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DISPERSÃO DE PARTÍCULAS FINAS E ULTRAFINAS NO BENEFICIAMENTO MINERAL: FUNDAMENTOS, MÉTODOS E APLICAÇÕES

DISPERSION OF FINE AND ULTRAFINE PARTICLES IN MINERAL PROCESSING: FUNDAMENTALS, METHODS, AND APPLICATIONS

DISPERSIÓN DE PARTÍCULAS FINAS Y ULTRAFINAS EN EL PROCESAMIENTO DE MINERALES: FUNDAMENTOS, MÉTODOS Y APLICACIONES

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Resumo

A dispersão de partículas finas e ultrafinas influencia a seletividade e a eficiência das operações de beneficiamento mineral, mas sua intensificação não produz benefícios uniformes em todos os sistemas. Esta revisão narrativa analisa os fundamentos das interações entre partículas, os métodos químicos e físicos de dispersão, suas formas de avaliação e suas aplicações em classificação, deslamagem, flotação e separação magnética. A pesquisa reuniu estudos clássicos e trabalhos disponíveis até novembro de 2026, com ênfase em minérios de ferro e rejeitos e comparação com bauxita, fosfatos e sulfetos associados a minerais argilosos. A análise distingue ruptura de agregados, prevenção da reagregação, remoção de recobrimentos e alteração da molhabilidade. Silicatos, polifosfatos, policarboxilatos e derivados de polissacarídeos apresentam respostas dependentes da mineralogia, do pH, da composição da água e da sequência de condicionamento. Agitação intensa e ultrassom podem remover recobrimentos e modificar associações entre partículas, mas também favorecer colisões, reagregação e alterações dos reagentes. Potencial zeta, sedimentação e

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granulometria devem ser interpretados conjuntamente com reologia, composição dos produtos e desempenho metalúrgico. As evidências sustentam a busca por um estado de associação adequado à operação, em vez da maximização indiscriminada da dispersão. A aplicação em escala industrial requer integração entre seletividade, energia efetivamente consumida, estabilidade ao longo do circuito e efeitos sobre o desaguamento e a recirculação de água.

Palavras-chave: dispersão mineral; partículas ultrafinas; química de superfícies; ultrassom; rejeitos de mineração.

Abstract

The dispersion of fine and ultrafine particles affects the selectivity and efficiency of mineral processing operations, but increasing dispersion does not consistently improve separation. This narrative review examines particle interactions, chemical and physical dispersion methods, assessment techniques, and applications in classification, desliming, flotation, and magnetic separation. The literature search covered classical contributions and studies available up to November 2026, emphasizing iron ores and tailings while considering bauxite, phosphate minerals, and sulfide ores containing clay minerals. The discussion distinguishes aggregate breakup, prevention of reaggregation, slime coating removal, and changes in wettability. Silicates, polyphosphates, polycarboxylates, and polysaccharide derivatives show responses that depend on mineralogy, pH, water composition, and conditioning sequence. Intense agitation and ultrasound may remove coatings and change particle associations, but can also promote collisions, reaggregation, and reagent modification. Zeta potential, sedimentation, and particle size measurements should be interpreted together with rheology, product composition, and metallurgical performance. The evidence supports controlling particle association according to the requirements of each operation instead of indiscriminately maximizing dispersion. Industrial implementation requires an integrated assessment of selectivity, actual energy consumption, stability throughout the circuit, and downstream effects on dewatering and water recycling.

Keywords: mineral dispersion; ultrafine particles; surface chemistry; ultrasound; mining tailings.

Resumen

La dispersión de partículas finas y ultrafinas influye en la selectividad y eficiencia del procesamiento de minerales, pero su intensificación no beneficia por igual a todos los sistemas. Esta revisión narrativa analiza las interacciones entre partículas, los métodos químicos y físicos de dispersión, las técnicas de evaluación y sus aplicaciones en clasificación, deslamado, flotación y separación magnética. La búsqueda reunió contribuciones clásicas y estudios disponibles hasta noviembre de 2026, con énfasis en minerales de hierro y relaves, e incluyó bauxita, fosfatos y sulfuros asociados a minerales arcillosos. Se distinguen la ruptura de agregados, la prevención de la reagregación, la eliminación de recubrimientos y los cambios de mojabilidad. Silicatos, polifosfatos, policarboxilatos y

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derivados de polisacáridos presentan respuestas dependientes de la mineralogía, el pH, la composición del agua y la secuencia de acondicionamiento. La agitación intensa y el ultrasonido pueden limpiar superficies y modificar asociaciones entre partículas, aunque también favorecer colisiones y reagregación. El potencial zeta, la sedimentación y la granulometría deben interpretarse junto con la reología y el desempeño metalúrgico. La evidencia favorece el control del estado de asociación según cada operación. Su aplicación industrial requiere evaluar conjuntamente selectividad, consumo energético, estabilidad durante el proceso y efectos sobre el desaguado y la recirculación de agua.

Palabras clave: dispersión mineral; partículas ultrafinas; química de superficies; ultrasonido; relaves mineros.

1. Introduction

The need to liberate finely disseminated minerals increases the proportion of small particles in mineral processing circuits. At the same time, recovering valuable minerals from desliming and concentration tailings requires overcoming limitations associated with particle size, mineralogical composition, and surface interactions. Small particle dimensions change the balance between surface forces, body forces, and hydrodynamic resistance. Consequently, a mineralogically liberated particle may not behave as an independent entity in the pulp: it may remain attached to another mineral, form part of an aggregate, or participate in a particle network.

The terms fine and ultrafine have no universal size boundaries applicable to every operation. A fraction that presents difficulties in conventional flotation may respond differently to magnetic separation, hydraulic classification, or selective flocculation. In this review, these terms follow the operational definitions used in the studies, retaining reported particle size ranges where available. The classical interpretation by Trahar (1981) demonstrates that flotation response depends on particle size and that the behavior of small particles cannot be explained solely by their chemical composition.

In iron ores, hematite, goethite, magnetite, quartz, and phyllosilicates may have different size distributions and surface properties. Slime generation does not necessarily mean that only gangue is produced: iron-bearing minerals may also become concentrated in the removed fractions. Studies on column flotation of

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slimes and magnetic separation of tailings demonstrate that these streams can be investigated as feeds for mineral recovery, although the outcome depends on the specific material characteristics (Filippov et al., 2021; da Rocha et al., 2021). Desliming must therefore be assessed together with the distribution of the valuable element across particle size fractions.

Dispersion matters because it changes how individual mineral properties influence separation. A clay coating can prevent collector access to a sulfide surface; a magnetite-quartz aggregate can carry silica into the magnetic product; a particle structure can increase resistance to flow. However, keeping all solids as individual particles is not always the most appropriate objective. Selective aggregation of valuable mineral particles can increase their probability of recovery while gangue remains dispersed. This coexistence is central to routes combining dispersion, selective flocculation, and concentration (Su et al., 2016; Lima and Abreu, 2020).

The scientific problem thus involves three related questions: which associations should be broken, which surfaces should be stabilized after breakup, and which state of association favors the next operation? Answering these questions requires combining surface chemistry with hydrodynamic conditions and metallurgical indicators. This article reviews these fundamentals, compares chemical and physical methods, and discusses their applications and limitations. Its scope covers aqueous mineral processing systems, emphasizing iron ores and tailings without assuming that mechanisms observed in one ore can be transferred automatically to another. The contribution of this review lies in connecting particle association mechanisms, dispersion assessment methods, and their implications for mineral separation performance.

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2. Literature Review Methodology

A narrative review was conducted, with sources searched and organized on November 11, 2026. Scientific publications were identified through web searches and consultations of journal websites and institutional repositories. Bibliographic identification was supplemented by title and DOI queries to the public Crossref API. Providers consulted included ScienceDirect, SciELO, ACS Publications, PubMed Central, MDPI websites, Taylor & Francis, Physicochemical Problems of Mineral Processing, J-STAGE, IUPAC, and NIST. No authenticated search of Scopus or Web of Science was performed, and exhaustive coverage of their collections is not claimed.

Queries were developed iteratively using combinations of English and Portuguese terms. Search expressions included “mineral dispersion fine particles hematite quartz sodium hexametaphosphate”, “iron ore slimes dispersion selective flocculation”, “ultrasonic pretreatment mineral flotation dispersion cavitation”, “mineral pulp rheology clay dispersion polyacrylate”, “dispersion sulfide ores flotation slime coating serpentine”, “dispersants hydrocyclone classification fine particles”, and “dispersão polpas minérios itabiríticos”. Retrieved titles were searched individually to confirm the correspondence between the study, DOI, and journal. References cited in the consulted studies guided the identification of classical contributions and additional research. Study selection prioritized thematic relevance rather than exhaustive literature coverage.

Sources were selected for their direct relevance to dispersion, heteroaggregation, coating removal, or the effects of these properties on mineral processing operations. Studies on colloidal fundamentals, electrokinetic interpretation, and sonication standardization were also included because they support the assessment of mechanisms and experimental comparability. Journal literature and technical reports from scientific institutions were prioritized. Duplicate preliminary and published versions were resolved in favor of the journal version. The time frame covered classical contributions and publications available by the search date, including one study published in 2026. The final collection comprises

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49 references.

The synthesis was thematic and qualitative, without meta-analysis, bibliometric assessment, or a systematic review protocol. Numerical comparisons were retained within individual studies, avoiding rankings based on recoveries obtained with different feeds. The discussion distinguishes experimental observations, interpretations proposed by the original authors, and engineering implications inferred by comparing sources.

3. Physicochemical Fundamentals of Mineral Dispersion

3.1 Particle Associations and the Operational Meaning of Dispersion

Dispersion can be understood as reducing associations between particles and maintaining sufficiently independent units during a processing stage. It is useful to distinguish deaggregation, which requires overcoming existing bonds, from stabilization, which reduces the probability of new persistent contacts. A suspension may appear dispersed during vigorous agitation and reaggregate shortly after agitation stops. Conversely, a chemical change that favors stability may not readily remove coatings formed before the treatment.

Homoaggregation refers to the association of particles of the same mineral species, whereas heteroaggregation involves different species. In practice, aggregates may contain several minerals, trapped water, and adsorbed reagents. Coagulation is commonly associated with a reduction in colloidal barriers, and flocculation often involves polymers or other forms of induced association; terminology, however, varies between articles. Analysis should therefore identify the mechanism and aggregate composition, without inferring selectivity solely from the term used.

Slime coating is a particularly relevant form of heteroaggregation: small particles adhere to larger particles and change the interface exposed to the medium. Classical work on pentlandite and serpentine minerals linked this phenomenon to the surface charges of the constituents (Edwards et al., 1980). Subsequent studies of slime removal from pentlandite reaffirm the need to

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distinguish surface cleaning from simply keeping particles suspended in the bulk pulp (Feng et al., 2018). Breaking an aggregate may expose a surface; keeping that surface accessible requires controlling subsequent interactions with the detached fines.

3.2 Colloidal Interactions and the Limits of Electrostatic Interpretation

Derjaguin-Landau-Verwey-Overbeek (DLVO) theory combines van der Waals attraction with the electrical double-layer contribution to interpret dispersion stability. The classical contribution by Derjaguin and Landau, consulted in its republished version, provides a basis for relating the interaction barrier to the persistence of dispersed particles (Derjaguin and Landau, 1993). Interaction energy depends on surface separation, geometry, medium properties, and electrical conditions. A sufficiently high barrier may restrict close approach, but it does not imply the absence of attraction at every separation distance.

In mixed mineral suspensions, surfaces have different potentials and properties. The heterocoagulation approach of Hogg et al. (1966) is especially relevant because a single potential used to represent the pulp may conceal particle pairs with different interactions. The stability of an isolated hematite suspension does not ensure the stability of a hematite-quartz mixture. Assessment must also consider surface heterogeneity, including crystallographic faces, defects, oxidized regions, and pre-existing coatings.

Electrostatic forces do not fully describe the problem. Adsorbed polymer layers may provide steric hindrance, while segments of the same chain may connect different surfaces and promote bridging. Hydration interactions, specific chemical affinities, and, for magnetic minerals, interactions associated with magnetization may also contribute. Attributing every increase in dispersion to a more negative zeta potential therefore oversimplifies systems in which adsorbed molecules alter surface contact. Results for hematite treated with different polymers demonstrate that dispersion and electrokinetic response do not always change proportionally (Alexandrino et al., 2016).

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3.3 Electrical Double Layer, pH, and Water Composition

Oxide and silicate surfaces develop charge through processes including protonation, deprotonation, and adsorption of dissolved species. pH changes the distribution of these species, but its effect should not be treated as a universal relationship between alkalinity and dispersion. In a mixture, the same pH change may increase repulsion between some constituents, bring another mineral closer to its isoelectric point, and induce precipitation of dissolved species. The isoelectric point corresponds to zero zeta potential, whereas the point of zero charge refers to net surface charge; their equivalence requires conditions that are not always satisfied (Delgado et al., 2005).

Ionic strength changes the extent of the diffuse layer and the distance over which electrostatic interactions remain relevant. Multivalent electrolytes may also adsorb specifically, form bridges, or contribute to the precipitation of surface phases. For this reason, two waters with similar conductivity may have different effects on the pulp. Chemical composition, particularly calcium and magnesium, should be recorded alongside pH and conductivity, especially in circuits with extensive water recirculation.

This dependence appears in studies of silicate and iron ores, in which calcium and magnesium species alter dispersion and flocculation response (Krishnan and Iwasaki, 1984). In kaolinite, comparisons of sodium, potassium, calcium, and magnesium electrolytes showed that hexametaphosphate performance depends on the saline environment (Ma, 2012). The reagent therefore cannot be interpreted as having a fixed action: its behavior results from its distribution among solution, surfaces, and possible precipitates.

An apparent contradiction illustrates this issue. In hematitic ore at pH 11, Haselhuhn (2013) observed that the action of inorganic dispersants depended on surface activation by calcium. However, calcium can also promote particle association and interfere with starch, as discussed by Arol and Iwasaki (2003). These results do not establish that this cation is universally beneficial or detrimental.

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They indicate that concentration, chemical form, site occupancy, and treatment sequence determine its role in the system.

3.4 Mineralogy, Shape, and Solids Concentration

Clay minerals have anisotropic surfaces, and their associations may involve edges and faces in different configurations. An open particle network changes the occupied hydrodynamic volume and pulp mobility even when solids mass remains constant. Comparisons of bentonite and kaolinites showed that gangue composition and crystallinity influence viscosity and the flotation response of copper and gold (Zhang and Peng, 2015). Clay content alone does not adequately describe these differences.

The 2026 study of pyrite, quartz, and serpentine adds microstructural evidence: higher serpentine proportions were associated with denser networks, increased flow resistance, and poorer flotation kinetics. The authors did not quantitatively separate coating effects from the rheological contribution, which limits causal interpretation (Wang et al., 2026). Flotation results should therefore be compared with suspension structure and mineral distribution, without attributing every performance loss to a single surface force.

Solids concentration influences encounter frequency, reagent demand, energy propagation, and sampling conditions. An electrokinetic measurement in a dilute suspension may help investigate the interface, but it does not reproduce the contact network in a concentrated pulp. In saline systems containing polymers, chain conformation itself changes with the medium, as discussed for carboxymethyl cellulose adsorbed on illite and dolomite (Pawlik et al., 2003). Transferring results between concentration levels requires preserving the relevant chemistry or explicitly reporting how it changes.

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4. Chemical Dispersion

A dispersant may modify charge, adsorb at specific sites, complex dissolved species, or form a layer that hinders particle contact. These functions can coexist. A commercial designation as a dispersant does not guarantee selectivity between valuable mineral and gangue, nor does it guarantee compatibility with the collector. Reagent selection should address the identified problem: preventing coating, reducing heteroaggregation, controlling rheology, or preparing a selective flocculation stage.

Dosage basis is another consideration. The unit g/t expresses reagent mass per mass of solids, whereas mg/L expresses concentration in a defined volume. Conversion depends on solids concentration and on whether the volume refers to the liquid phase or the suspension. In addition, two feeds with the same mass may have very different surface areas. Comparisons should report active content, preparation method, and solution aging, without treating commercial products of different compositions as equivalent substances.

Table 1 summarizes reagent groups and the main conditions governing their use. The listed functions are possibilities supported by the cited studies, not guaranteed responses for every ore.

Table 1. Dispersant groups and conditions governing their application in mineral suspensions.

Group	Evidence and function	Critical variable	Studies
Silicates	Control of associations and coagulating species.	Formulation, pH, calcium, and compatibility with starch.	Totou et al. (2011); Arol and Iwasaki (2003); Krishnan and Iwasaki (1984)
Polyphosphates	Reduced heteroaggregation and altered rheology.	Ionic composition, dosage, and mineralogy.	Liu et al. (2025); Ye et al. (2018); Leiva et al. (2021); Ma (2012)

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Polycarboxylates	Adsorption and coating control.	Molecular weight, coverage, and collector interaction.	Silva et al. (2025); Zhao et al. (2017)
Citrate and oxalate	Association control, potentially involving complexation and surface alteration.	Consumption by minerals and dissolved species.	Tang and Chen (2020); Liu et al. (2021); Luo et al. (2016); Yin et al. (2017)
Polysaccharide derivatives	Dispersion, depression, or flocculation depending on product and medium.	Molecular structure and adsorption selectivity.	Alexandrino et al. (2016); Pawlik et al. (2003); Alvim and Fernandes Lima (2024); Liu et al. (2024)
Lignosulfonates	Clay dispersion with additional effects on froth.	Formulation composition and water recovery.	Wang et al. (2016)

The studies in Table 1 show that selection must combine mineralogy with the destination of the particles. The same chemical group may reduce coating, depress a surface that should float, or hinder the desired flocculation. The relevant comparison includes the performance of the subsequent operation as well as the dispersion indicator measured during conditioning.

Sodium silicate is used in different mineral systems, but its action depends on pH, product composition, and species present in the water. The silica-to-sodium oxide ratio distinguishes commercial formulations and should be reported. In isolated hematite, different silicates produced no significant change in dispersion at pH 10 in the study by Alexandrino et al. (2016). In itabiritic ore, however, metasilicate and other reagents favored slime removal, although the highest dispersion did not necessarily coincide with the best flotation selectivity (Totou et al., 2011).

In the presence of calcium, interpretation becomes even more specific. Arol and Iwasaki (2003) observed interference from silicate and calcium silicate precipitates in starch adsorption at pH 11. The concentration limits identified in that study apply to the investigated system and should not be converted into universal water specifications. Comparison with Krishnan and Iwasaki (1984) indicates that controlling coagulating species may favor dispersion, but excess reagent may

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compromise a stage requiring selective flocculant adsorption.

Sodium hexametaphosphate and sodium tripolyphosphate are of interest because of their interactions with mineral surfaces and dissolved cations. In mixtures of magnetite and fine quartz, hexametaphosphate reduced heteroaggregation that was detrimental to magnetic separation (Liu et al., 2025). For collophane, Ye et al. (2018) observed better dispersing performance with hexametaphosphate than with silicate or carbonate under the conditions examined. These results support including it in comparative studies, but do not establish a ranking applicable to every mineral feed.

Tripolyphosphate also affects concentrated pulps. In kaolin prepared with seawater at pH 8, Leiva et al. (2021) reported a decrease in yield stress from approximately 231 to 80 Pa. This demonstrates a change in suspension structure, not direct proof of improved recovery. The distinction between rheological response and separation is necessary because a more mobile pulp may improve transport and mixing without necessarily increasing interfacial selectivity.

Sodium carbonate should be considered beyond its role as an alkalizing agent. In the nickel ore studied by Feng et al. (2015), sedimentation, coating removal, and flotation results were interpreted in terms of the interaction between carbonate and lizardite. The study indicates that changes in dissolved species and mineral surfaces can contribute independently of a simple pH increase. Tests at comparable pH using different regulators help prevent incorrect attribution of the mechanism.

Polyacrylates and other polycarboxylates provide functional groups that interact with surfaces and ions in solution. Their performance depends on molecular weight, the density of ionizable groups, and chain conformation. In a pyrite-serpentine system at pH 5, the low-molecular-weight polyacrylate investigated by Zhao et al. (2017) restored pyrite recovery impaired by coating: at 25 mg/L, recovery increased from 32 to 83% in microflotation. This result applies to that specific system and should not be confused with the performance of the subsequent real-ore test.

Citric acid and citrate combine acid-base behavior with the ability to interact with surfaces and metallic species. Luo et al. (2016) reported benefits from small additions in fine hematite flotation, while Yin et al. (2017) investigated chlorite

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dispersion in a reverse hematite flotation system. Joint interpretation suggests that reagent distribution among minerals may be as important as its ability to increase negative charge. Carbonates, iron minerals, and phyllosilicates change reagent demand and the possible reactions within the system.

For sulfides associated with serpentine, studies using oxalic and citric acids also explore coating control and selective separation (Tang and Chen, 2020; Liu et al., 2021). Colloidal dispersion must be distinguished from chemical alteration of the mineral: surface dissolution and complexation may remove sites responsible for attachment. Describing these reagents only as pH regulators would obscure relevant mechanisms. Conversely, a clean surface may remain poorly floatable if the reagent interferes with collector adsorption.

Polysaccharide derivatives introduce an additional difficulty: the same family may produce dispersion, depression, or flocculation, depending on molecular structure, surface coverage, and medium conditions. Carboxymethyl cellulose and dextrins should not automatically be equated with the starch used to flocculate or depress iron oxides. The hematite study by Alexandrino et al. (2016) and the comparison of starch and polyacrylamides in iron slimes by Alvim and Fernandes Lima (2024) reinforce the need to characterize the function actually performed by the product. Natural origin does not, by itself, establish selectivity or environmental advantage.

Biopolymers based on lignosulfonates and alginate broaden the available control strategies. For lignosulfonates applied to copper ore containing kaolinite, froth properties also influence dispersant assessment (Wang et al., 2016). The study of alginate in pentlandite-serpentine systems jointly addresses dispersion and gangue entrainment (Liu et al., 2024). These examples shift the assessment criterion toward froth behavior and water transport, alongside suspension behavior in the conditioner.

The dosage response may show a region of improvement followed by a plateau or deterioration. A plateau may indicate sufficient surface coverage, limited mixing, or persistent resistant aggregates; its interpretation requires additional evidence. High dosages also increase dissolved species and may change ionic

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strength, polymer conformation, and interactions with other reagents. Selecting the highest tested dosage merely because it produces greater turbidity is therefore insufficient.

Conditioning sequence controls which surfaces are available at each stage. Adding dispersant before mechanical treatment may hinder reaggregation of the liberated fragments; adding it afterward may allow the applied energy to remove coatings and expose new sites first. These possibilities are experimental design hypotheses, not a universal sequence demonstrated for all systems. Comparisons should keep initial pH, solids concentration, energy, and the interval between treatments constant, distinguishing sequence effects from total conditioning time.

It is also necessary to recognize that reducing coating does not always require maximizing gangue dispersion. In pyrite-serpentine systems, Liu et al. (2018) used a potassium aluminum salt to increase the apparent size of serpentine and limit its association with pyrite. This example of beneficial aggregation differs from routes seeking to individualize the same gangue. The choice depends on which association is favored and how the aggregated product behaves in the next operation.

5. Physical Dispersion and Combined Treatments

Agitation distributes reagents and solids, renews contacts, and transmits stresses to aggregates. At sufficient intensity, it may remove coatings and fragment particle structures. However, it also increases collision frequency. The observed state results from the balance between association formation and breakup, and this balance changes with size, concentration, surface properties, and equipment geometry. Keeping particles suspended is therefore not equivalent to ensuring that they remain individual.

High-intensity conditioning of nickel ore investigated by Chen et al. (1999) removed slime coatings from mineral surfaces, with effects dependent on agitation intensity and time. For gold fines, Valderrama and Rubio (1998) demonstrated a non-monotonic response to energy: different conditions favored attachment to carriers, detachment, or aggregation among fines. Both cases preclude interpreting

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mechanical energy solely as a variable that continuously increases dispersion. Its usefulness depends on the intended recovery mechanism.

Revolutions per minute do not allow direct comparison of conditioners with different diameters, impellers, and volumes. Scale-up requires characterizing power per unit volume, residence time, solids concentration, and shear distribution. Even at similar specific energy, one device may concentrate dissipation in a small region while another distributes it more uniformly. The number of passages through the intense region and aggregate resistance then become relevant design variables.

Ultrasound transmits pressure oscillations through the liquid. Under suitable conditions, cavitation produces bubble growth, oscillation, and collapse, accompanied by local disturbances capable of displacing particles and removing surface material. The response depends on the acoustic field, gas content, temperature, and liquid properties. Particles may provide nucleation sites, but they also modify energy propagation and dissipation.

During suspension preparation, sonication may reduce agglomerate size without changing the size of the constituent crystals. This distinction must be verified before attributing a decrease in measured particle size to comminution. Studies of nanostructured oxides show that aggregate structure limits the attainable dispersion and that high energy doses introduce heating and probe-wear problems (Retamal Marín et al., 2017). Although these materials do not directly represent ores, the measurement and control limitations are relevant to mineral experiments.

In the goethitic tailings investigated by Silva et al. (2025), treatment at 20 kHz and pH 10.5 was compared with chemical dispersants and combinations of both methods. Sonication favored recovery, but combining it with reagents produced antagonistic behavior in reverse flotation. The study illustrates that coating removal can coexist with undesirable changes in gangue response. Recovery gains should therefore be assessed alongside concentrate composition, without presenting ultrasound as a treatment free of operational trade-offs.

The earlier work using a ternary collector-frother formulation examined sonication as part of the same goethitic slime recovery problem (Marques et al., 2025). These publications provide complementary evidence, but do not necessarily

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constitute independent validations on different materials. Application to reverse flotation of kaolinite from bauxite provides another mineralogical context, in which the effects were associated with dispersion and reduced gibbsite coating (Batista e Silva et al., 2024). The comparison strengthens the plausibility of the cleaning mechanism while preserving differences in surface properties and reagent systems.

Frequency, amplitude, and power are different quantities. The percentage amplitude displayed by a device is a relative setting and does not directly indicate how many watts reach the pulp. Nominal power, electrical consumption, and power actually dissipated in the medium must also be distinguished. The standardization recommendations of Taurozzi et al. (2011) emphasize that failing to make this distinction hinders the reproducibility of ultrasonically prepared suspensions.

For comparison, specific electrical energy can be calculated by integrating consumed power over time and dividing by the dry mass treated. A volumetric basis may also help characterize the reactor, provided solids concentration is reported. For mechanistic investigation, calorimetric power estimates thermal dissipation under controlled conditions; it does not replace electrical consumption when the question is economic. Results using different denominators, such as pulp mass and solids mass, should not be compared directly.

Temperature control is essential because sonication may simultaneously alter hydrodynamics and physicochemical conditions. Comparisons should record the temperature history and, where necessary, include a control without ultrasound subjected to a similar thermal history. Probe diameter and immersion depth, working volume, vessel position, pulsed or continuous mode, and sonotrode condition should also be documented. Table 2 summarizes the main characteristics of the physical methods discussed.

Table 2. Physical methods and criteria for comparing dispersion results.

Method	**Relevant action**	**Minimum parameters**	**Main limitation**
Mechanical agitation	Mixing and breakup of weak associations.	Geometry, rotational speed, time, solids, and power.	Suspension does not prove particle individualization.

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High intensity	Cleaning and reorganization of contacts (Chen et al., 1999; Valderrama and Rubio, 1998).	Specific energy, residence time, and shear history.	May favor aggregation or destroy useful structures.
Ultrasound	Local disturbances, deaggregation, and cleaning (Silva et al., 2025; Batista e Silva et al., 2024).	Frequency, probe, volume, temperature, and measured energy.	Non-uniform field and medium-dependent response.
Physical and chemical	Potentially complementary breakup and stabilization.	Sequence, pH, and controls using individual methods.	Synergy cannot be assumed (Silva et al., 2025).

Table 2 shows that comparability depends on how energy is transmitted. A short, intense treatment is not automatically equivalent to a longer, moderate treatment, even when total energy is similar. Breakup occurs in specific regions and competes with new collisions, adsorption, and reaggregation. Energy and time should therefore be treated as related but non-interchangeable variables.

5.1 Combining Physical and Chemical Action

Combined treatments seek to break existing associations and stabilize the exposed surfaces. This complementarity is physically plausible, but it must be demonstrated by comparison with the individual treatments. Improvement relative to an untreated control does not prove synergy: it may result solely from the method that was already more effective. A suitable assessment compares the control, chemical treatment, physical treatment, and their combination using equivalent preparation conditions and measuring the final separation outcome.

Ultrasound may change reagent distribution, and shear may alter the structure of aggregates that should be preserved. If a polymer acts as a selective flocculant, a subsequent physical treatment of excessive intensity may destroy useful structures. If it acts as a dispersant, its adsorption may compete with that of a collector or depressant. Figure 1 represents these possibilities and guides

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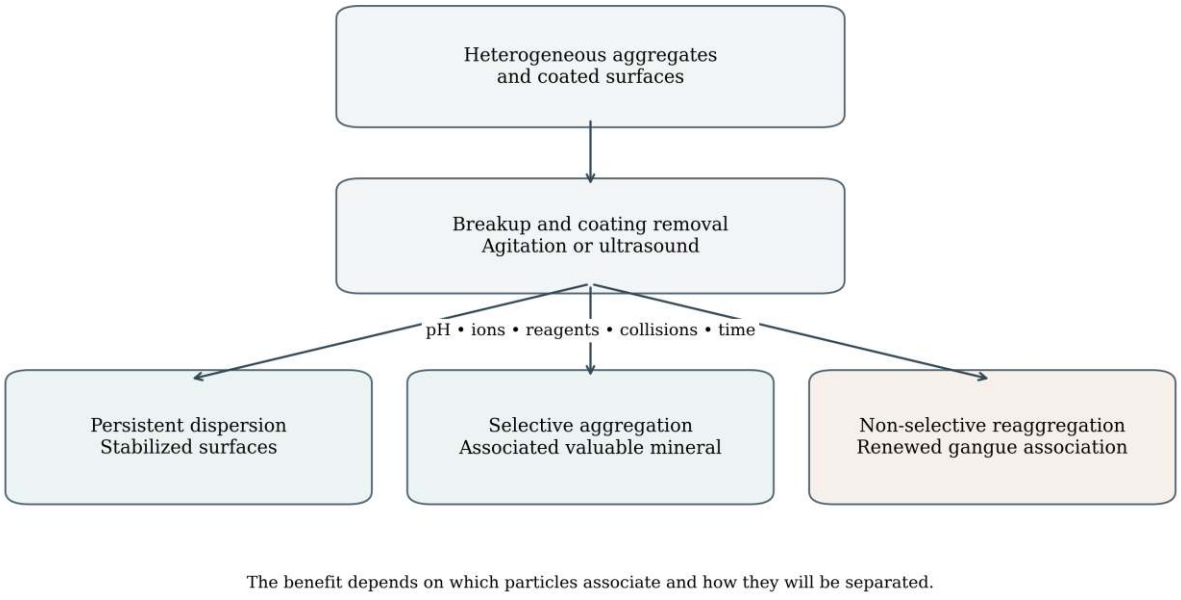
interpretation without assuming that a combined treatment is necessarily beneficial.

Figure 1. Possible outcomes after aggregate breakup. Medium chemistry and collisions determine whether surfaces remain separate or associate again.



6. Methods for Assessing Dispersion

Sedimentation tests are accessible and allow comparison of the same sample under different treatments. However, settling velocity depends on size, density, shape, concentration, and aggregate structure as well as aggregation. A more turbid supernatant may indicate a greater quantity of suspended fines, but it does not directly show whether these fines are gangue or valuable mineral. It may also reflect particle breakage or differences in the optical response of the minerals.

Degree of dispersion is an operational definition, and its expression should accompany the protocol used. Some studies relate suspended mass to initial mass; others withdraw an aliquot at a defined height and time. In the magnetic separation study by Su et al. (2016), assessment used the mass remaining unsettled after a specified interval. Studies with hematite used sedimentation tubes and their own

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sampling conditions (Alexandrino et al., 2016). Absolute values should not be placed on a single performance scale when procedures differ.

To make the test interpretable, vessel geometry, volume, solids mass, conditioning time and intensity, settling time, sampling height, and aliquot treatment should be reported. In mixed ores, chemical or mineralogical analysis of the supernatant and sediment provides information on selectivity. An increase in suspended mass enriched in silica has a different implication from an increase dominated by hematite. Combining mass distribution and composition turns a bulk indicator into a separation diagnostic.

Zeta potential is inferred from electrokinetic phenomena and refers to the potential associated with the slipping plane, not a direct measurement of surface charge. Its interpretation depends on the model, liquid properties, and interfacial structure (Delgado et al., 2005). In polymer-coated particles, changes in the effective location of this plane and in the adsorbed layer can complicate simple relationships between measured potential and intersurface forces.

There is no single zeta potential value that guarantees stability for every mineral pulp. Magnitude-based criteria used for simple suspensions should be treated cautiously in concentrated, saline, and multicomponent media. Moreover, the dilution needed for measurement may change pH, ion concentrations, and adsorption equilibria. Where possible, the dilution medium should preserve the composition of the liquid phase, and conditions should be recorded so that treatment effects are not confused with sample preparation effects.

Interpretation becomes stronger when electrokinetic measurements are combined with adsorption, solution analysis, and spectroscopy. However, reagent depletion from the liquid phase does not alone prove adsorption: precipitation, decomposition, or retention in another phase may also decrease its concentration. Infrared and photoelectron spectra help identify interactions, but band and energy shifts should be assessed using suitable controls and resolution. Surface evidence should be consistent with suspension behavior and separation results.

Particle size measurements after treatment may reveal smaller aggregates, but the analytical procedure itself may change the object being measured. Agitation

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and ultrasound incorporated into the analyzer can erase differences between previously conditioned samples. Investigating aggregation therefore requires distinguishing the distribution in the process state from that obtained after deliberately dispersive preparation. The first describes the transported units; the second approaches a reference distribution for constituent particles, within the limitations of the method.

Laser diffraction provides equivalent diameters that depend on the optical model, whereas dynamic light scattering measurements are strongly weighted toward larger particles and face difficulties in broadly polydisperse mixtures. Chord length measurements can track structural changes in more concentrated pulps, as in the study of tripolyphosphate and kaolin (Leiva et al., 2021), but should not be presented as directly equivalent diameter distributions. Comparisons must preserve the identity of the quantity measured.

Optical and electron microscopy can identify coatings and associations between minerals. However, drying and preparation may create contacts that were absent in suspension or destroy fragile aggregates. Images of dry powder are therefore insufficient to fully characterize pulp structure. Observation of networks by cryogenic scanning electron microscopy in serpentine-containing suspensions offers a way to reduce some of these artifacts (Wang et al., 2026), although the technique still requires careful interpretation and does not replace quantitative assessment of metallurgical performance.

Rheology provides a collective measure of resistance to movement and suspension structure. Stress-shear rate curves, yield stress, and response to deformation history help identify particle networks. Apparent viscosity should be associated with shear rate because a single value without this reference prevents meaningful comparison. Bingham and Herschel-Bulkley models are useful descriptions, but their parameters depend on the fitting range and experimental protocol.

In iron ore concentrate, Vieira and Peres (2013) related dispersion, rheological behavior, and regrinding. Investigations of additives in concentrated iron ore slurries also demonstrate the relevance of including rheology in conditioning

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assessment. Nevertheless, a lower yield stress does not independently demonstrate greater selectivity. The indicator must be compared with stream composition and the transport mechanism of the operation under assessment.

The most informative strategy combines measurements at three levels. The first characterizes the interface and medium, including pH, water chemistry, and electrokinetic properties. The second describes the suspension through sedimentation, particle size analysis, microscopy, and rheology. The third verifies separation through mass and valuable-element balances, product quality, and, in flotation, water recovery. Convergence among these levels strengthens interpretation; disagreement signals additional mechanisms that require investigation.

7. Applications in Mineral Processing Operations

In hydraulic classification, aggregates may behave differently from the particles that compose them. Dispersion can redistribute fines associated with larger particles among streams, changing apparent partitioning. However, classification does not depend only on size: density, shape, viscosity, and equipment conditions also contribute. Tests with silica-magnetite mixtures in a 75 mm hydrocyclone demonstrate the importance of considering the multicomponent nature of the feed (Padhi et al., 2019).

The study by Gonçalves et al. (2022) assessed fine suspensions at different concentrations and viscosities in an optimized hydrocyclone. It does not directly demonstrate the benefit of a dispersant, but supports considering rheology when interpreting classification. The engineering inference is that a treatment changing pulp structure and viscosity may alter partitioning without changing primary particle size. This hypothesis should be tested using efficiency curves and balances by size and mineral component.

In iron ore desliming, dispersion may favor the removal of fine gangue and reduce coatings detrimental to flotation. However, it may also release ultrafine iron-bearing particles into the discarded stream. Totou et al. (2011) showed that

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dispersant assessment should consider subsequent flotation, particularly the preservation of quartz floatability. Decisions to remove a fraction should include its mass, composition, and recovery potential, avoiding supernatant clarity or the quantity of removed slimes as the sole criterion of success.

There is also an interaction with grinding. Changes in pH and pulp structure affect flow and contact between particles and grinding media, as investigated by Vieira and Peres (2013). However, an additive that facilitates regrinding may remain in the circuit and influence collection, depression, or flocculation. The addition point should be selected with the reagent's path through the circuit in mind. Optimizing one operation in isolation may transfer consumption, losses, or difficulties to another stage.

In flotation, dispersion can expose surfaces previously covered by slimes, favoring collector adsorption and bubble contact. This mechanism appears in sulfide-serpentine systems and in oxide materials containing fine gangue (Feng et al., 2018; Luo et al., 2016). The response nevertheless depends on which particles are recovered in the froth. Direct flotation seeks to recover the valuable mineral; in reverse iron ore flotation, gangue should float while iron remains in the non-floated product. The same surface change can therefore have opposite consequences in different routes.

Coating removal does not eliminate the hydrodynamic limitations of ultrafines. Individual particles may have a low probability of effective encounters with bubbles, whereas selective aggregates or carriers can improve recovery (Trahar, 1981; Valderrama and Rubio, 1998). Surface cleaning and the effective size of the floatable unit should therefore be assessed separately. A system may require initial dispersion to eliminate gangue associations followed by aggregation to recover the valuable mineral.

Hydraulic entrainment is another limitation. Hydrophilic fines may follow water into the froth regardless of selective collector adsorption. The study of kaolinite in copper and gold flotation related clay aggregation, transport into the froth, and decreased grades (Zhang et al., 2015). An increase in mass recovery after treatment does not therefore prove increased true flotation. Water recovery and

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component distributions must be measured to distinguish improved capture from increased non-selective transport.

In seawater, dispersing reagents must operate under strong influences from ions and hydrolyzed species. Studies of chalcopyrite-kaolinite (Ramirez et al., 2018), molybdenite-kaolinite (Ramirez et al., 2020), and sulfides associated with micas (Yepsen et al., 2021) show that gangue mineralogy and water chemistry govern the observed effect. A reagent scheme established in deionized water should not be transferred directly to saline water. A dosage that improves suspension behavior may also alter collector adsorption and froth properties.

Results for bauxite (Batista e Silva et al., 2024) and collophane-quartz (Ye et al., 2018) broaden the scope beyond iron ores and sulfides. The comparison indicates that coating and heteroaggregation mechanisms occur in different systems, but the species to be dispersed depends on the desired product. In partially soluble minerals, release of species into solution introduces another variable. The study of apatite, hematite, and phlogopite in different media demonstrates that the supernatant from one mineral can change the behavior of another (Wang and Heiskanen, 1992).

In magnetic separation, associations between magnetic particles and gangue can compromise concentrate purity. A dispersant can reduce heterogeneous contacts and facilitate removal of the non-magnetic fraction during transport and washing. The study of magnetite and fine quartz treated with hexametaphosphate provides direct evidence for this strategy (Liu et al., 2025). However, chemistry alone does not resolve the problem: field intensity and gradient, matrix configuration, pulp velocity, and washing conditions govern capture.

For very small particles, individualization may reduce the capture of weakly magnetic minerals or units whose field response is already limited. An alternative is to disperse the mixture initially and promote selective aggregation of the valuable mineral. Su et al. (2016) obtained 62.82% Fe and a total recovery of 79.12% using a route combining dispersion, flocculation, and magnetic separation, compared with 61.54% Fe and 74.04% recovery in the reference condition. These figures represent the performance of the combined route, not an isolated hexametaphosphate effect.

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In Brazil, Lima and Abreu (2020) studied dam slimes from the Quadrilátero Ferrífero and reported 48.4% mass recovery under a condition combining silicate, starch, and magnetic separation. This value should not be compared directly with total iron recovery in the magnetite study because the indicators and feeds differ. The comparison of starch and polyacrylamides in another iron-bearing tailings material (Alvim and Fernandes Lima, 2024) reinforces the need to consider flocculant affinity for the phases present and aggregate resistance to transport.

Differences between magnetite and minerals such as hematite and goethite also prevent automatic transfer of field and aggregation conditions. In addition to magnetic response, morphology, surface composition, porosity, and gangue associations differ. Assessing only total iron grade may obscure the contribution of each phase. A more informative analysis tracks product mineralogy, recovery by particle size, and the behavior of particles remaining in the tailings.

Industrial tests of magnetic separation of tailings presented by da Rocha et al. (2021) produced a concentrate containing 63% Fe at approximately 15% mass recovery in three stages. This demonstrates application of the concentration technology, but does not prove an industrial benefit from dispersive pretreatment. The distinction is necessary to avoid confusing the maturity of magnetic separation with validation of any associated dispersion scheme.

Table 3 presents representative applications, their conditions, and the limits of interpretation. Values retain the basis reported in each study and do not constitute a ranking of method effectiveness. The studies encompass different experimental contexts, including microflotation, mineral processing tests, and industrial magnetic separation. These differences must be considered when assessing the applicability of the reported findings.

Table 3. Selected applications and limits to result interpretation.

System and study	Treatment or condition	Reported response	Interpretation
Itabirite (Totou et al., 2011)	Dispersion before desliming and flotation.	Benefit depends on the reagent.	Preserve quartz floatability.

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Pyrite-serpentine (Zhao et al., 2017)	Polyacrylate; 25 mg/L; pH 5.	Pyrite recovery increased from 32 to 83%.	Microflotation; not Fe recovery from tailings.
Magnetite (Su et al., 2016)	Hexametaphosphate and carboxymethyl starch; pH 11.	62.82% Fe; 79.12% total Fe recovery.	Effect of a multistage route including flocculation.
Iron-bearing slimes (Lima and Abreu, 2020)	Silicate and starch; pH 10.5; 3575 G.	48.4% mass recovery.	Different indicator from metallurgical recovery.
Goethitic tailings (Silva et al., 2025)	Ultrasound at 20 kHz and dispersants.	Combination produced antagonism in flotation.	Assess quality and recovery jointly.
Dam tailings (da Rocha et al., 2021)	Magnetic separation in three industrial stages.	63% Fe; approximately 15% mass recovery.	Does not isolate a dispersant effect.

The comparison in Table 3 shows that solids concentration, mineralogy, and route objectives vary substantially. A sedimentation result does not have the same meaning as metallurgical recovery, and an increase in grade may be accompanied by loss of mass or valuable element. Conditions should therefore be assessed through complete balances and grade-recovery trade-off curves instead of a single indicator selected after testing.

For tailings recovery, the reference condition must also be explicit. Comparing a treated route against a different feed or a different number of stages can overestimate the conditioning effect. Wherever possible, feed mass, size distribution, grade, water conditions, and separation parameters should be preserved. When the proposal modifies the entire circuit, the result should be attributed to the route, explicitly stating that the effect of each individual stage was not isolated.

8. Challenges, Limitations, and Perspectives

Dispersion should persist for the time required by the operation, not

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necessarily indefinitely. Between the conditioner and separator, changes in pH, dilution, mixing with return streams, and contact with other reagents may alter the state of association. Aging tests are therefore relevant. Work on kaolin, hexametaphosphate, temperature, and calcium shows that rheological response should be interpreted with its time dependence in mind (Andreola et al., 2006).

A circuit with recirculated water introduces chemical memory: dispersants, flocculants, collectors, and dissolved species may return in varying proportions. Behavior in fresh water does not necessarily predict behavior in an established operation. Assessment should include representative waters and, where feasible, recirculation tests that track ionic composition and residual reagents. This approach is particularly important when dispersant consumption has been defined using a single water sample or a short test.

The consequences for thickening are not necessarily negative or uniform. In synthetic tailings prepared with seawater, Yepsen et al. (2022) observed that residual hexametaphosphate modified the aggregates formed with polyacrylamide: smaller, denser structures could settle faster while small particles increased turbidity. This result demonstrates a trade-off between settling velocity and clarified-water quality. Assessing only interface velocity could incorrectly suggest that water return had been equally improved.

Economic assessment should consider the entire circuit. Pretreatment consumes energy and may require reagents, but it can also change the number of stages, concentrate quality, and the amount of water needed. Potential benefits must be measured: higher recovery should not be assumed to compensate for any additional consumption. For tailings, pumping, homogenization, classification, and dewatering must also be included because they may account for substantial portions of the operation.

For ultrasound, increasing volume while maintaining the device amplitude does not automatically preserve the acoustic field. Energy distribution, attenuation by the pulp, residence time, and particle access to active regions must be demonstrated under continuous flow. Studies of suspension preparation highlight sonotrode wear and dispersion limits (Retamal Marín et al., 2017), while

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recommendations for energy standardization (Taurozzi et al., 2011) provide a methodological basis. These contributions do not replace pilot tests using representative ore and water.

Dispersant cost also depends on feed variability. A fixed dosage per tonne may be insufficient as the proportion of clay or surface area increases, and excessive as the material becomes coarser. Control based on measurable pulp properties may be more robust, but requires validated relationships between signal and performance. Turbidity, conductivity, or viscosity alone do not automatically identify aggregate composition: their use for control should be calibrated to the feed and circuit.

Mechanistic effects must be separated from protocol effects. Chemical tests should distinguish changes in pH, ionic composition, and specific adsorption. Physical tests should report energy, temperature, and geometry. Combined experiments should include individual treatments and preserve comparable conditions. These requirements do not imply that every study must be complex; they prevent a simple result from being interpreted more broadly than the data allow.

Another priority is to track selectivity over time. Measuring dispersion immediately after treatment and separation after a waiting period does not represent the same condition. Sampling, transport, and feeding intervals should be recorded, especially where reaggregation is rapid. For heterogeneous materials, replicates should begin with representative, independent aliquots; repeating instrumental measurements of the same suspension does not replace repeating conditioning and separation.

Studies reporting no improvement or antagonistic combinations are also needed. The goethitic tailings case combining ultrasound and dispersants (Silva et al., 2025) demonstrates the value of reporting recovery and quality simultaneously. Literature on polymers and froth (Wang et al., 2016) indicates that effects beyond the solid-liquid interface may determine the response. These results help avoid selecting explanatory mechanisms merely because they match the expected treatment outcome.

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The most promising opportunities involve connecting pulp structure with performance under representative conditions. One direction is to quantify aggregate and coating composition by combining microscopy, chemical analysis of fractions, and interaction models. Another is to investigate dispersion and selective aggregation as complementary stages, preserving valuable ultrafine recovery while limiting gangue transport. Mineralogy should guide this choice, particularly where goethite, clays, and partially soluble minerals are present.

For physical treatments, the priority is to develop relationships between energy transmitted, treated volume, and a persistent separation effect. For reagents, formulations should be evaluated in recirculated water, recognizing that products within the same family may differ in their effects on froth and dewatering. The renewable origin of a polymer or the absence of chemical addition in one stage does not remove the need to assess consumption, residues, and circuit impact. Environmental advantage should be supported by route indicators, not solely by the treatment description.

9. Conclusions

Mineral dispersion should be defined in relation to the association being controlled and the operation receiving the pulp. Aggregate breakup, coating removal, and prevention of reaggregation are related but distinct phenomena. The objective is not necessarily to individualize every particle: keeping gangue dispersed while forming selective aggregates of the valuable mineral may be more favorable for ultrafine recovery.

Chemical dispersants respond to mineralogy, pH, water composition, molecular structure, and conditioning sequence. Silicates, polyphosphates, polycarboxylates, and polysaccharide derivatives cannot be assigned a universal effectiveness ranking. Their selection should consider interactions with collectors, depressants, and flocculants, as well as effects on froth and dewatering stages.

Intense agitation and ultrasound may remove coatings and modify particle associations, but increasing energy does not necessarily produce a monotonic

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response. Combined treatments must demonstrate benefits relative to the individual methods; coexistence of physical and chemical effects may result in complementarity or antagonism. Nominal power and amplitude do not replace determination of consumed energy and effective treatment conditions.

Assessment requires combining interfacial, structural, and metallurgical indicators. Zeta potential, turbidity, or particle size alone do not demonstrate selectivity. Sedimentation protocols should be explicit, analytical preparation should not erase the suspension state, and mass recovery must be distinguished from metallurgical recovery. Product chemistry and mineralogy are needed to identify which particles remained dispersed or were aggregated.

For iron ores and tailings, the evidence favors integrating dispersion with desliming, flotation, and magnetic separation while preserving the balance between grade and recovery. Industrial implementation of new treatments remains dependent on continuous-flow validation, control of mineralogical variability, and assessment of the water circuit. Studies using measured energy, comparable conditions, and monitoring of downstream stages offer the most direct path from laboratory results to process decisions. By connecting interfacial mechanisms, suspension behavior, and metallurgical performance, this review provides an integrated perspective for evaluating dispersion strategies in mineral processing.

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