removing clay coatings. Similar benefits are observed in silica sand purification, which reduces surface-related iron contamination.

These improvements often face operational limitations: mineralogical variability can affect flotation consistency, excessive scrubbing in alluvial deposits note that they can create ultrafine particles that are lost during gravity separation, and many studies report concentrate grade improvements without detailed energy or cost data, limiting assessment of industrial benefits.

Though attrition scrubbing can improve surface cleanliness, cleaner particles do not necessarily enhance metallurgical results (Anticoi et al., 2022; Li et al., 2023).

Reported improvements in concentrate grade are often emphasized across different commodities; however, these results are rarely accompanied by complete circuit-level evaluations. In several cases, the absence of energy consumption data, wear rates, and mass balance closure limits the interpretation of industrial relevance.

The value of attrition scrubbing depends on how surface cleaning improves subsequent separation methods. The next section explores its effect on flotation, magnetic separation, leaching, and classification.

Influence on Downstream Processes

Attrition scrubbing's practical value hinges on its capacity to enhance downstream beneficiation performance. Removing coatings and slimes exposes cleaner mineral surfaces, affecting flotation, magnetic separation, or leaching. However, better surface cleanliness does not always mean higher metallurgical recovery (Fish 2025).

In several reported cases, improvements in surface cleanliness do not translate into proportional gains in recovery, particularly when mineral locking or inclusion-dominated systems control separation efficiency (Bilal et al., 2022).

Several studies show improved concentrate quality after scrubbing pretreatment, especially where clay coatings hinder reagent adsorption or magnetic response (Han et al., 2020; Severov et al., 2022). However, the extent of improvement varies by ore type. Sometimes, benefits are offset by ultrafine particles, altered pulp rheology, or reagent redistribution.

Many studies report improvements in concentrate grade or recovery but lack a full evaluation of the beneficiation circuit, rarely measuring variables such as energy use, slime losses, and stability. This leaves the link between scrubbing intensity and overall metallurgical performance poorly documented.

Flotation

Attrition scrubbing improves flotation by removing clay coatings, exposing clean mineral surfaces for collector adsorption. Clay minerals and slimes reduce efficiency by masking surfaces or increasing viscosity.

Several studies show flotation recovery improves after attrition pretreatment, especially in phosphate and graphite systems (Aarab et al., 2023; Wang et al., 2021). However, flotation depends on surface cleaning and the creation of fines. Excessive scrubbing can generate ultrafine particles, increasing entrainment or reducing bubble–particle attachment.

Improvements in flotation depend on the efficiency of cleaning and the resulting from scrubbing.

Magnetic Separation

In magnetic separation, attrition scrubbing can improve efficiency by removing non-magnetic coatings from particles. Clay films and gangue attached to minerals can lower magnetic response and reduce separation selectivity (Ahmed et al., 2025).

Scrubbing pretreatment can boost concentrate grade by exposing cleaner mineral surfaces. Its effectiveness depends on whether contaminants are surface films or inclusions within mineral grains. When impurities are locked in the mineral matrix, attrition scrubbing has limited impact on separation.

Leaching

Surface cleaning can impact hydrometallurgical processes by exposing reactive mineral surfaces and enhancing mass transfer, as seen in lithium-bearing clay systems and other applications (Arthur et al., 2026).

However, the link between attrition scrubbing and leaching kinetics is rarely described in detail. Few studies report changes in reaction rate constants or diffusion coefficients after scrubbing. Thus, the mechanistic connection between surface cleaning and leaching efficiency remains poorly understood.

Hydraulic Classification and Desliming

Attrition scrubbing typically occurs before hydraulic classification or desliming. It disperses clay aggregates and detaches slimes, aiding the removal of fine particles during classification.

This step can enhance downstream flotation or gravity separation but excessive fines from scrubbing increase slime losses and reduce recovery (Wang et al., 2022). Therefore, the optimal scrubbing intensity balances cleaning efficiency and control of ultrafine particles.

Recycling and Secondary Resource Processing

Attrition scrubbing recycles secondary resources such as lithium-ion batteries and industrial residues by liberating active materials from composite particles or by separating loosely attached phases (Widijatmoko et al., 2020; Bedekovic & Tenjer, 2021).

However, reported benefits often rely on the mechanical stability of composite materials. In some recycling systems, attrition can cause excessive fragmentation of active materials instead of selective liberation.

Attrition scrubbing boosts beneficiation by removing coatings such as clays, oxides, and gangue, thereby improving mineral liberation and process selectivity. Effectiveness varies with ore mineralogy, particle size, and impurities. See Table 6 for details.

Table 6. Reported influence of attrition scrubbing on downstream beneficiation performance. Adapted from: Abdullah (2020); Alali (2023); Ahmed et al. (2025); Arthur et al. (2025, 2026); Bedekovic & Tenjer (2021); Ibrahim et al. (2025a); Liu et al. (2023); Ma et al. (2021); Othman et al. (2023).

Ore Type	Downstream Process	Typical Improvement	Main Limitation
Iron ore	Magnetic separation	Fe grade increase 2–6%	Limited energy reporting
Phosphate ore	Flotation	Recovery increase 8–18%	Strong mineralogical variability
Silica sand	Magnetic separation	Fe_2O_3 reduction 40–70%	Ineffective for locked impurities
Graphite	Flotation	Carbon grade increase 3–10%	Fine particle generation
Lithium claystone	Leaching	Li recovery increase 10–20%	Limited kinetic data

Table 6 shows that attrition scrubbing can greatly improve beneficiation, especially when surface contamination limits performance. For instance, silica sand and iron ore achieve better impurity removal and again benefit from improved surface conditions for flotation.

However, the results highlight key limitations. In ores with complex mineral intergrowths, such as lithium claystones, improvements are limited by mineralogical factors rather than by surface cleanliness. Also, fine particles from scrubbing may harm downstream processes by increasing entrainment or lowering separation efficiency.

Overall, attrition scrubbing should be viewed as a conditional pre-treatment step whose success depends on balancing surface cleaning, particle integrity, and downstream process needs. Its best use requires careful adjustment of operating parameters such as residence time, pulp density, and scrubbing intensity, as well as integration with the overall beneficiation flowsheet.

While attrition scrubbing improves beneficiation, its effectiveness depends on scrubbing intensity. The relationship is non-linear, balancing cleaning, particle liberation, and degradation.

At low intensities, energy can't remove coatings such as clays and oxides, leading to poor liberation and limited selectivity. Increasing scrubbing removes surface contaminants, exposing minerals and boosting performance. Nevertheless, exceeding hurts the optimal point leads to particle breakage and ultrafine particle production, which reduces selectivity and efficiency. Figure 6 shows this trade-off between scrubbing intensity and metallurgical response.

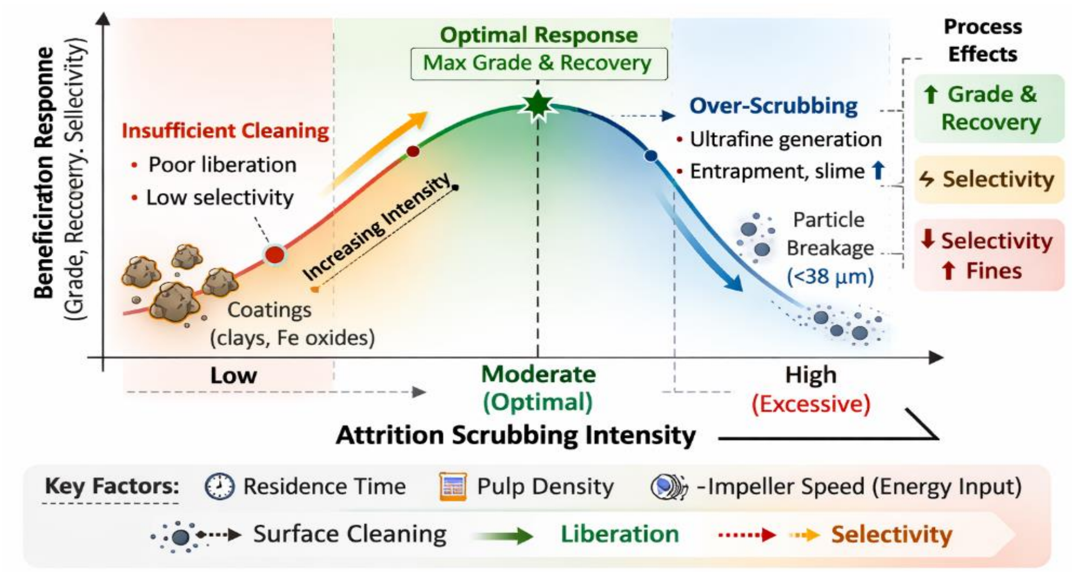

Figure 6. Conceptual relationship between attrition scrubbing intensity and downstream metallurgical response. Adapted from: Abdullah (2020); Bedekovic & Tenjer (2021); Wang et al. (2021, 2022); Widijatmoko et al. (2020); Sahoo et al. (2021); Liu et al. (2023); Arthur et al. (2025, 2026); Othman et al. (2023).

Figure 6 shows optimizing attrition scrubbing for beneficiation by tailoring intensity to the ore's traits rather than applying it indiscriminately. The ideal region depends on factors like particle hardness, coating, and mineral intergrowth. Moderate scrubbing improves separation of surface-contaminated ores, but higher intensity yields little additional benefit and increases fines in mineral-locked ores.

Process optimization should identify the surface-cleaning threshold that maximizes cleaning while minimizing particle degradation. This balance is essential for maintaining flotation selectivity and minimizing losses in fine fractions during later beneficiation stages.

Although attrition scrubbing effectively removes surface contaminants, its impact on beneficiation performance isn't always proportional to the degree of cleaning. In several ore systems, surface improvements do not necessarily lead to better recovery, grade, or efficiency.

This discrepancy stems from mineralogical constraints such as locked particles and inclusions, which surface cleaning can't address. Table 7 shows cases in which attrition scrubbing improved the surface but yielded limited downstream benefits.

Table 7. Cases where attrition scrubbing improved surface cleaning but did not significantly improve overall beneficiation performance. Adapted from: Sahoo et al. (2021); Wang et al. (2021, 2022); Liu et al. (2023); Othman et al. (2023); Widijatmoko et al. (2020).

Ore Type	Observed Cleaning Effect	Limited Process Benefit
Iron ore	Clay removal	Limited change in recovery
Phosphate	Reduced slimes	Minor flotation improvement
Silica sand	Surface iron removal	Persistent inclusions

Table 7 shows that surface cleaning alone isn't enough for beneficiation. Removing clay from iron ore improves the feed but does not guarantee better magnetic separation if iron minerals remain in the gangue. In silica sand, surface iron removal has a limited effect if iron inclusions in quartz remain. Reducing slimes in phosphate ores can remain the same if mineralogy and particle liberation don't change significantly.

These findings highlight the need to integrate attrition scrubbing into a broader mineral processing strategy. Its use should be guided by mineralogical characterization to address system limitations, rather than used as a generic pre-treatment.

Overall, attrition scrubbing can improve downstream beneficiation performance when surface coatings are the dominant factor limiting separation efficiency. However, its effectiveness depends on a balance between surface cleaning and particle breakage. Excessive scrubbing intensity may generate ultrafine particles that reduce separation selectivity or increase slime losses.

Downstream performance depends on scrubbing intensity and circuit configuration, making equipment design crucial for translating lab results into industrial applications.

Process Design and Equipment

Attrition scrubbing effectiveness in beneficiation relies on surface-cleaning mechanisms and equipment setup that create particle abrasion and shear. Usually, attrition scrubbers are mechanically agitated tanks with impellers that operate at high solids concentrations to promote collisions (Behera & Dwari, 2026).

Translating and overlook factors such as slurry circulation, equipment wear, and residence time. Hence, similar cleaning results may require different equipment at scale (Li et al., 2020).

Single-Stage and Multi-Stage Scrubbing Systems

Industrial attrition scrubbing circuits can be single-cell or multi-stage. Single-stage units are cheaper and suitable for light cleaning, such as removing loose slime, but less effective against stubborn coatings. Multi-stage systems, used in large plants, improve cleaning by passing material through several scrubbers, but consume more energy and cause more wear.

Literature shows that multi-stage systems improve cleaning, but the incremental benefit is rarely measured. Sometimes, extra stages mainly produce fines rather than improved cleaning.

Attrition scrubbing can be performed using single- or multi-stage scrubbers, depending on cleaning needs, throughput, ore characteristics, residence time, energy requirements, and slime removal.

Single-stage scrubbers suit moderate cleaning, offering simplicity and lower costs. Multi-stage systems improve cleaning with longer residence times and staged removal of fine particles, providing more control. Figure 7 compares these setups, showing their operation differences and implications for downstream processing.

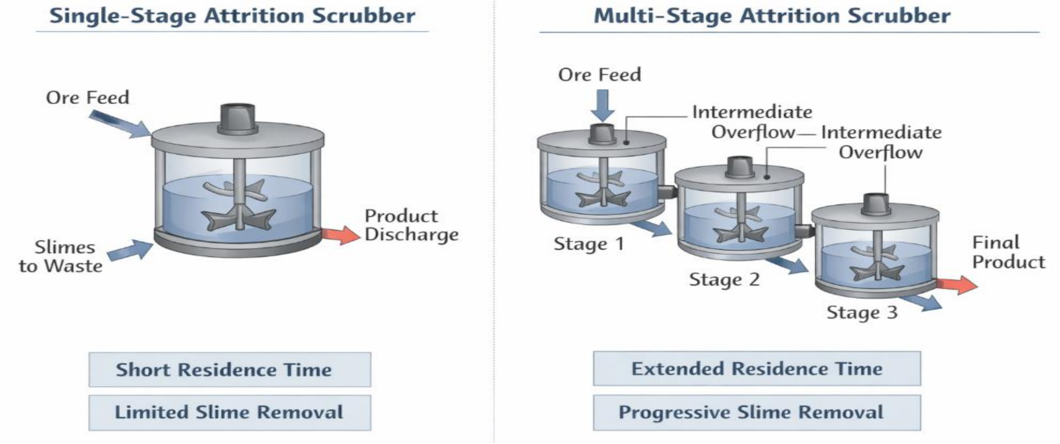

Figure 7. Comparison between single-stage and multi-stage attrition scrubber configurations. Adapted from: Sahoo et al. (2021); Wang et al. (2021, 2022); Liu et al. (2023); Othman et al. (2023); Arthur et al. (2025, 2026).

Figure 7 highlights the benefits of multi-stage scrubbing for persistent surface contamination or high fines removal before downstream processing. Removing slimes between stages reduces re-coating and fine buildup, boosting efficiency.

However, these benefits entail higher capital and operating costs and add process complexity, requiring additional equipment, pumps, and control systems to ensure stable multi-stage operation.

Single-stage systems are simpler and cheaper for ores with less complex surface where characteristics or for which downstream processes are less sensitive to fines. The decision between single-stage and multi-stage setups should consider ore mineralogy, product needs, and economic factors.

Solids Concentration and Residence Time Control

Effective attrition scrubbing usually requires a high solids concentration, which efficiency.

Industrial systems usually operate between 40-70 wt% solids, depending on particle size and mineralogy. High solids increase slurry viscosity and hinder mixing, while low solids decrease particle collisions and cleaning efficiency.

Residence time affects cleaning; too long can cause slimes, harming separation.

Integration with Classification Circuits

Attrition scrubbing circuits are often combined with hydrocyclones, screens, or classifiers to remove slimes and maintain an appropriate solids concentration.

This integration enables the beneficiation circuit to continuously remove detached fine particles and recycle coarser material for further scrubbing if needed. It's common in silica sand purification, phosphate beneficiation, and iron ore processing (Rao et al., 2023).

Despite these advantages, the effectiveness relies heavily on classification efficiency. Poor hydrocyclone performance can cause slimes to be recycled to the scrubber, reducing cleaning effectiveness.

In industrial mineral processing circuits, attrition scrubbing is rarely applied as a standalone operation. Instead, it is typically integrated within a broader process flowsheet that includes classification, slime rejection, and downstream separation stages. This integration is essential to maximize the benefits of surface cleaning while preventing the negative effects associated with the accumulation of fines and particle recoating (Khalifa & Hagrass 2023).

Hydrocyclone classification plays a critical role in this context by enabling the efficient removal of liberated fines immediately after scrubbing. This step not only improves pulp quality but also enhances the performance of subsequent separation processes by reducing entrainment and stabilizing operating conditions. Figure 8 illustrates a generic industrial configuration in which attrition scrubbing is combined with hydrocyclones and downstream beneficiation processes.

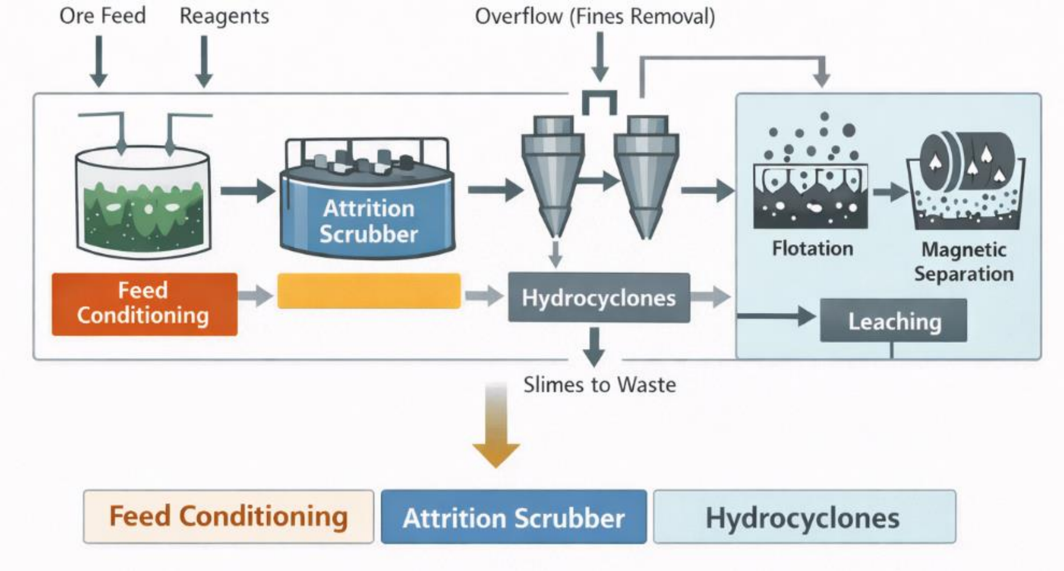

Figure 8. Generic attrition scrubbing circuit integrated with hydrocyclones and downstream separation processes. Adapted from: Maranhão et al. (2020); Bedekovic and Tenjer (2021); Hussein and El-Midany (2022); Ahmed et al. (2025); Arthur et al. (2025).

Figure 8 highlights an integrated circuit that couples attrition scrubbing with classification for optimized performance. Removing slimes after scrubbing prevents interference in downstream separation, especially in flotation systems where fine particles increase entrainment and reduce selectivity.

The downstream stage's flexibility allows it to adapt to various ore types and processing goals. Flotation is used for fine particles via surface chemistry, magnetic separation suits magnetic ores, and leaching benefits from increased surface exposure during scrubbing.

Overall, the efficiency of integrated circuits depends on balancing scrubbing intensity, classification, and downstream needs. Optimizing these is key to high recovery, better quality, and lower operational losses.

Equipment Wear and Maintenance

Attrition scrubbers experience intense particle abrasion and turbulent flow, resulting in significant equipment wear.

Wear rates depend on mineral hardness, particle size, impeller design, and solids concentration. Highly abrasive minerals like quartz can cause rapid damage to impellers and tank liners.

Laboratory studies show improvements in cleaning efficiency but rarely evaluate equipment wear or maintenance costs. In industrial systems, downtime due to wear and replacement costs can offset some of the metallurgical benefits of scrubbing pretreatment.

Attrition scrubbing performance depends on equipment design and operating conditions, affecting particle interactions, abrasion, and cleaning efficiency. These must be controlled to balance contaminant removal with the avoidance of particle damage.

Key design variables such as impeller speed, solids concentration, residence time, and circuit setup are crucial to scrubbing efficiency. Adding classification systems, such as hydrocyclones, can improve performance by continuously removing fine particles. Table 8 lists key equipment variables, effects, and limitations.

Table 8. Main equipment design variables affecting attrition scrubbing performance. Adapted from: Sahoo et al. (2021); Wang et al. (2021, 2022); Liu et al. (2023); Othman et al. (2023); BedekovicandTenjer (2021).

Design Variable	Operational Effect	Potential Limitation
Impeller speed	Increases particle collisions	Higher energy consumption
Solids concentration	Enhances abrasion efficiency	Increased slurry viscosity
Residence time	Improves surface cleaning	Slime generation
Multi-stage configuration	Higher cumulative abrasion	Capital and operating cost
Hydrocyclone integration	Continuous slime removal	Classification inefficiency

Variables in Table 8 show trade-offs in attrition scrubbing. Higher impeller speed boosts particle impact and cleaning but increases energy use and wear.

Higher solids concentration promotes interparticle contact and abrasion efficiency but may increase slurry viscosity, negatively impacting mixing and mass transfer. Longer residence time improves cleaning but also increases the risk of generating ultrafine particles.

Multi-stage setups increase abrasion and cleaning costs in complex ores. Hydrocyclones enable continuous slime removal, aiding downstream processing, but depend on classification and design.

Optimizing attrition scrubbing requires a holistic approach considering equipment design, operating parameters, and ore characteristics.

Equipment setup alone does not ensure process viability; energy demand and operating costs determine if attrition scrubbing is justified beyond lab results. The next section covers energy use and economic impact in mineral beneficiation.

Energy and Process Efficiency

Attrition scrubbing is often described as a low-energy alternative to grinding. However, this characterization can be misleading when high solids concentration, multi-stage operation, and wear-intensive conditions are considered. These conditions can lead to high energy costs affecting beneficiation expenses (Leon & Bengtsson, 2022; Behera & Dwari, 2026).

The key question isn't whether attrition scrubbing uses less energy than grinding, but whether its higher operating costs are offset by better metallurgical performance, such as higher recovery, better concentrate grade, lower reagent use, improved classification, or less recirculation in the circuit.

Despite its importance, few studies connect energy use, cleaning efficiency, and metallurgical response. Most reports describe qualitative improvements in mineral surfaces but lack details on energy or costs (Baritto & Kumar, 2025).

Specific Energy Consumption

Reported specific energy consumption of attrition scrubbing ranges from 0.5 to 5 kWh/t, depending on equipment, solids concentration, and residence time. These are usually lower than fine grinding but can approach the energy use of light milling with multiple stages.

Energy consumption increases with:

- Higher impeller speed
- Increased solids concentration
- Longer residence time
- multi-stage scrubbing circuits

The energy needed for attrition scrubbing should be assessed alongside the additional metallurgical gains in downstream separation.

Attrition scrubbing's energy demand is measured in specific energy consumption (kWh/t), indicating the mechanical intensity needed for effective cleaning. Values vary by ore type, solids concentration, equipment setup, and number of scrubbing stages.

Although attrition scrubbing is usually less energy-intensive than grinding, its total energy use can become significant in multi-stage circuits or high-intensity operations. Typical energy consumption ranges for different mineral systems are summarized in Table 9.

Table 9. Reported ranges of specific energy consumption for attrition scrubbing operations. Adapted from Abdullah (2020); Wang et al. (2021); Behera and Dwari (2026); and Baritto and Kumar (2025).

System	Typical Specific Energy (kWh/t)	Notes
Silica sand scrubbing	0.5 – 1.5	Surface iron removal
Phosphate ore scrubbing	1 – 3	Clay dispersion prior to flotation
Iron ore scrubbing	1 – 4	Slime removal before magnetic separation
Multi-stage scrubbing systems	2 – 5	Higher cumulative residence time

Table 9 shows that energy use for attrition scrubbing varies across mineral systems but remains moderate compared with fine grinding. Lower energy is typical in silica sand scrubbing, which focuses on removing surface iron. Higher energy is required in multi-stage systems that need more residence time and repeated interactions for effective cleaning.

However, these values should be interpreted with caution. Most studies report energy consumption separately from downstream metallurgical performance, making it difficult to determine whether higher energy input improves recovery or concentrate grade in proportion. Consequently, the link between energy use and process efficiency is not well quantified in current literature.

Capital and Operating Cost Implications

Introducing attrition scrubbing into a beneficiation circuit demands extra power, equipment, and maintenance. Industrial systems typically involve:

- Attrition scrubbers
- slurry pumps
- classification equipment (hydrocyclones or screens)
- slurry circulation pipelines

These components increase CAPEX and OPEX, with wear-related maintenance essential for processing abrasive minerals such as quartz-rich ores.

Impeller blades and tank liners may require frequent replacement in abrasive conditions. Excessive scrubbing creates slimes, increasing downstream handling costs in classification and tailings management.

Water Demand and Slurry Circulation

Attrition scrubbing requires controlled solids levels in the slurry, often necessitating substantial water circulation through the scrubbing and classification stages to achieve the desired rheology.

Water demand may increase with the addition of scrubbing circuits in beneficiation plants, especially when hydrocyclones or desliming stages are used to remove fines. More pumping energy might also be needed to circulate slurry.

Although water consumption is rarely quantified in experimental studies, it can become an important operational parameter in large-scale mineral processing plants.

Residence Time and Throughput Trade-Off

Another key operational factor is the link between residence time and plant throughput. Longer residence time in the scrubber can boost cleaning efficiency but decrease equipment capacity.

Industrial circuits must therefore balance:

- Scrubbing intensity
- residence time
- plant throughput
- downstream process stability

Excessive scrubbing may clean surfaces but also generate fines and increase energy use, making economic benefits uncertain.

Integrating attrition scrubbing in mineral beneficiation circuits affects costs and performance. Higher scrubbing boosts surface cleaning and can improve recovery or concentrate grade, but increases energy use, wear, and operational complexity.

Attrition scrubbing isn't always beneficial; its effectiveness depends on whether the metallurgical benefits outweigh the extra costs, as shown in Figure 9.

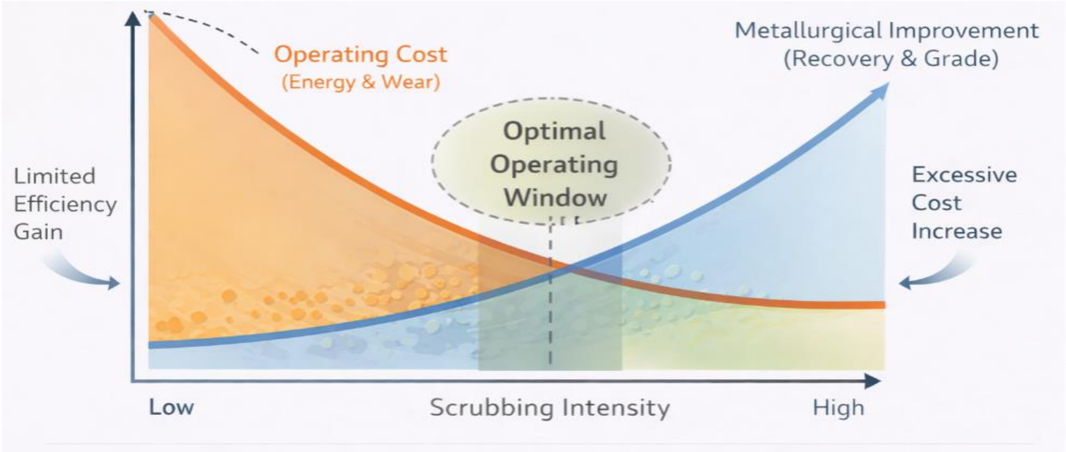

Figure 9. Conceptual cost–benefit framework for the integration of attrition scrubbing into mineral beneficiation circuits. Adapted from Wills and Finch (2016); Abdullah (2020); Wang et al. (2021, 2022); Sahoo et al. (2021); Behera and Dwari (2026); and Baritto and Kumar (2025).

As shown in Figure 9, the link between scrubbing intensity and process performance is non-linear. Low intensity limits surface cleaning, with little downstream effect. As intensity rises, recovery and concentrate grade improve, especially where surface coatings hinder separation.

Further increases in intensity may cause diminishing returns, the formation of ultrafine particles, higher slurry viscosity, and issues with flotation or classification. Operating costs also rise due to more energy use and equipment wear.

This framework stresses that the justification for attrition scrubbing depends not just on technical performance but also on balancing metallurgical gains and costs. Although important, this balance is seldom quantified; most studies report process improvements without integrated economic analysis.

Table 10 shows that each attrition scrubbing factor involves a trade-off between cost and metallurgical performance. Higher energy use and equipment wear increase operating costs, while multi-stage setups can raise capital expenses. These factors may also contribute to improved surface cleaning, higher recovery, and better process stability.

Table 10. Conceptual framework for evaluating the economic impact of attrition scrubbing. Adapted from Abdullah, 2020; Wang et al., 2021, 2022; Sahoo et al., 2021; Behera & Dwari, 2026; Baritto & Kumar, 2025.

Factor	Potential Cost Penalty	Potential Metallurgical Benefit
Specific energy consumption	Increased operating cost	Improved downstream recovery
Equipment wear	Maintenance and replacement cost	Stable long-term cleaning performance
Slime generation	Lossof fine particles	Improved classification efficiency
Additional water circulation	Pumping energy	Better slurry rheology control
Multi-stage scrubbing	Higher CAPEX and OPEX	Greater surface cleaning

However, these benefits are not always proportional to costs. For example, slime generation may improve classification efficiency in some systems but cause mineral losses in others. Similarly, extra water circulation may improve slurry control but increase pumping and handling needs.

This framework demonstrates that the economic justification for attrition scrubbing depends on the overall process response, not on individual performance metrics. However, few studies provide comprehensive techno-economic analyses that quantify these trade-offs in industrial environments, leaving a notable gap in the existing literature.

A complete attrition scrubbing assessment must consider water use, fines, reagents, and tailings, not just energy, as these impact sustainability and environmental footprints.

Environmental and Sustainability Aspects

The environmental impact of attrition scrubbing mainly depends on its effects on reagent use, water consumption, and fine-particle production in beneficiation circuits. It can improve mineral surface cleanliness, boost the selectivity of downstream separation, reduce reagent requirements in flotation, and reduce the number of repeated cleaning stages (Rødland et al., 2022).

The environmental benefits of attrition scrubbing depend on trade-offs such as increased water use, fines, and complex tailings management, which should be evaluated at the circuit level rather than just the scrubbing step (Silin et al.,2024).

Reagent Consumption

In flotation circuits, surface coatings such as clay and iron oxide reduce collector adsorption and increase reagent consumption. Attrition scrubbing can before flotation.

Several studies show reduced reagent use with scrubbing pretreatment, especially in phosphate and graphite flotation (Farid et al., 2025). The extent of reduction depends on mineralogy and coating features.

In ore systems with impurities locked in inclusions, attrition scrubbing offers little benefit, and reagent demand remains largely unchanged.

Water Demand

Attrition scrubbing requires maintaining controlled solids concentration in slurry, often increasing water circulation in beneficiation plants, especially when integrated with hydraulic classification or desliming circuits.

Additional water handling may raise pumping energy and water treatment needs, posing a major constraint in water-scarce mining areas.

Water use in attrition scrubbing is rarely quantified; most data focus on cleaning efficiency rather than the overall water balance.

Fines Generation and Tailings Management

Attrition scrubbing can produce fine particles (slimes) by mechanical abrasion. While primarily intended to remove surface coatings, excessive scrubbing may break mineral grains and increase the number of ultrafine particles.

These slimes must be managed in the tailings system. Increased fines may affect sedimentation, thickening, and storage design (Bouabdallah et al., 2023).

The environmental impact of attrition scrubbing depends on how effectively fine particles are removed and managed in the beneficiation circuit.

Selectivity and Resource Efficiency

Under favorable mineralogical conditions, attrition scrubbing can improve separation Selectivity by removing surface coatings that interfere with downstream processes. Higher selectivity can lower recirculation loads in beneficiation circuits and boost overall resource efficiency.

In such cases, the operation can indirectly reduce the environmental footprint by lowering reagent use and improving recovery.

However, these benefits are not universal. In systems where surface coatings do not primarily limit separation, attrition scrubbing may impose environmental burdens without providing significant metallurgical advantages.

The environmental impact of attrition scrubbing depends on how it is integrated. While it can improve separation and reduce reagent use, it also affects the slurry, water demand, and the presence of fine particles. These effects make the environmental assessment of attrition scrubbing context-dependent. The main trade-offs are shown in Figure 10.

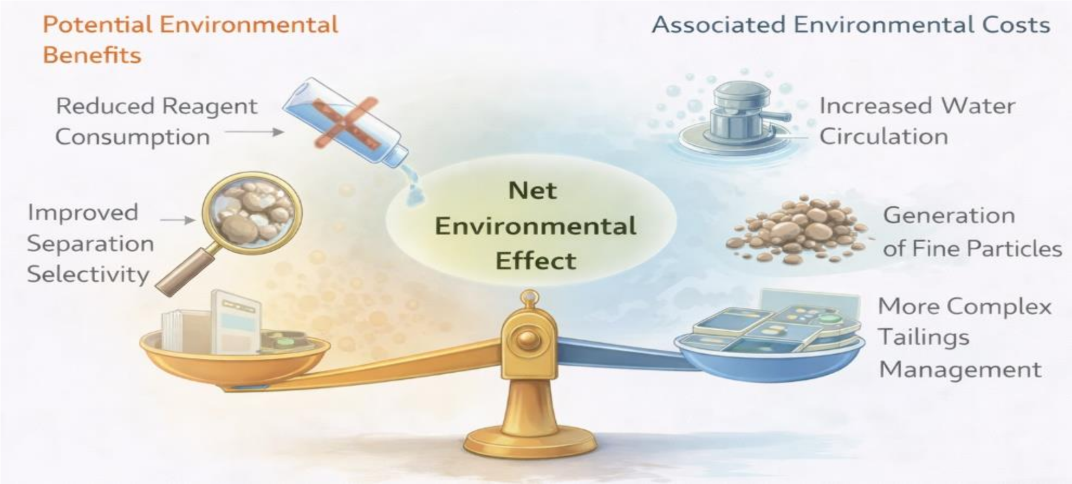

Figure 10. Environmental trade-offs associated with attrition scrubbing in mineral beneficiation circuits. Source: Author's own elaboration based on the reviewed literature on attrition scrubbing, flotation performance, and tailings management.

As shown in Figure 10, attrition scrubbing offers environmental benefits but also presents operational challenges. Better surface cleanliness can lower reagent use, improve separation, and reduce chemical discharge, especially in systems affected by clay coatings or surface contamination.

However, these benefits may be offset by increased water circulation and the presence of fine particles during scrubbing. Slimes can complicate solid–liquid separation, burden tailings systems, and cause losses of valuable material. Higher water demand may also raise pumping energy and water treatment needs.

These observations suggest that the environmental performance of attrition scrubbing varies and should be assessed at the circuit level, accounting for process efficiency and waste management.

The environmental impact of attrition scrubbing depends on the mineral system and its role in beneficiation. While it can improve surface cleaning, by reducing reagent use and boosting selectivity, it also poses challenges for water use, fines, and tailings management. These effects vary by application and should be evaluated in specific mineral processing routes. Table 11 summarizes reported environmental benefits and limitations for attrition scrubbing applications.

Table 11. Environmental implications of attrition scrubbing across different mineral processing applications. Source: Author's own elaboration based on published studies on attrition scrubbing, flotation performance, and waste management in mineral processing systems.

Application	Potential Environmental Benefit	Potential Environmental Limitation
Phosphate flotation	Reduced reagent consumption	Increased slime generation
Iron ore processing	Improved separation selectivity	Additional water circulation
Silica sand purification	Reduced chemical treatment	Fine particle disposal
Recycling of secondary materials	Improved liberation of components	Increased fines handling

Table 11 shows that the environmental impact of attrition scrubbing depends on the balance between process improvements and side effects. In phosphate flotation, lower reagent use can reduce chemical discharge, but more slime makes solid–liquid separation harder. In iron ore processing, better separation improves efficiency, but extra water circulation raises pumping and water management needs.

In silica sand purification, attrition scrubbing can reduce chemical use but can create fine particles that require proper disposal or processing. In recycling, better liberation of valuable parts can boost recovery, but managing fines remains a key operational challenge.

These observations show that the environmental performance of attrition scrubbing is conditional and should be assessed at the circuit level rather than assumed as an inherent benefit.

A balance between improved separation efficiency and additional material handling requirements, therefore, determines the environmental profile of attrition scrubbing. When surface coatings represent the primary limitation to beneficiation performance, scrubbing may contribute to more efficient resource utilization. In other cases, the environmental benefit may be marginal or uncertain.

These trade-offs have stimulated interest in more controlled, data-rich scrubbing systems, including digitally monitored units and advanced hydrodynamic modeling approaches to improve process predictability and operational efficiency.

Emerging Trends

Recent studies have explored several approaches to improve the control and predictability of attrition scrubbing, including high-intensity operation, digital monitoring, and hydrodynamic modeling.

Although these approaches offer promising opportunities to improve the predictability and efficiency of attrition-based circuits, their industrial implementation remains uneven across commodities and processing scales. Many of the proposed technologies have been demonstrated primarily at laboratory or pilot scales, while their performance and economic viability in full-scale beneficiation plants remain insufficiently documented (Gungoren et al., 2024).

High-Intensity Attrition Systems

One emerging direction is through higher impeller speeds, rotor modifications, or increased slurry turbulence.

These systems improve surface cleaning and reduce residence time but may accelerate equipment wear, increase energy use, and increase ultrafine particle formation.

Consequently, the operational advantage of high-intensity systems depends on whether the increased cleaning efficiency outweighs the additional energy and maintenance costs.

Digital Torque Monitoring and Process Sensors

Another emerging trend is the use of digital torque-monitoring systems integrated with attrition scrubbers. These systems measure the torque needed to keep the impeller spinning and can give indirect insights into slurry rheology, solids concentration, and particle interaction strength.

Additionally, online slurry sensors that can measure variables such as density, viscosity, and particle-size distribution are increasingly being suggested as tools for process monitoring.

Despite these advances, most industrial attrition circuits still rely on conventional operational control based on feed rate, solids concentration, and residence time. The adoption of sensor-based monitoring remains limited, partly due to the abrasive nature of mineral slurries and challenges in sensor durability.

Hydrodynamic Modeling and CFD

The use of computational fluid dynamics (CFD) modeling has attracted attention as a tool for analyzing slurry flow patterns, turbulence levels, and particle interaction mechanisms inside attrition scrubbers (Karthik & Buwa, 2022).

CFD simulations can provide insights into impeller design, residence time distribution, and energy dissipation within the scrubber. These models may help optimize equipment design and operating conditions before industrial implementation.

However, CFD models of attrition scrubbing remain challenging due to the complex interactions between solid particles, turbulent flow, and slurry rheology. Validation against industrial-scale data is still limited.

Hybrid Scrubbing and Cleaning Systems

Another emerging concept involves hybrid scrubbing systems that combine attrition with methods such as hydraulic washing, ultrasonic agitation, or chemical dispersion.

These hybrid systems aim to improve the removal of strongly adhered surface coatings while limiting mechanical fragmentation of mineral particles. Although promising, these approaches remain largely experimental and have not yet been widely adopted in industrial mineral processing circuits.

Data-Driven Optimization

Recent studies explore data-driven methods like machine learning and advanced process control to enhance scrubbing performance.

These approaches correlate operational parameters like solids concentration, impeller speed, and residence time with metallurgical response. They could enable dynamic scrubbing adjustments based on ore variability.

The industrial use of these approaches is limited by the scarcity of reliable datasets linking scrubbing conditions to beneficiation outcomes, hindering the development of robust predictive models.

Digital monitoring, CFD-assisted design, and hybrid cleaning are often discussed but rarely adopted in industry, with many innovations still in pilot testing. Their long-term impact on industrial scrubbing circuits is uncertain.

Recent developments in attrition scrubbing enhance process control, energy efficiency, and performance prediction across mineral systems. They include equipment innovations and data-driven methods to better understand interactions between slurry and particles.

The maturity of these technologies varies; some are tested on pilot or industrial scales, while others are still conceptual or limited to labs. The main directions in attrition scrubbing are summarized in Figure 11.

Figure 11. Emerging technology roadmap for attrition scrubbing systems in mineral beneficiation. Source: Author's own elaboration based on recent studies on process intensification, slurry hydrodynamics, and digital monitoring in mineral processing systems.

Figure 11 shows innovation efforts in attrition scrubbing fall into two categories: equipment-focused developments and data-driven approaches. High-intensity scrubbers aim to boost particle interaction efficiency, while CFD modeling improves understanding of slurry flow and shear distribution.

At the same time, digital technologies such as torque monitoring and online slurry sensors are being explored to enable real-time control of operating conditions. Data-driven approaches, including advanced process control and machine learning, have also been proposed to optimize scrubbing performance under variable feed conditions.

Despite these developments, industrial adoption remains uneven. Many of these technologies lack long-term operational validation, and their economic benefits have not yet been consistently demonstrated across mineral commodities. Their role in future beneficiation circuits depends on technical performance, cost-effectiveness, and ease of integration.

The roadmap illustrates key innovation areas, including:

- high-intensity scrubber design
- digital torque monitoring
- online slurry sensors
- CFD-based equipment optimization
- Hybrid scrubbing systems
- data-driven process control

Emerging attrition scrubbing technologies aim to boost efficiency, monitoring, and predictive control through equipment redesign, digital tools, and data-driven methods. Their industrial maturity varies, with many still at the pilot or lab stage.

To assess their relevance, consider benefits, limitations, and deployment readiness. Table 12 summarizes emerging technologies and their maturity levels.

Table 12. Emerging technological approaches in attrition scrubbing and their current level of industrial maturity. Source**:** Author's own elaboration based on reported developments in process intensification, slurry hydrodynamics, and digitalization in mineral processing systems.

Technology	Potential Benefit	Limitation	Technology Readiness Level (TRL)
High-intensitys crubbers	Increased cleaning efficiency	Higher wear and energy consumption	TRL 6–7
Digital torque monitoring	Real-time process control	Sensor durability in abrasive slurries	TRL 5–6
Online slurry sensors	Improved monitoring of solids concentration and rheology	Calibration challenges	TRL 4–6
CFD-based scrubber design	Improved hydrodynamic understanding	Limited industrial validation	TRL 4–5
Hybrid scrubbing systems	Enhanced removal of strong coatings	Limited industrial implementation	TRL 3–5
Data-driven optimization	Adaptive process control	Scarcity of reliable datasets	TRL 3–4

As shown in Table 12, most emerging technologies in attrition scrubbing are at intermediate or low maturity. High-intensity scrubbers are the most advanced, with some operating at pilot or industrial scale. In contrast, digital monitoring and data-driven optimization are still developing and face challenges with sensors, data, and process integration.

CFD-based design and hybrid scrubbing systems offer promising avenues for improving process understanding and performance, but their industrial validation remains limited. Similarly, data-driven approaches depend on the availability of high-quality datasets, which are often scarce in mineral processing operations.

These observations suggest that, although technological innovation in attrition scrubbing is progressing, its translation into industrial practice is uneven and constrained by both technical and economic factors.

Techno-Economic Considerations

From an industrial perspective, attrition scrubbing should be viewed as a circuit-level investment rather than a simple cleaning step. It alters mineral surface condition and impacts capital costs, energy use, water flow, and maintenance (Uysal, 2022).

Most studies focus on technical outcomes but provide limited data on the incremental cost of achieving these improvements.

Capital Investment (CAPEX)

Adding attrition scrubbing to a beneficiation circuit needs extra capital for equipment and installation.

Typical CAPEX components include:

- Attrition scrubber units
- electric motors and power supply systems
- slurry pumps and pipelines
- structural supports and foundations
- hydrocyclones or classification equipment
- instrumentation and process control systems

The magnitude of these investments depends strongly on plant throughput and circuit configuration. Multi-stage scrubbing circuits or high-capacity units may require substantial structural and electrical infrastructure.

As a result, the economic feasibility of attrition scrubbing cannot be assessed solely based on laboratory-scale cleaning performance.

Operating Costs (OPEX)

Beyond capital investment, attrition scrubbing also adds operating costs.

The most relevant operational expenditures include:

- **specific energy consumption** associated with impeller agitation
- **water handling and pumping energy**
- **wear-related replacement costs** for impellers and liners
- routine **maintenance and downtime**

Highly abrasive minerals such as quartz-rich ores may accelerate equipment wear and increase maintenance frequency. In such cases, the cost associated with replacement parts may represent a significant fraction of the scrubbing operating cost.

Potential Metallurgical Value

Although attrition scrubbing increases capital and operating costs, it may also generate economic value through improvements in downstream beneficiation performance.

Potential benefits include:

- Higher **mineral recovery**
- Increased **concentrate grade**
- reduced **reagent consumption** in flotation circuits
- improved **process stability** and lower recirculation loads

For example, removing clay coatings can significantly improve flotation selectivity in certain ore systems, decreasing reagent usage and enhancing concentrate quality. In magnetic separation circuits, surface cleaning might boost separation efficiency by revealing magnetically responsive mineral surfaces.

However, the magnitude of these benefits varies widely between ore types. In systems where surface coatings are not the primary factor limiting separation efficiency, attrition scrubbing may provide little economic advantage.

Circuit-Level Economic Evaluation

A realistic assessment of attrition scrubbing requires a circuit-level techno-economic analysis comparing the scrubbing costs with the benefits of improved metallurgical performance.

Such assessments should ideally include:

- incremental **energy consumption** (kWh/t)
- changes in **reagent consumption**
- variations in **recovery and concentrate grade**
- impacts on **throughput and recirculation load**
- **maintenance and wear costs**

However, very few studies provide integrated datasets that allow such evaluations. As a result, the economic justification for attrition scrubbing often remains based on empirical plant experience rather than systematic techno-economic analysis.

Deciding to implement attrition scrubbing in mineral beneficiation needs a circuit-level evaluation, not just surface cleaning or metallurgical indicators. It must weigh the process costs against the value from better downstream performance.

Attrition scrubbing adds CAPEX and OPEX, such as equipment, energy, water, and maintenance costs. These costs must be balanced against gains in recovery, concentrate grade, and process stability. The economic viability depends on this trade-off, as shown in Figure 12.

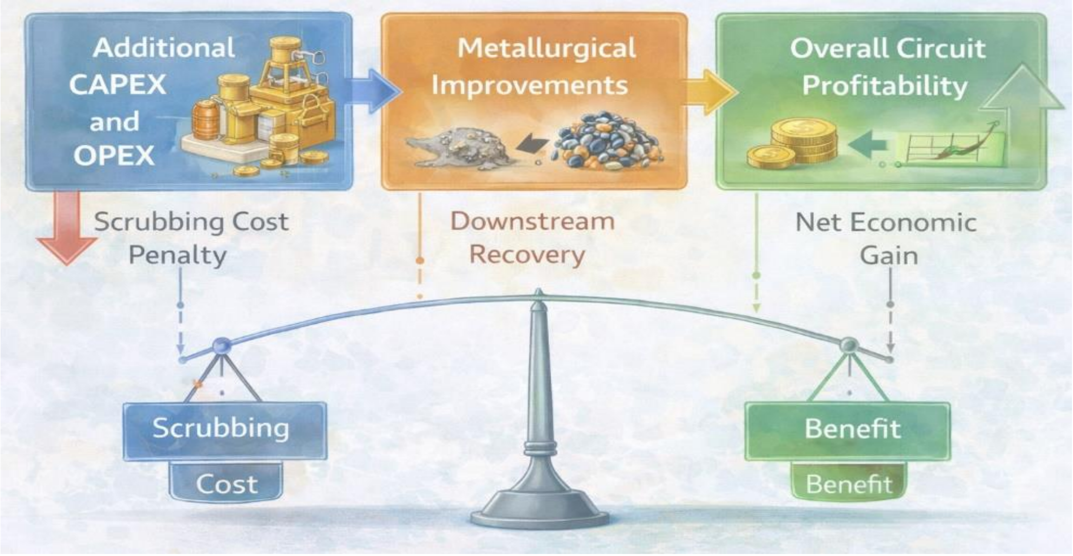

Figure 12. Decision framework for the economic justification of attrition scrubbing in mineral beneficiation circuits—source**:** Author's own elaboration based on techno-economic evaluation principles applied to mineral processing systems.

As illustrated in Figure 12, the economic justification of attrition scrubbing depends on the interaction between cost and performance variables. The introduction of the process increases capital and operating expenditures, which are typically associated with equipment installation, energy demand, wear, and water management. At the same time, improved surface cleaning may enhance downstream recovery, increase concentrate grade, and stabilize process performance.

However, these benefits are not guaranteed and may vary significantly depending on mineralogical characteristics and circuit configuration. In some cases, improvements in recovery or grade may not be sufficient to offset the additional operating cost, particularly when energy consumption or wear rates are high. Conversely, in systems where surface contamination strongly limits separation efficiency, even moderate improvements may justify the added cost.

This framework reinforces that attrition scrubbing should be evaluated as part of an integrated beneficiation strategy, rather than as an isolated unit operation.

A thorough techno-economic evaluation of attrition scrubbing must consider both costs and metallurgical performance. Analyzing individual variables like energy or recovery alone is insufficient to assess economic viability.

A structured framework is needed to link operational variables to economic outcomes by quantifying the cost penalties of scrubbing and the value of better beneficiation. Main parameters and metrics are summarized in Table 13.

Table 13. Framework for techno-economic evaluation of attrition scrubbing integration. Source: Author's own elaboration based on techno-economic analysis approaches applied to mineral processing systems.

Parameter	Economic Impact	Evaluation Metric
Specific energy consumption	Increased operating cost	kWh/t processed
Equipment wear	Maintenance and replacement cost	Component lifetime
Water handling	Pumping and treatment cost	m^3/t processed
Recovery improvement	Increased metal production	% recovery increase
Concentrate grade improvement	Higher product value	% grade increase

Table 13 shows the economic evaluation of attrition scrubbing, including cost drivers such as energy, wear, and water, and value factors such as recovery and concentrate grade, which impact costs and revenue.

The relationship between these parameters isn't linear. Additional energy input yields only marginal improvements in recovery, while slight increases in scrubbing can significantly enhance product quality. This variability highlights the need for evaluation frameworks that consider both costs and metallurgical results.

Despite its importance, such integrated techno-economic analysis is rarely reported in the literature, where studies often focus on either process performance or operational cost in isolation.

The industrial feasibility of attrition scrubbing depends on whether it addresses a critical limitation in the beneficiation circuit. It is not always required and offers limited value if surface coatings do not impact downstream separation.

A simplified feasibility matrix assesses whether scrubbing is likely to generate economic benefit under specific conditions, highlighting the relationship between mineralogical constraints and expected economic outcomes.

As shown in Table 14, the economic viability of attrition scrubbing is primarily determined by the extent to which surface coatings limit downstream process performance. When coatings strongly interfere with separation mechanisms—such as flotation selectivity or magnetic response—scrubbing is more likely to be justified, as improvements in recovery or concentrate quality may offset the additional operating cost.

Table 14. Industrial feasibility matrix for the implementation of attrition scrubbing. Source: Author's own elaboration based on synthesis of mineralogical, operational, and techno-economic considerations in attrition scrubbing applications.

Condition	Economic Outcome
Surface coatings strongly limit separation	Scrubbing likely economically justified
Coatings weakly affect separation	Limitede conomic benefit
High abrasive mineral content	Increased maintenance cost
Low downstream sensitivity to surface condition	Scrubbing often unnecessary

In contrast, when surface coatings have a limited effect on separation, introducing scrubbing may not provide sufficient economic benefit to justify implementation. Similarly, ores with high abrasive content may increase equipment wear, raising maintenance costs and reducing overall process viability.

These observations reinforce that attrition scrubbing should be applied selectively, based on mineralogical characterization and circuit sensitivity, rather than as a standard step in beneficiation flowsheets.

=The justification for attrition scrubbing depends on the overall metallurgical and economic response of the complete beneficiation circuit, not just the cleaning efficiency of the scrubbing stage.

Critical Synthesis and Research Gaps

Despite its widespread use, attrition scrubbing remains insufficiently understood from both mechanistic and economic perspectives.

Key gaps

- Lack of standardized performance metrics
- Limited quantitative modeling
- Insufficient mineralogical integration
- scarce industrial data
- limited energy analysis
- confusion with mechanical activation

Future research

- mechanistic modeling of surface cleaning
- integration with digital monitoring
- machine learning optimization
- lifecycle assessment (LCA)

Despite the widespread application of attrition scrubbing in mineral beneficiation, several fundamental and applied aspects remain insufficiently understood. Much of the existing literature focuses on qualitative improvements in surface cleaning, while quantitative relationships between operating parameters, mineralogical characteristics, and downstream metallurgical performance are rarely established.

In addition, the lack of standardized evaluation criteria and the scarcity of industrial-scale data limit the ability to generalize results across different mineral systems. These limitations highlight the need for a more structured research agenda.

The main research gaps and future directions are summarized in Figure 13.

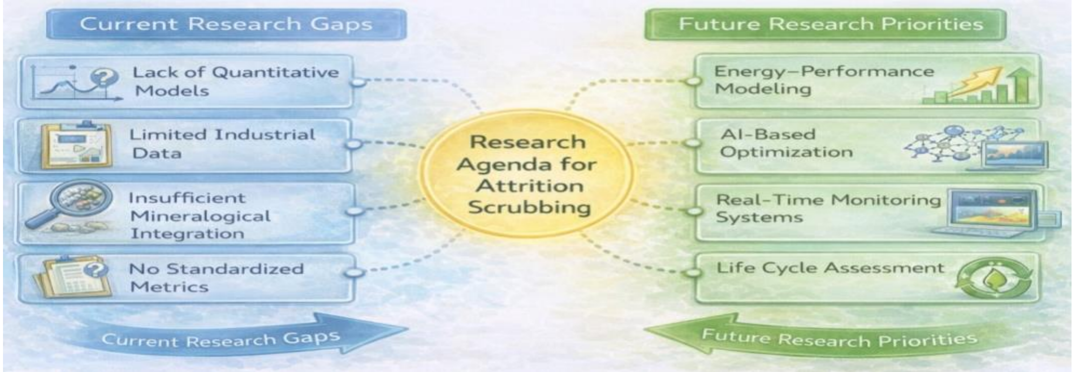

Figure 13. Research gaps and future research agenda for attrition scrubbing in mineral beneficiation—source: Author's own elaboration based on critical synthesis of the reviewed literature.

Figure 13 shows that research on attrition scrubbing has limitations. Most studies note improvements in surface cleanliness but don't measure effects on recovery, grade, or circuit performance. Energy use and equipment wear are discussed qualitatively with inconsistent operational data.

A significant gap exists in integrated models linking scrubbing intensity, mineralogy, and metallurgical response. Limited industrial data also hampers the validation of lab results and scale-up.

Future research should create quantitative frameworks that combine process variables, mineralogy, and performance metrics. Using real-time monitoring, digital control, and data tools can improve predictability. Including life cycle assessment (LCA) provides a comprehensive view of the environmental and economic impacts of attrition scrubbing.

In addition to the general research gaps identified in the literature, several fundamental questions remain unresolved regarding the role of attrition scrubbing in mineral beneficiation. These questions are not only scientific but also operational, as they directly affect process design, scale-up, and economic justification.

Rather than focusing solely on reported improvements, a critical review must also identify where the current understanding remains incomplete. The main unresolved questions are summarized in Table 15.

Table 15. Major unresolved questions in attrition scrubbing for mineral beneficiation. source: Author's own elaboration based on critical analysis of the reviewed literature.

Topic	Unresolved Question
Mechanistic understanding	What is the quantitative contribution of particle–particle abrasion versus hydrodynamic shear?
Energy–performance relationship	How does specific energy consumption correlate with actual metallurgical improvement?
Mineralogical dependence	How do coating thickness and adhesion strength affect scrubbing efficiency?
Fines generation	At what point does scrubbing intensity become detrimental due to the production of ultrafine particles?
Scale-up	How do laboratory results translate to industrial-scale scrubbers?
Process integration	Under which conditions does scrubbing improve overall circuit performance rather than isolated steps?
Economic evaluation	What is the threshold at which additional CAPEX and OPEX are justified by metallurgical gains?
Data availability	Why are industrial datasets on energy, wear, and performance still scarce?

Table 15 shows that knowledge of attrition scrubbing has unresolved issues that hinder science and industry. Many studies focus on operational variables without identifying the mechanisms behind surface cleaning. Also, the link between energy input and metallurgical performance is not well quantified, complicating process optimization.

The lack of detailed mineralogical characterization further complicates the interpretation of results, as coating properties such as thickness and adhesion strength are rarely measured systematically. In addition, the generation of ultrafine particles introduces a critical trade-off that is not consistently addressed in experimental studies.

Perhaps the most significant limitation is the scarcity of industrial-scale data, particularly regarding energy consumption, equipment wear, and long-term performance. This gap restricts the validation of laboratory findings and limits the development of predictive models for process design and scale-up.

Conclusions

Attrition scrubbing plays a well-established role in mineral beneficiation circuits where surface coatings, adhered slimes, or weathering products interfere with downstream separation processes. By promoting particle–particle abrasion in high-solids slurries, the process can remove surface contaminants without substantial particle-size reduction, thereby increasing the exposure of mineral surfaces for flotation, magnetic separation, classification, or leaching.

The effectiveness of attrition scrubbing depends on the nature of the impurities. It works best with surface films or loose particles. When contaminants are embedded within mineral grains, it is less effective. Many studies report clearer surfaces, but few measure impacts on recovery, grade, or circuit performance.

Operational parameters such as solids concentration, residence time, impeller speed, and specific energy consumption strongly influence scrubbing efficiency. Excessive scrubbing intensity may generate ultrafine particles that reduce downstream separation efficiency and increase slime losses. Consequently, the optimal operating window for attrition scrubbing often represents a balance between effective surface cleaning and controlled fines generation.

From an engineering perspective, the addition of attrition scrubbing should be evaluated as a circuit-level modification rather than an isolated unit operation. The process introduces additional capital investment, energy consumption, water handling requirements, and equipment wear. Its economic justification therefore depends on whether these costs are offset by improved metallurgical performance, reduced reagent consumption, or increased process stability in downstream operations.

Environmental implications are similarly conditional. While improved surface cleanliness may enhance separation selectivity and reduce reagent demand, attrition scrubbing may also increase fines generation and water circulation within the beneficiation circuit. The overall sustainability profile of scrubbing operations must therefore be assessed in the context of the complete mineral processing flowsheet.

Emerging technologies like high-intensity scrubbers, digital torque monitoring, slurry sensors, and CFD modeling may enhance process understanding and control. However, industrial adoption is limited, and their economic benefits vary across mineral commodities.

Several important research gaps remain. In particular, the literature lacks systematic datasets linking specific energy consumption, scrubbing intensity, mineralogical characteristics, and downstream metallurgical response. Quantitative studies addressing these relationships would significantly improve the ability to evaluate attrition scrubbing as a process-intensification strategy in modern beneficiation circuits.

Attrition scrubbing is valuable but context-dependent in mineral processing. It needs careful integration with classification, separation, and economic factors. Future research should focus on quantitative metrics, scale-up validation, and techno-economic evaluation to define its role in complex flowsheets.

Declarations

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Conflicts of Interest / Competing Interests

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Antonio Clareti Pereira: Conceptualization, literature review, analysis and interpretation of data, writing – original draft, writing – review and editing.

Data Availability

No new datasets were generated or analyzed in this study. The review is based exclusively on previously published literature.

References

1. Aarab, I., Amari, K. E., Yaacoubi, A., Etahiri, A., & Bacaoui, A. (2023). Optimization of the flotation of low-grade phosphate ore using DOE: a comparative evaluation of fatty acid formulation to sodium oleate. *Mining, Metallurgy & Exploration*, *40*(1), 95-108.https://doi.org/10.1007/s42461-022-00706-w
2. Abbadi, A. I., Mádai-Üveges, V., & Bokányi, L. (2022). Water Quality Change Due to the Mine Backfilling and Its Possible Response to Talc Flotation. *Geosciences and Engineering*, *10*(15), 5-21.https://doi.org/10.33030/geosciences.2022.15.005
3. Abdullah, W. R. (2020). Standard Sand Specifications Development by Mechanical Attrition Scrubbing to Make it Convenient for the Cement Industry. *Key Engineering Materials*, *870*, 61-70.https://doi.org/10.4028/www.scientific.net/KEM.870.61
4. Ahmed, M. M., Hassan, M., Saleh, A. M., & Hassan, E. S. R. (2025). Optimizing Upgrading of Abu-Tartur Phosphate Ore Using Attrition Scrubbing And Magnetic Separation Techniques. *Journal of Al-Azhar University Engineering Sector*. https://doi.org/10.21608/ejchem.2025.365180.11391
5. Alali, J. (2023). Mineral Processing of Silica Sand in Hanout Area South of Jordan. *Open Journal of Geology*, *13*(7), 667-696.
6. Aleksandrova, T., Elbendari, A., & Nikolaeva, N. (2022). Beneficiation of a low-grade phosphate ore using a reverse flotation technique. *Mineral Processing and Extractive Metallurgy Review*, *43*(1), 22-27.https://doi.org/10.1080/08827508.2020.1806834
7. Ali, M. A., Ahmed, H. A., El-Midany, A. A., & Farag, R. M. (2025). Achieving high-alumina pyrophyllite by DHIMS and collector less flotation. *Mining, Metallurgy & Exploration*, *42*(2), 1117-1125.https://doi.org/10.1007/s42461-025-01223-2
8. Amalia, D., Singh, P., Zhang, W., & Nikoloski, A. N. (2025). Liberation of valuable materials from spent cylindrical lithium-ion batteries via semi-autogenous attrition. *Mineral Processing and Extractive Metallurgy Review*, *46*(1), 101-115.https://doi.org/10.1080/08827508.2023.2259576
9. Anticoi, H., Moncunill, J. O., Sampaio, C. H., Pérez-Álvarez, R., & Malagón-Picón, B. (2022). Ore processing technologies applied to industrial waste decontamination: a case study. *Minerals*, *12*(6), 695.https://www.mdpi.com/2075-163X/12/6/695#
10. Antoniak, D. P. (2020). *Exploring high pressure slurry ablation as a mineral processing technology* (Doctoral dissertation, University of British Columbia).http://hdl.handle.net/2429/75705

11. Arroug, L., Elaatmani, M., & Zegzouti, A. (2024). A preliminary study to investigate the beneficiation of low-grade phosphate sludge using reverse flotation: Modeling and optimization through Box-Behnken design and response surface methodology. *Chemical Engineering Research and Design*, *204*, 228-237.https://doi.org/10.1016/j.cherd.2024.02.041
12. Arthur, S. E., Mends, E. A., Tita, A. M., & Chu, P. (2025). The development of a beneficiation process to remove carbonates from lithium sedimentary claystones. *Cleaner Engineering and Technology*, *26*, 100949.https://doi.org/10.1016/j.clet.2025.100949
13. Arthur, S. E., Mends, E. A., Gargiulo, M., Muthoni, F., Hussaini, S., & Chu, P. (2026). Improving lithium extraction from claystone: Maximizing efficiency and sustainability with integrated beneficiation and sulfuric acid leaching. *Journal of Cleaner Production*, *538*, 147332.https://doi.org/10.1016/j.jclepro.2025.147332
14. Baritto, M., & Kumar, A. (2025). The development of process-based techno-economic models to assess critical mineral recovery from bitumen extraction tailings. *Minerals Engineering*, *232*, 109583.https://doi.org/10.1016/j.mineng.2025.109583
15. Baştürkcü, E., Şavran, C., Yüce, A. E., & Timur, S. I. (2022). Revealing the effects of mechanical attrition applied on Eskisehir-Beylikova REE ore utilizing MLA. *Minerals Engineering*, *186*, 107733.https://doi.org/10.1016/j.mineng.2022.107733
16. Bedekovic, G., & Tenjer, D. (2021). Influence of independent variables on recovering electrode material from lithium-ion batteries via attrition scrubbing. *Environmental technology & innovation*, *24*, 101836.https://doi.org/10.1016/j.eti.2021.101836
17. Beeks, M., & Keller, D. (2020). Aqueous Cleaning Essentials. In *Handbook for Critical Cleaning, Second Edition-2 Volume Set* (pp. vol1-35). CRC Press.https://www.taylorfrancis.com/chapters/edit/10.1201/9780429185335-2/aqueous-cleaning-essentials-michael-beeks-david-keller
18. Behera, M. R., & Dwari, R. K. (2026). Hydrodynamics and Response Analysis of a Cutting-Edge Pulse Bed Mineral Scrubber (PBMS) Featuring U-Type Motion, Pulsation Bed, and Fluidization for Low-Grade Iron Ore Processing. *Mineral Processing and Extractive Metallurgy Review*, *47*(1), 155-172.https://doi.org/10.1080/08827508.2024.2429023
19. Bilal, M., Park, I., Hornn, V., Ito, M., Hassan, F. U., Jeon, S., & Hiroyoshi, N. (2022). The challenges and prospects of recovering fine copper sulfides from tailings using different flotation techniques: A review. *Minerals*, *12*(5), 586.https://www.mdpi.com/2075-163X/12/5/586#
20. Bouabdallah, S., Chaib, A., Bounouala, M., Dovbash, N., Benselhoub, A., & Bellucci, S. (2023). Recycling of siliceous by-products to reduce their impacts on the environment. *Technology audit and production reserves*, *2*(3/70), 31-36.doi:10.15587/2706-5448.2023.277784.
21. Bulut, G., Aydın, Ş. B., Perek, K. T., & Arslan, F. (2025). Enrichment of boron using physical and chemical methods: A review. *Mineral Processing and Extractive Metallurgy Review*, 1-18.https://doi.org/10.1080/08827508.2025.2502360
22. Chen, C. S., & Tien, C. J. (2023). Remediation of lubricant-contaminated soils by cavitation microjet shock wave soil washing system with ozonation. *Soil and Sediment Contamination: An International Journal*, *32*(8), 1053-1065.https://doi.org/10.1080/15320383.2022.2164558
23. Chiu, J. C., & Gani, P. (2024). Soil washing methods for effective removal of heavy metal contaminants. *Industrial and Domestic Waste Management*, *4*(1), 56-71https://doi.org/10.53623/idwm.v4i1.444
24. Cho, K., Kim, H., Purev, O., Choi, N., & Lee, J. (2021). Physical separation of contaminated soil using a washing ejector based on hydrodynamic cavitation. *Sustainability*, *14*(1), 252.https://www.mdpi.com/2071-1050/14/1/252#
25. Datta, B., & Nandi, A. (2021). Bauxite beneficiation: an approach to value addition in mining. In *Innovations in Sustainable Mining: Balancing Environment, Ecology and Economy* (pp. 99-114). Cham: Springer InternationalPublishing.https://doi.org/10.1007/978-3-030-73796-2_7.
26. El-Mofty, S. E., El-Bendary, A. M., El-Midany, A. A., & El-Rahman, M. A. (2023). Effect of Hydrophobicity on Talc Grinding in Attritor Mill. *Theoretical Foundations of Chemical Engineering*, *57*(6), 1424-1430.https://doi.org/10.1134/S0040579523060039
27. Elshwehy, R. A., Fawzy, M. M., Fakhry, F., & Hamdy, M. M. (2025). High-purity kaolinite-based electrodes for supercapacitor application: New approach of the Egyptian silica sand added-value. *Journal of Alloys and Compounds Communications*, 100110.https://doi.org/10.1016/j.jacomc.2025.100110
28. El-Wekil, M., Yassin, K., Abouellaban, S. A., & Hagrass, A. A. (2024). Characterization and upgrading of Abu Shaar manganese ores using dry high-intensity magnetic separation. *The Bulletin Tabbin Institute for Metallurgical Studies (TIMS)*, *113*(1), 50-66.
29. Farid, Z., Abdennouri, M., Barka, N., & Sadiq, M. H. (2025). Current and sustainable approaches in phosphate ore flotation: A review of eco-friendly reagents and their applications. *Journal of Industrial and Engineering Chemistry*. https://doi.org/10.1016/j.jiec.2025.04.029

30. Fawzy, M. M., Salem, H. M., Orabi, A. H., & Ibrahim, S. S. (2022). Preparation of gamma alumina nanoparticles from kaolinitic sandstone and their application as a selective adsorbent for REEs from liquid waste. *Hydrometallurgy*, *213*, 105940.https://doi.org/10.1016/j.hydromet.2022.105940
31. Fish, A. (2025). *Enhancing Processing Strategies of Claystone Ores: Li-Bearing Smectites from Oregon, USA* (Master's thesis, University of Nevada, Reno).
32. Garcia, E. M. P., & García, E. M. P. (2020). *Dynamic simulation of industrial grinding circuits: mineral liberation, advanced process control, and real-time optimisation* (Doctoral dissertation, Université Laval).https://corpus.ulaval.ca/entities/publication/08d4c833-166e-420c-b2cb-f9d326b1469a
33. Gerber, M., & Grobler, J. (2023). Particle coating characterisation and linking of particle surface quality with downstream valuable mineral recovery. *Countering risks in an evolving future for heavy minerals*, 91.
34. Guan, C., Yin, Z., Zhai, J., Hu, Y., Chen, P., & Sun, W. (2020). Surface modification of ilmenite by a novel surfactant dodecyl imino dimethylene diphosphoinc acid and its sequent influence on ilmenite floatability. *Separation Science and Technology*, *55*(2), 358-368.https://doi.org/10.1080/01496395.2019.1577270
35. Gungoren, C., Ozkan, S. G., & Ozdemir, O. (2024). Use of ultrasound in physical and chemical mineral processing operations. In *Advances in Minerals Research* (pp. 25-54). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-49175-7_2
36. Guo, J., Li, B., Peng, H., & Tao, C. (2024). Recovery of phosphors by beneficiation technology. *Journal of Composites and Biodegradable Polymers*, *12*, 7-15.https://doi.org/10.12974/2311-8717.2024.12.02
37. Han, G., Wen, S., Wang, H., & Feng, Q. (2020). Selective adsorption mechanism of salicylic acid on pyrite surfaces and its application in flotation separation of chalcopyrite from pyrite. *Separation and Purification Technology*, *240*, 116650.https://doi.org/10.1016/j.seppur.2020.116650
38. Huang, L., An, S., Zhang, F., Peng, J., Chen, Y., Ping, X., & Liu, C. (2024). Synergistic treatment of blast furnace slag and basic oxygen furnace slag for efficient recovery of iron: Phase transformation and oxidation mechanisms. *Journal of Materials Research and Technology*, *28*, 2347-2362.https://doi.org/10.1016/j.jmrt.2023.12.022
39. Hussein, N. T., & El-Midany, A. A. (2022). Size reduction of oil shale by attrition scrubbing and its effect on kerogen content. *International Journal of Coal Preparation and Utilization*, *42*(6), 1664-1674.https://doi.org/10.1080/19392699.2020.1749054
40. Ibrahim, S. S., Fathy, W. M., Elsayed, M. A., & Boulos, T. R. (2021). Iron bearing minerals flotation from silica sand using hydroxyl surfactants. *J. Miner. Mater. Charact. Eng*, *9*, 327-344.https://doi.org/10.4236/jmmce.2021.94023
41. Ibrahim, S. S., Boulos, T. R., Abdullah, S., Elbendary, A., Khalifa, M., & Hagrass, A. (2025a). Improving the quality of silica sand as a proppant for hydraulic fracking industry purposes. *Rudarsko-geološko-naftnizbornik*, *40*(1), 145-163.https://doi.org/10.17794/rgn.2025.1.11
42. Ibrahim, S. S., Boulos, T. R., Abdullah, S. M., Elbendari, A. M., Khalifa, M. G., & Hagrass, A. A. (2025b). Poboljšanje kvalitete silikatnog pijeska kao propanta za potrebe hidrauličkog afrakturiranja. *Rudarsko-geološko-naftnizbornik*, *40*(1), 145-163.https://doi.org/10.17794/rgn.2025.1.11
43. Ismail, S. A., Kamarudin, M. K., Mahmud, M. H., & Idham, M. (2020). Physico-chemical study of silica rocks from the East Coast Malaysia Region for crystal glass application. *Journal of Geological Resource and Engineering*, *8*, 106-113.doi:10.17265/2328-2193/2020.04.002
44. Jadeppa, H., Kumar, P. S., & Ravi, B. P. (2024). Process characterization of a low-grade pyrophyllite from Nambulapulakunta, Anantapur, Andhra Pradesh. *Journal of Applied Geochemistry*, *26*(3), 183-192.
45. Jain, P. K. (2025). Electrostatic Separation. In *Treatise on Process Metallurgy, Volume 2B* (pp. 169-183). Elsevier.https://doi.org/10.1016/B978-0-443-40294-4.00009-8
46. Jin, N., Zhang, F., Cui, Y., Sun, L., Gao, H., Pu, Z., & Yang, W. (2022). Environment-friendly surface cleaning using micro-nano bubbles. *Particuology*, *66*, 1-9.https://doi.org/10.1016/j.partic.2021.07.008
47. Karthik, G. M., & Buwa, V. V. (2022). Enabling Process Innovations via Mastering Multiphase Flows: Gas–Liquid and Gas–Liquid–Solid Processes. *Multiphase Flows for Process Industries: Fundamentals and Applications*, *1*, 203-240. https://doi.org/10.1002/9783527812066.ch4
48. KhAlifA, M. G. E., & AlYhAGrASS, A. (2023). KhAlEdYASSin, MAhMoudAhMEd 2. https://doi.org/10.24425/ams.2023.144315
49. Leon, L. G., & Bengtsson, M. (2022). Selective comminution applied to mineral processing of a tantalum ore: A technical, economic analysis. *Minerals*, *12*(8), 1057.http://dx.doi.org/10.3390/min12081057
50. Li, D., Zhang, C., Li, X., Yang, L., Yan, X., Wang, L., ... & Zhang, H. (2020). Experimental study on the preconditioning of fine coal particles surface modification using a new type flow mixer. *Fuel*, *268*, 117361.https://doi.org/10.1016/j.fuel.2020.117361

51. Li, M., Widijatmoko, S. D., Wang, Z., & Hall, P. (2023). A methodology to liberate critical metals from waste solar panels. *Applied Energy*, *337*, 120900.https://doi.org/10.1016/j.apenergy.2023.120900
52. Liu, C., Wang, W., Wang, H., Zhu, C., & Ren, B. (2023). A review on the removal of iron impurities from quartz mineral. Minerals, 13(9), 1128.https://www.mdpi.com/2075-163x/13/9/1128#
53. Ma, F., Tao, D., Tao, Y., & Liu, S. (2021). An innovative flake graphite upgrading process based on HPGR, stirred grinding mill, and nanobubble column flotation. *International Journal of Mining Science and Technology*, *31*(6), 1063-1074.https://doi.org/10.1016/j.ijmst.2021.06.005
54. Mweene, L., Gomez-Flores, A., Jeong, H. E., Ilyas, S., & Kim, H. (2024). Challenges and Future in Ni Laterite Ore Enrichment: A Critical Review. *Mineral Processing and Extractive Metallurgy Review*, *45*(6), 539–563. https://doi.org/10.1080/08827508.2023.2214668
55. OO, A., Gbadamosi, Y. E., & Akinpelumi, T. (2021). Desliming process of kuru columbite (Plateau state) using scrubbing method towards niobium pentoxide recovery. https://doi.org/10.53430/ijeru.2021.1.1.0044
56. Othman, N., Mustaffar, M. I., Ismail, S. A., & Ibrahim, M. H. (2023). Upgrading silica rock quality by using attrition scrubbing and magnetic separation techniques. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.04.659
57. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). *The PRISMA 2020 statement: An updated guideline for reporting systematic reviews*. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71
58. Pereira, A. C. (2026a). *Phosphorus control in titanium feedstocks for TiO₂ pigment production: A critical review of mineralogical constraints, dephosphorization routes, and rutilization performance*. International Journal of Frontiers in Engineering and Innovation, 3(2), 8–30. https://doi.org/10.54660/IJFEI.2026.3.2.08-30
59. Pereira, A. C. (2026b). *Mechanical activation in metallurgical processing: Mechanisms, applications and industrial perspectives*. IKR Journal of Engineering and Technology, 2(2). https://doi.org/10.5281/zenodo.18912251
60. Phengsaart, T., Srichonphaisan, P., Kertbundit, C., Soonthornwiphat, N., Sinthugoot, S., Phumkokrux, N., ... & Ito, M. (2023). Conventional and recent advances in gravity separation technologies for coal cleaning: A systematic and critical review. *Heliyon*, *9*(2).https://doi.org/10.1016/j.heliyon.2023.e13083
61. Rao, N. D., Chakraborty, D. P., Shukla, V., & Kumar, N. (2023). Iron ore beneficiation: an overview. *Mineral processing*, 55-77https://doi.org/10.1016/B978-0-12-823149-4.00003-X.
62. Rizk, S. A. M. (2022). Highlights on the beneficiation trials of the Egyptian phosphate ores. *JES. Journal of Engineering Sciences*, *50*(1), 1-21.
63. Rødland, E. S., Lind, O. C., Reid, M., Heier, L. S., Skogsberg, E., Snilsberg, B., ... & Meland, S. (2022). Characterization of tire and road wear microplastic particle contamination in a road tunnel: From surface to release. *Journal of Hazardous Materials*, *435*, 129032.https://doi.org/10.1016/j.jhazmat.2022.129032
64. Sahoo, S., Sahu, S. N., Sahoo, R. K., Soren, S., & Biswal, S. K. (2021). A study on the removal of clay minerals from the Barbil region iron ore: effect of scrubbing followed by pelletization. *Mining, Metallurgy & Exploration*, *38*(1), 105-116.https://doi.org/10.1007/s42461-020-00292-9
65. Severov, V. V., Filippova, I. V., & Filippov, L. O. (2022). Use of fatty acids with an ethoxylated alcohol for apatite flotation from old fine-grained tailings. *Minerals Engineering*, *188*, 107832.https://doi.org/10.1016/j.mineng.2022.107832
66. Silin, I., Dertmann, C., Cvetković, V. S., Stopic, S., & Friedrich, B. (2024). Prevention of silica gel formation for eudialyte study using a new digestion reactor. Minerals, 14(2), 124.https://www.mdpi.com/2075-163X/14/2/124#
67. Sochea, R., Somsak, S., & Numprasanthai, A. (2020). Study on beneficiation of silica sand by Wet High-Intensity Magnetic Separators (WHIMS) and reverse flotation technique for glass application: A case study from Sihanoukville, Cambodia. https://doi.org/10.7186/wg463202007
68. Tinesha, S., Ismail, I., Roshaida, A., Anuar, O., & Voon, C. H. (2025). Beneficiation method and iron removal from feldspar ore. *Journal of Engineering and Technology (JET)*, *16*(1), 227-237.https://doi.org/10.54554/jet.2025.16.1.016
69. Uysal, T. (2022). Economic analysis of rare earth element processing methods for Mountain Pass ore. *Journal of the Southern African Institute of Mining and Metallurgy*, *122*(7), 407-412.https://doi.org/10.17159/2411-9717/1989/2022
70. Vidal, A., Klöffel, T., Guigue, J., Angst, G., Steffens, M., Hoeschen, C., & Mueller, C. W. (2021). Visualizing the transfer of organic matter from decaying plant residues to soil mineral surfaces controlled by microorganisms. *Soil Biology and Biochemistry*, *160*, 108347.https://doi.org/10.1016/j.soilbio.2021.108347

71. Wang, X., Bu, X., Ni, C., Zhou, S., Yang, X., Zhang, J., ... & Xie, G. (2021). Effect of scrubbing medium's particle size on scrubbing flotation performance and mineralogical characteristics of microcrystalline graphite. *Minerals Engineering*, *163*, 106766.https://doi.org/10.1016/j.mineng.2020.106766
72. Wang, X., Bu, X., Alheshibri, M., Bilal, M., Zhou, S., Ni, C., ... & Xie, G. (2022). Effect of scrubbing medium's particle size distribution and scrubbing time on scrubbing flotation performance and entrainment of microcrystalline graphite. *International Journal of Coal Preparation and Utilization*, *42*(10), 3032-3053. https://doi.org/10.1080/19392699.2021.1932843
73. Wang, Z., Lu, Q., Wang, J., Liu, J., Liu, G., Sun, W., ... & Zeng, H. (2023). Nanomechanical insights into hydrophobic interactions of mineral surfaces in interfacial adsorption, aggregation and flotation processes. *Chemical Engineering Journal*, *455*, 140642.https://doi.org/10.1016/j.cej.2022.140642
74. Wencheng, L., Zhijun, M., Xingyuan, W., Yunsheng, Z., Hao, G., Yushu, W., ... & Linfeng, C. (2025). Experimental Investigation and Mechanism Analysis of Quartzite to Quartz Sand: Process Mineralogy-oriented Physical Purification Technology. *Silicon*, 1-19.https://doi.org/10.1007/s12633-025-03565-4
75. Widijatmoko, S. D. (2020). *Recovery of positive electrode active material from spent lithium-ion battery*. University of Nottingham.
76. Widijatmoko, S. D., Fu, G., Wang, Z., & Hall, P. (2020). Recovering lithium cobalt oxide, aluminium, and copper from spent lithium-ion battery via attrition scrubbing. *Journal of Cleaner Production*, *260*, 120869.https://doi.org/10.1016/j.jclepro.2020.120869
77. Wongkaewphothong, B. (2022). Whitening of calcium carbonate tailings using attrition process: a case study of Khar Toum deposit, Lopburi province, Thailand.10.58837/CHULA.THE.2022.171
78. Wongkaewphothong, B., Kertbundit, C., Srichonphaisan, P., Julapong, P., Homchuen, P., Juntarasakul, O., ... & Phengsaart, T. (2023). The improvement in whiteness index of calcite tailings using attrition-scrubbing process. *Separation Science and Technology*, *58*(11), 2077-2085.https://doi.org/10.1080/01496395.2023.2219380
79. Wu, C., Zhang, S., Wang, G., Lv, S., Li, D., Liu, L., ... & Wang, H. (2020). Efficient heterogeneous formation of ammonium nitrate on the saline mineral particle surface in the atmosphere of East Asia during dust storm periods. *Environmental science & technology*, *54*(24), 15622-15630.https://doi.org/10.1021/acs.est.0c04544
80. Yassin, K., Mourad, S., Khalil, M., Abdel-Khalek, N., Elbendari, A., Selim, K., & Hassan, E. L. S. A. Y. E. D. (2024). Upgrading and surface coating of Egyptian white sand with polymers and silanes. *Rudarsko-geološko-naftnizbornik*, *39*(1), 115-130.https://doi.org/10.17794/rgn.2024.1.9
81. Zeng, G., Zhu, Y., & Chen, W. (2023). A brief review of micro-particle slurry rheological behavior in grinding and flotation for enhancing fine mineral processing efficiency. *Minerals*, *13*(6), 792.https://www.mdpi.com/2075-163X/13/6/792#
82. Zhai, J., Wang, H., Chen, P., Hu, Y., & Sun, W. (2020). Recycling of iron and titanium resources from early tailings: From fundamental work to industrial application. *Chemosphere*, *242*, 125178.https://doi.org/10.1016/j.chemosphere.2019.125178
83. Zhou, J. Z. (2021). Role of mineral flotation technology in improving bitumen extraction from mined A thabasca oil sands III. Next generation of water-based oil sands extraction. *The Canadian Journal of Chemical Engineering*, *99*(3), 755-777.https://doi.org/10.1002/cjce.23874
84. Zhu, Z., Wang, D., Yang, B., Yin, W., Ardakani, M. S., Yao, J., & Drelich, J. W. (2020). Effect of nano-sized roughness on the flotation of magnesite particles and particle-bubble interactions. *Minerals Engineering*, *151*, 106340.https://doi.org/10.1016/j.mineng.2020.106340