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Hydrodynamic Cavitation in Circular Hydrometallurgical Flowsheets: Function-Specific Evidence and Process Integration for Secondary-Resource Recovery

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Abstract

Metal-bearing tailings, slimes, metallurgical residues, spent catalysts, ashes, sludges, batteries, and electronic wastes are increasingly important secondary resources, but recovery is constrained by low and variable grades, fine particles, complex phase associations, passivation, and impurity-sensitive downstream processing. Hydrodynamic cavitation (HC) can modify selected flowsheet functions through interfacial renewal, localized mechanical action, gas–liquid transfer, fine-bubble generation, particle conditioning, and phase dispersion. The evidence was critically appraised across three independent dimensions: system relevance, causal attribution, and endpoint completeness. Application-level evidence is most developed for transport intensification in selected scheelite, uranium-bearing, and refractory-gold systems; particle conditioning and washing; spent-catalyst coating liberation; metal-bearing sludge treatment; copper cementation; and preparation of liquid emulsion membranes. Representative secondary-feed studies report conditioning, preconcentration, mobilization, and downstream separation responses, but complete feed-to-product recovery with controlled liquid and solid loops remains uncommon. Evidence is especially limited for battery black mass, electronic wastes, rare-earth-bearing residues, complex slags, metallurgical dusts, and multi-metal streams. HC is therefore most credible as a targeted module applied to a verified process limitation. A flowsheet advantage is established only when local gains persist through product recovery without offsetting increases in chemical use, water demand, energy consumption, equipment wear, or residual-stream burden.

Keywords: hydrodynamic cavitation; circular hydrometallurgy; secondary resources; process integration; process intensification; metal recovery; preconcentration; leaching; scale-up

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Academic Editor: Yuanbo Zhang

Received: 30 July 2026
Revised: 22 August 2026
Accepted: 1 September 2026
Published: 3 September 2026

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1. Introduction

The transition toward low-carbon energy systems, electrified transport, digital infrastructure, and resource-efficient manufacturing is increasing demand for critical and strategic metals while exposing the limitations of continued dependence on primary resources. Mine tailings, concentrator slimes, metallurgical residues, spent catalysts, industrial ashes and sludges, end-of-life batteries, electronic wastes, and other processed materials retain metals that were unrecovered or uneconomic under previous operating conditions. Their use as secondary resources can supplement supply, reduce long-term liabilities, and preserve material value, but low and variable grades, fine particles, complex phase associations, passivation, aging, moisture, impurities, and hazardous constituents complicate recovery [1–4].

Rare-earth-bearing residues, battery materials, zinc-rich wastes, and mine wastes illustrate both the scale of the opportunity and the diversity of the associated mineralogical and chemical barriers [5–7].

Hydrometallurgical routes can combine selective dissolution, solution purification, and product recovery at lower bulk temperatures than many pyrometallurgical alternatives. Aqueous processing, however, is not inherently circular. High extraction may coexist with excessive acid or alkali demand, nonselective dissolution, extensive washing, difficult impurity removal, unstable residues, or secondary effluents. Circular performance therefore depends on the complete material pathway, including conditioning, dissolution, separation, reagent and water management, product quality, and residue fate [8–10]. Transfer of a target element from a solid into solution remains an intermediate result unless it is subsequently concentrated into a usable product and the associated liquid and solid streams are controlled.

Secondary-resource recovery is often limited by insufficient phase accessibility, interfacial transport, gas transfer, or solids dispersion. Conventional responses such as finer grinding, stronger lixiviants, higher temperature, longer residence time, greater oxidant dosage, or more intensive agitation can improve conversion but may also increase energy demand, equipment wear, neutralization requirements, impurity transfer, filtration difficulty, and residual waste generation. Process intensification is therefore useful only when it addresses a verified limitation without creating a comparable or greater burden elsewhere in the flowsheet.

These limitations define the principal interface between hydrometallurgy and HC. HC can be introduced at selected hydrometallurgical unit operations to intensify transport, gas–liquid contact, solids dispersion, or surface accessibility where one of these functions constrains process performance.

Hydrodynamic cavitation (HC) arises from pressure reduction and recovery in a flowing liquid or slurry. Transient cavity formation and collapse, turbulence, shear, localized impact, interfacial renewal, gas–liquid transfer, and residual micro- or nanobubble populations can modify wetting, dispersion, surface accessibility, mass transfer, and phase contact. Venturi and orifice devices, cavitating jets, washing ejectors, multiphase pumps, and high-shear hydrodynamic systems impose different pressure histories, particle stresses, gas–liquid interfacial areas, and exposure patterns. Depending on device configuration and flowsheet position, HC may support feed conditioning, leach recirculation, gas–liquid contacting, coating detachment, fine-particle recovery, cementation, emulsion preparation, or residue washing.

The observed response cannot be attributed to cavitation from the device designation alone. Pumping, recirculation, mixing, heating, gas injection, particle attrition, acoustic excitation, electrochemistry, and chemical additives may act concurrently with pressure-driven cavity dynamics. Faster extraction may also be offset by poorer selectivity, greater energy demand, more difficult purification, or unstable residual streams. The relevant criterion is therefore whether a defined hydrodynamic function improves the resource-to-product sequence rather than whether a local extraction or removal response increases.

Recent syntheses have clarified cavitation-induced reactive microenvironments in metal leaching and the role of micro- and nanobubbles in mineral processing and hydrometallurgy [11,12]. Evidence directly connecting pressure-driven HC to complete recovery from representative secondary resources nevertheless remains fragmented across conditioning, dissolution, separation, product formation, solution recycle, and residue management. Primary ores and model particles can isolate transferable mechanisms, but they do not establish performance on heterogeneous secondary feeds. Physical separation contributes to circular hydrometallurgy only when it concentrates value, reduces the mass or impurity

burden entering subsequent treatment, improves access to a target phase, or produces a reusable fraction.

Within circular hydrometallurgical flowsheets, HC is more appropriately treated as a function-specific process module than as a universally superior reactor class. Its relevance depends on whether a measured process limitation is modified, whether the response can be distinguished from concurrent hydraulic, thermal, acoustic, or chemical effects, and whether the resulting gain persists through purification, product recovery, solution recirculation, and residue management.

The analytical architecture shown in Figure 1 connects metal-bearing secondary resources, HC-enabled process functions, and circular endpoints while retaining whole-route performance as the governing criterion.

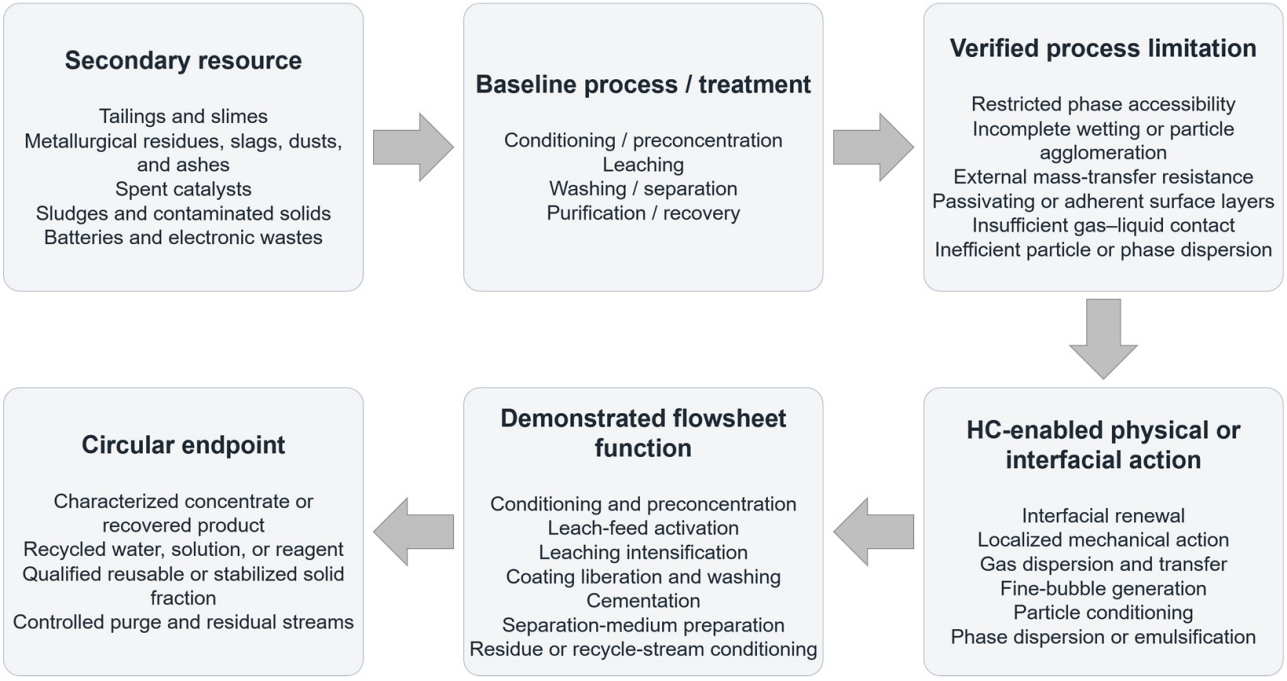


Figure 1. Scope and analytical architecture of hydrodynamic cavitation in circular hydrometallurgy.

The framework separates the physical or interfacial action of HC from the endpoint used to judge process and circular performance. Improvements in wetting, surface renewal, gas transfer, dispersion, or dissolution support only the function demonstrated experimentally. Stronger claims require progression to target recovery in a characterized product together with appropriate management of recirculating solutions, residual solids, and other material outputs.

2. Scope, Literature Basis, and Evidence Appraisal

Evidence contributing directly to HC claims is retained only when a pressure-driven hydrodynamic treatment is linked to a defined function within a metal recovery or resource valorization sequence. Resource origin, cavitation mode, process function, comparator, and downstream endpoint define the admissible claim and distinguish circular hydrometallurgy from adjacent applications involving pollutant degradation, disinfection, generic flotation, or wastewater polishing.

2.1. Definitions, Scope Boundaries, and Literature Selection

Circular hydrometallurgy denotes aqueous or predominantly aqueous processing directed toward the recovery of metals or metal-bearing products from secondary resources

while limiting material losses, chemical and water demand, and residual waste generation. Relevant feeds include tailings, slimes, slags, metallurgical dusts and residues, spent catalysts, ashes, contaminated solids, sewage and industrial sludges, batteries, electronic wastes, and process solutions derived from these materials. Hydrodynamic cavitation is restricted to pressure-driven cavity formation in a flowing liquid or slurry, including Venturi and orifice devices, cavitating jets, ejectors, multiphase pumps, and high-shear hydrodynamic systems. Acoustic irradiation is treated separately, even when analogous bubble growth and collapse occur.

Eligible functions include leaching, coating detachment, surface renewal, liberation, washing, preconcentration, gas–liquid intensification, cementation, membrane or emulsion preparation, solution recirculation, and residue conditioning. Physical separation is included only when it contributes to a secondary-resource flowsheet or provides a mechanism directly transferable to one. Studies limited to pollutant destruction, disinfection, or dissolved-metal removal without a defined conditioning, concentration, or recovery endpoint are excluded from the core evidence. Primary ores and pure minerals are retained only as mechanistic or process benchmarks for tailings, residues, or recycled materials.

Relevant literature was identified through targeted searches of Scopus and Web of Science, supplemented by Google Scholar, using the core Boolean structure ("hydrodynamic cavitation" OR "hydrodynamic cavitation reactor") AND (leaching OR separation OR "secondary resources" OR "metal recovery"). Reference lists and citing articles were examined to identify additional studies. Preprints, theses, conference abstracts, and other non-journal sources were excluded. The literature search was updated through August 2026.

Heterogeneity in device geometry, pressure drop, recirculation history, solids loading, particle size, lixiviant chemistry, temperature, treatment exposure, energy reporting, and analytical endpoints precludes defensible statistical pooling or a universal ranking of device performance. Evidence is therefore synthesized critically and narratively, with quantitative outcomes interpreted within the feed, chemistry, exposure, and control conditions reported. Closely related publications from the same experimental program are treated as cumulative rather than independent evidence, while missing process information limits the supported inference.

2.2. Evidence Appraisal and Claim Boundaries

Each study is appraised independently across system relevance, causal attribution, and endpoint completeness. System relevance distinguishes simplified or model systems, primary-mineral and process benchmarks, representative secondary resources, and integrated secondary-resource flowsheets. Causal attribution considers whether pressure-driven HC is evaluated against matched noncavitating hydraulic controls and whether additional acoustic, electrochemical, oxidative, thermal, or chemical contributions are experimentally separable or unresolved. Endpoint completeness differentiates mechanistic responses, enabling process functions, unit-operation performance, characterized product recovery, and integrated recovery extending to solution and residue management.

Conventional hydrometallurgical routes are retained only as comparators and do not constitute HC evidence. Likewise, resource–function combinations lacking direct pressure-driven validation are recorded as evidence gaps rather than inferred from acoustic cavitation, simplified feeds, or adjacent separation processes. The appraisal dimensions summarized in Table 1 define the maximum inference supported by each study without collapsing distinct evidentiary attributes into a single class or score.

Table 1. Multidimensional framework for appraising evidence on hydrodynamic cavitation in circular hydrometallurgical flowsheets.

Appraisal Dimension	Category Within Dimension	Minimum Evidence Required	Maximum Supported Inference
System relevance	Simplified or model system	Pure compounds, model particles, synthetic solutions, or other matrices of defined composition used to isolate a physicochemical response under controlled conditions.	Mechanistic plausibility under simplified conditions; no direct inference for heterogeneous secondary resources.
	Primary-mineral or process benchmark	Primary ore, pure mineral, conventional process stream, or another non-secondary system reproducing a limitation relevant to hydrometallurgical processing.	Transferable mechanistic or unit-operation insight; applicability to secondary resources requires direct validation.
	Representative secondary resource	Characterized tailings, slimes, residue, slag, ash, sludge, spent catalyst, battery-derived material, electronic waste, or other secondary feed retaining its relevant heterogeneity, phase associations, and impurity burden.	Performance of the demonstrated function for the tested secondary resource, feed characteristics, and operating conditions.
	Integrated secondary-resource process sequence	A representative secondary feed evaluated across two or more physically connected unit operations under a defined process configuration.	Applicability of the demonstrated response within the tested process sequence; causal strength, product recovery, and loop closure remain independently assessed.
Causal attribution	HC nominally present; contribution unresolved	A device or treatment is identified as hydrodynamically cavitating, but no suitable control distinguishes HC-associated effects from pumping, mixing, heating, gas injection, recirculation, particle attrition, acoustic excitation, electrochemistry, or chemical additives.	Association between the complete treatment configuration and the measured response; no isolated attribution to HC.
	Comparative treatment with unmatched process duty	Comparison with untreated material, conventional stirring, pumping, mixing, or another reference treatment, but hydraulic power, pressure history, temperature, gas supply, residence time, recirculation, or chemical exposure is not adequately matched.	Incremental benefit of the intensified treatment configuration; the specific contribution of HC remains partly confounded.
	Matched noncavitating hydraulic control	Cavitating and noncavitating operation compared at matched or appropriately normalized flow, hydraulic power, mixing duty, temperature, gas supply, chemistry, solids loading, and treatment history.	Attribution of the observed process response to pressure-driven cavitating operation under the tested conditions, without necessarily resolving the active HC-mediated mechanism.
	Mechanism-resolved attribution	Matched hydraulic controls combined with direct diagnostics or independently varied conditions sufficient to distinguish the specified HC-mediated response from bulk mixing, pumping, heating, externally imposed gas transfer, acoustic excitation, electrochemistry, and chemical-additive effects.	Strong attribution of the demonstrated process response to a specified HC-mediated physical or interfacial mechanism under the tested conditions.
Endpoint completeness	Mechanistic or local physicochemical response	Direct measurement of cavity-related, pressure, bubble, particle, surface, wetting, dispersion, mass-transfer, or other local physicochemical behavior.	Existence of a local response associated with the tested HC treatment; no automatic inference for unit-operation performance.
	Enabling process function	Demonstrated wetting, deagglomeration, surface renewal, coating detachment, gas transfer, particle conditioning, phase dispersion, or another defined function relevant to a recovery sequence.	Support for the specific enabling function measured; no inference for recovery, selectivity, product quality, or circular performance.

Table 1. *Cont.*

Appraisal Dimension	Category Within Dimension	Minimum Evidence Required	Maximum Supported Inference
Endpoint completeness	Unit-operation performance	Quantified conditioning, preconcentration, leaching, washing, cementation, emulsification, or separation performance assessed against an appropriate comparator.	Performance claim for the tested unit operation; downstream product recovery and management of associated streams remain unresolved.
	Characterized product or reusable fraction	The target is followed into a concentrate, cemented solid, separated internal phase, purified solution, regenerated material, or reusable solid fraction, with yield and relevant compositional or functional quality characterized.	Recovery or valorization claim for the defined product or fraction under the tested feed and process conditions.
	Integrated recovery with liquid- and solid-stream management	Feed-to-product accounting; tracking of target and major impurities; characterization of product and residual solids; defined solution recycle or purge; chemical, water, and energy inventories; and appropriate mass-balance closure.	Integrated circular-flowsheet claim limited to the tested feed, product specification, operating duration, process boundary, and demonstrated management of liquid and solid outputs.

Note: The three appraisal dimensions are independent and must not be combined into a single numerical score or overall evidence class. Categories are ordered only within their respective dimensions. High system relevance does not establish causal attribution or endpoint completeness, and a high extraction or recovery value does not compensate for unresolved hybrid contributions, incomplete product characterization, or missing liquid- and solid-stream balances. The maximum defensible claim is determined by the complete evidence profile and applies only to the demonstrated process function, feed, operating conditions, comparator, and system boundary. Closely related publications from the same experimental program should be treated as cumulative rather than independent evidence. Table 1 provides a conceptual appraisal framework and does not summarize individual studies.

System relevance, causal attribution, and endpoint completeness remain independent appraisal dimensions. A well-controlled experiment on a simplified mineral system may provide strong causal evidence but limited secondary-resource relevance, whereas pilot operation on a representative feed may demonstrate practical operability without isolating cavitation from pumping, mixing, gas transfer, or particle attrition. The supported claim therefore depends on the complete evidence profile rather than on feed origin, scale, or a single recovery value.

Evidence maturity is assigned to the demonstrated function rather than to HC as a general technology. Improved bubble–particle attachment cannot be used to infer enhanced dissolution, mobilization into solution cannot be equated with product recovery, and a high recovery percentage cannot compensate for unresolved hybrid contributions or incomplete material balances. Conditioning, washing, decontamination, cementation, or phase preparation support recovery-level claims only when the target is followed into a defined product or reusable fraction and the associated liquid and solid streams have specified downstream routes.

3. Hydrodynamic Cavitation Functions and Flowsheet Integration

HC becomes technically relevant when a specific physical action is matched to a verified process limitation and applied where that limitation governs performance. Secondary-resource processing may be constrained by incomplete wetting, external mass-transfer resistance, restricted access to reactive phases, passivating layers, inadequate gas–liquid transfer, poor solids suspension, particle agglomeration, or inefficient phase contact. Depending on the controlling limitation, HC may operate as a pretreatment, a recirculating leach module, a gas–liquid contactor, a bubble-generation stage, a localized washing unit, or a downstream phase-conditioning device. The process function is therefore determined

by the stream treated, the active-zone position, and the intended response rather than by the device designation alone.

The relationships summarized in Table 2 connect flowsheet position, controlling limitation, HC function, relevant performance endpoint, and principal failure mode.

Table 2. Function-specific roles of hydrodynamic cavitation across circular hydrometallurgical flowsheets.

Flowsheet Position and Controlling Limitation	HC-Enabled Function	Decision-Relevant Endpoint	Principal Failure Mode
Feed conditioning before physical separation. Incomplete wetting, particle agglomeration, poor solids dispersion, or nonuniform reagent–particle contact	Wetting enhancement, deagglomeration, slurry homogenization, and conditioning of particle surfaces	Degree of deagglomeration; particle-size distribution; slurry rheology; reagent utilization; subsequent separation response under unchanged downstream conditions	Excessive attrition; fines generation; increased viscosity; reagent degradation; wear-derived contamination
Preconcentration or fine-particle separation. Inefficient particle–bubble attachment, weak selective aggregation, or poor recovery of fine and ultrafine particles	Fine-bubble generation, particle conditioning, and enhancement of selective particle–bubble contact	Target recovery; concentrate grade; mass pull; impurity rejection; target loss to rejected streams; reduction of downstream feed mass	Nonselective gangue entrainment; aggregate disruption; unstable froth; excessive water demand; insufficient concentrate upgrading
Leach-feed activation before dissolution. Restricted access to target phases, weakly attached product layers, adherent coatings, passivation, or incomplete exposure of reactive surfaces	Surface renewal, coating or deposit removal, and exposure of reactive phases before conventional leaching	Subsequent extraction kinetics and selectivity at equivalent lixiviant concentration, temperature, solids loading, and treatment duty	Exposure of gangue phases; increased non-target dissolution; fines accumulation; greater reagent demand; impaired solid–liquid separation
Leach-slurry recirculation. External mass-transfer resistance, poor solids suspension, insufficient gas–liquid contact, or nonuniform liquid–solid interaction	Repeated interfacial renewal, solids dispersion, gas transfer, and renewal of liquid–solid contact during dissolution	Extraction kinetics; target selectivity; impurity transfer; gas and reagent utilization; recovery at equivalent product specification; specific energy and throughput	Excessive cumulative exposure; temperature rise; reagent degradation; particle erosion; equipment wear; limited single-pass productivity
Dedicated liquid or classified-solids side-stream loop. Poor gas dissolution, inadequate reagent dispersion, or incompatibility of the bulk feed with a restrictive active zone	Conditioning of lixiviant, gas-containing solution, low-solids stream, or classified fine-solids fraction before its return to the main process	Treated-stream fraction; dissolved-gas concentration; reagent utilization; stream-property stability; effect on overall recovery, selectivity, or residence time	Negligible influence on the total process inventory; excessive gas suppressing vaporous cavitation; pump instability; untreated bulk-fraction limitation
Localized washing or coating-liberation stage. Adherent catalytic or mineral coatings, retained soluble species, localized contamination, or valuable phases attached to a support	Jet impact, localized shear, coating detachment, washing, and selective liberation	Liberation or washing yield per pass; recovered-fraction mass and composition; support integrity; wash efficiency; dry-solids throughput	Support fragmentation; nozzle or throat erosion; wear contamination; low single-pass productivity; difficult recovery of detached fines
Cementation stage. Passivation of the solid reductant, poor reductant dispersion, or insufficient renewal of the metal–reductant interface	Reductant dispersion, removal of weak passivating deposits, and renewal of reactive surfaces during cementation	Recovered-metal mass; purity; morphology; filterability; residual dissolved target; reductant consumption; dissolved reductant metal	Excessive reductant attrition; generation of unrecoverable fines; increased reductant dissolution; poor product purity; difficult filtration
Separation-medium or liquid-emulsion-membrane preparation. Insufficient phase dispersion, large or nonuniform droplets, limited interfacial area, or slow mass transfer across the dispersed phase	Rapid emulsification and formation of fine, comparatively uniform dispersed phases	Droplet-size distribution; extraction and stripping efficiency; emulsion stability; swelling; rupture; phase disengagement; membrane reuse	Emulsion instability; slow phase separation; extractant or surfactant loss; excessive chemical inventory; incomplete recovery from the internal phase

Table 2. *Cont.*

Flowsheet Position and Controlling Limitation	HC-Enabled Function	Decision-Relevant Endpoint	Principal Failure Mode
Residue-washing stage. Retained mother liquor, soluble salts, residual lixiviant or complexant, and dissolved target entrained within the solid product or residue	Intensified washing, release of retained liquid, and improved liquid–solid contact during residue cleaning	Wash efficiency; cake moisture; dissolved-target and reagent loss; water demand; residue leachability; suitability for reuse, stabilization, or disposal	Persistent fine suspensions; increased clarification or filtration demand; greater wash-water inventory; contaminant transfer to the liquid stream; deterioration of residue quality
Recycle-liquor or purge-stream conditioning. Accumulation of dissolved gangue, salts, suspended fines, degraded reagents, organics, or wear products in recirculating solutions	Conditioning of recycled liquor or a controlled purge stream through dispersion, gas transfer, reagent redistribution, or removal of selected deposits	Recycle fraction; reagent make-up; impurity accumulation; purge composition; stability of extraction and product quality over repeated cycles	Burden transfer without recovery; progressive impurity accumulation; reagent degradation; unstable cavitation behavior; increased purification or purge-treatment demand

Note: The relevant HC role is defined by the controlling process limitation and the stream exposed to the active zone, rather than by the nominal device type. The categories describe distinct functions and are not sequential stages required in every flowsheet. Decision-relevant endpoints should be assessed against an appropriate non-HC or noncavitating reference at equivalent feed characteristics, chemistry, product specification, and process duty. Failure modes identify the principal pathways through which local intensification may increase the overall chemical, water, energy, equipment, or residual-stream burden.

Flowsheet position determines the appropriate performance endpoints. Conditioning and preconcentration are assessed through accessibility, grade, mass pull, impurity rejection, and downstream mass burden. Leaching requires kinetic and selectivity endpoints, whereas downstream phase preparation and recovery require separation efficiency, product characteristics, and compatibility with subsequent operations. Evidence obtained for one function cannot be transferred automatically to another, even when the same device is used.

3.1. Transport, Interfacial, Bubble, and Particle Responses

Leaching requires transport of the lixiviant to the reactive interface, dissolution or chemical transformation of the target phase, and removal of reaction products from the surface. In heaps and packed beds, nonuniform flow, variable wettability, tortuosity, particle size distribution, and evolving pore structure introduce additional resistances, making bulk residence time an incomplete measure of local liquid–solid contact [13]. HC cannot overcome mineralogical locking or reproduce prolonged contact throughout a heterogeneous fixed bed. Its more plausible contribution lies in reducing selected external transport resistances through local acceleration, pressure fluctuations, recirculation, and repeated interfacial renewal in slurries or external solution-conditioning loops.

Cavity collapse near a solid boundary can generate localized liquid microjets, pressure impulses, and shear, while reactor-scale turbulence, extensional deformation, high-velocity particle motion, and repeated pressure-recovery cycles modify interfacial and particle interactions [11,12]. Weak deposits or product layers may be detached, agglomerates dispersed, and external-film resistance reduced. These responses are not equivalent. Surface cleaning may improve accessibility without substantial comminution, whereas more severe particle breakage can expose gangue, increase non-target dissolution, generate fines, alter slurry rheology, impair filtration, and accelerate equipment wear. The relevant response must therefore be identified from changes in surface condition, particle size distribution, and process behavior rather than inferred from cavitation occurrence alone.

Scheelite, uranium, and refractory-gold systems illustrate how the controlling resistance determines the hydrodynamic response. Hybrid hydrodynamic–acoustic treat-

ment accelerated alkaline scheelite dissolution, acoustic and hydrodynamic configurations improved access to uranium-bearing phases, and opposing pulp jets enhanced oxygen dispersion, slurry contact, and interfacial renewal during gold cyanidation [14–17]. The benefit depended on mineral texture, particle size, gas requirement, chemical regime, and phase accessibility. Extensive size reduction diminished the additional value of particle disruption in uranium leaching, whereas the gold configurations relied more strongly on coupled gas–liquid and solid–liquid contact. These cases therefore represent distinct transport functions rather than a common cavitation mechanism.

Transient vapor cavities and persistent gas bubbles are physically related but analytically distinct. Cavities form and collapse over short timescales and may generate localized mechanical or chemical effects. Residual micro- or nanobubbles can persist after pressure recovery, providing interfacial area, low rise velocity, altered surface properties, and sites for particle attachment. Hydrodynamic tubes and multiphase pumps generate bubble populations whose size, concentration, lifetime, and surface flux depend on geometry, gas content, water chemistry, and operating history [18–20]. Measurement of persistent bubbles does not quantify collapse intensity, while pressure fluctuations, acoustic emissions, or cavitation noise do not establish the concentration or stability of residual bubbles.

Fine bubbles can increase gas–liquid interfacial area, provide nuclei for subsequent cavitation, attach to conditioned particles, promote bridging between fine solids, and modify apparent wettability. Hydrodynamically generated nanobubbles have been associated with powder flotation, particle–bubble interaction, selective recovery of fine particles, and carrier-assisted separation [21–24]. Phosphate, chalcopyrite, complex-sulfide, and coal systems further show that performance depends on pulp rheology, particle size, hydrophobicity, collector concentration, solution composition, and the stage at which bubbles are introduced [25–28]. These studies support transferable mechanisms for conditioning and fine-particle separation but do not independently establish enhanced dissolution or complete recovery from secondary resources.

The hydrodynamic response also evolves with matrix composition and treatment history. Solids loading, viscosity, ionic strength, dissolved gas, surface-active compounds, oxidants, complexants, and suspended fines can alter cavity inception, pressure recovery, bubble persistence, interfacial tension, and reaction pathways. Conversely, repeated HC exposure can modify particle size distribution, expose target or gangue phases, release passivating or catalytically active species, degrade reagents, and introduce wear products [11,12]. Initial deagglomeration or surface cleaning may therefore be followed by progressive attrition, fines accumulation, aggregate disruption, rheological changes, or declining selectivity. Clean-water bubble measurements and nominal hydraulic descriptors cannot be transferred directly to particle-laden process streams without confirmation under the actual solids loading and solution chemistry [18–20]. Time-resolved particle, surface, rheological, and extraction measurements are consequently more informative than a single endpoint selected at an apparent optimum.

3.2. Flowsheet Positioning and Operating Modes

A short HC pretreatment can remove weak surface deposits or disrupt agglomerates before conventional leaching, whereas continuous recirculation through an active zone can sustain interfacial renewal during dissolution. Side-stream treatment may instead condition a lixiviant, gas-containing solution, or classified solids fraction while limiting the exposure of coarse or abrasive material. Cavitating jets and ejectors are suited to localized impact and washing, multiphase pumps and high-shear devices favor gas dispersion and fine-bubble generation, and HC-assisted emulsification can prepare a downstream separation medium. The appropriate configuration depends on the process bottleneck, the required

physical function, and the tolerance of the feed to attrition, blockage, gas entrainment, and shear [15,17,19,24].

The principal HC integration modes are represented in Figure 2 within a circular hydrometallurgical flowsheet.

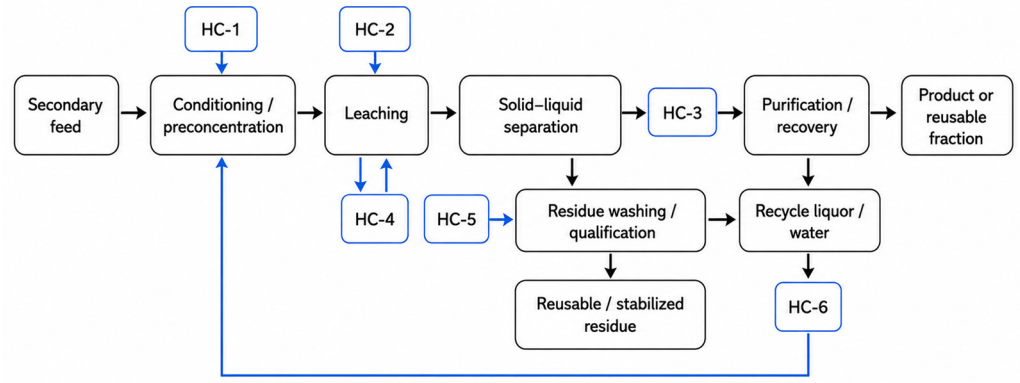


Figure 2. Representative positions of hydrodynamic cavitation modules within a circular hydrometallurgical flowsheet.

Figure 2 maps the principal process route from the secondary feed through conditioning or preconcentration, leaching, solid–liquid separation, purification or recovery, and formation of a characterized product or reusable fraction. The solid branch leads to residue washing and qualification and subsequently to a reusable or stabilized residue, while recovered process water and liquor may enter a recycle loop. These positions represent alternative or complementary integration modes and are not sequential stages required in every process.

Fixed heaps and low-permeability beds provide a less direct integration opportunity because the solid mass cannot be passed uniformly through a restrictive active zone. More credible configurations involve lixiviant preparation, oxygenation, reagent dispersion, treatment of circulating fines, or conditioning of pregnant and barren liquors. These operations may modify gas transfer or solution chemistry, but they cannot be assumed to reproduce liquid distribution throughout a heterogeneous bed. Changes in infiltration, wettability, gas content, solution composition, and metal recovery require direct verification before a heap-scale benefit is inferred [13].

Gas and reagent placement can alter both the dominant hydrodynamic function and the resulting process response. Gas injection upstream of a restriction may increase nucleation and interfacial area, whereas excessive gas content can suppress vaporous cavitation, destabilize pumping, or shift the system toward bubble-mediated contacting. Oxidants, complexants, collectors, and surfactants may be introduced before, within, or after the active zone depending on whether rapid dispersion, interfacial exposure, or protection from local degradation is required [18–20].

Partial treatment may be more practical than forcing the entire feed through the active zone. A low-solids side stream can condition gas, lixiviant, or recycled solution without exposing coarse abrasive particles to a narrow passage, while a classified fine fraction can receive more intensive treatment and the bulk solid follows a conventional route. The value of partial treatment depends on the treated fraction and on whether modification of that stream controls overall flowsheet performance.

4. Application Evidence Across Circular Hydrometallurgical Flowsheets

Application evidence spans feed conditioning, preconcentration, intensified dissolution, coating liberation, metal mobilization, and downstream phase separation. The examples considered below were selected because they provide direct or transferable evidence for these distinct HC-enabled functions and collectively represent the principal application domains identified in the literature, rather than because the corresponding materials are assumed to be intrinsically more susceptible to cavitation. The available evidence does not support classifying HC as generally beneficial or detrimental: positive responses arise when a defined process limitation is relieved, whereas most reported metal-recovery applications use HC as an enabling or intensification step rather than as a stand-alone primary extraction or remediation process. Mechanistic and transferable studies clarify potentially useful responses, whereas representative secondary feeds provide the stronger basis for flowsheet-level assessment.

4.1. Upstream Conditioning and Preconcentration

Conditioning and preconcentration are relevant when they increase value density, reduce the mass or impurity burden entering subsequent treatment, expose valuable phases, or generate reusable fractions. Appropriate indicators extend beyond recovery percentage to concentrate grade, mass pull, gangue rejection, target loss, reagent and water demand, and the characteristics of both recovered and rejected streams.

High-shear HC improved recovery from tailings containing platinum-group metals by modifying interactions between fine particles and bubbles [29]. A flowsheet advantage requires preferential concentration of phases bearing Pt, Pd, or Rh while limiting chromite and silicate entrainment. High recovery accompanied by a large mass pull may provide little reduction in downstream grinding, leaching, or smelting demand, whereas excessive conditioning may increase fine-gangue recovery, slurry viscosity, and water consumption. Concentrate composition and rejected-tailings quality are therefore as important as total metal recovery.

Phosphate slimes and apatite tailings provide transferable evidence for nanobubble-assisted recovery of fine particles [30,31]. Characterized bubble populations of approximately 60–70 nm improved flotation and, under selected conditions, reduced collector adsorption [21,25]. Performance remained sensitive to reagent chemistry, ionic composition, clay content, and pulp rheology. These systems demonstrate the potential of fine bubbles in dilute fine fractions, but transfer to metal-bearing secondary resources requires confirmation of enrichment, entrainment, process water compatibility, and downstream concentrate quality.

Ultrafine scheelite provides a complementary mechanistic example because HC has been associated with aggregation and flotation under different generation modes [32,33]. Treatment of the complete pulp generally produced stronger aggregation than treatment of the reagent solution alone, with reported bubble diameters of approximately 200–300 nm. The response depended on hydrophobicity, collector concentration, residence time, and treatment location. Cavitation-generated bubbles have also extended particle attachment beyond the conventional flotation size range in coarse-particle systems [34]. Excessive shear can nevertheless disrupt aggregates or destabilize froth, producing a function-specific operating window rather than a monotonic benefit with increasing intensity.

Washing ejectors applied to contaminated soils provide direct evidence of solids fractionation relevant to secondary-resource processing. At approximately 5 MPa and a liquid-to-solid ratio close to 2, a Venturi ejector removed about 40–60% of the measured metals while reducing the volume of fine particles by approximately 28–47% [35]. Coupling ejector washing with microbubble column flotation at pilot scale partitioned the material

into approximately 60% coarse and 40% fine fractions, increased Fe concentration in the selected fraction from 9.67% to 13.76%, and reduced the total treated volume by about 30% [36,37]. These outcomes establish volume reduction and enrichment; practical value depends on metal yield, water recirculation, residual leachability, and the route assigned to the metal-rich fine fraction or liquid stream.

Municipal solid waste incineration fly ash and waste phosphogypsum extend conditioning evidence from metal concentration to matrix upgrading. Washing ejector treatment removed soluble salts from fly ash and enabled use of a Ca-containing stream for carbon dioxide capture [38]. HC pretreatment followed by froth flotation improved separation of impurity-bearing phases from phosphogypsum and increased the quality of the remaining mineral fraction [39]. In these cases, preservation or upgrading of the bulk solid may be more valuable than direct metal production, provided that losses of useful solids, water demand, concentrated contaminants, and rejected fines remain within the process boundary.

Coal gasification fine slag and graphite provide additional but less directly transferable examples. HC altered the flotation behavior of fine slag, although circular relevance depends on whether the enriched carbon or mineral fraction enters a defined reuse or recovery route [40]. HC-generated nanobubbles of approximately 180–400 nm increased graphite recovery by about 15% and the flotation rate by approximately 33%, with maximum recovery approaching 98% under the reported conditions [41]. Upstream removal of hydrophobic graphite could reduce the mass, acid demand, and impurity burden associated with subsequent leaching of battery metals. Single-component microflotation, however, does not reproduce mixed black mass, for which graphite purity, loss of active material to the froth, binder and current collector carryover, process water chemistry, and regeneration performance remain decisive.

The evidence therefore supports selective conditioning and fractionation functions, but their flowsheet value depends on material partitioning and the quality of the fractions produced rather than on flotation or removal percentage alone.

4.2. Cavitation-Assisted Leaching and Metal Mobilization

Scheelite dissolution is among the better documented examples of cavitation-assisted leaching. A flow-through reactor combining orifice-induced HC with acoustic excitation in 10 mol L^{-1} NaOH at 40–80 °C increased tungsten recovery under intensified conditions [14]. The response is consistent with reduced boundary-layer and product-layer resistance, but the contribution of HC cannot be isolated because acoustic power, hydraulic flow, temperature, and particle transport acted within the same configuration. Neither purified ammonium paratungstate nor tungsten oxide was recovered, and alkali regeneration was not demonstrated. The evidence therefore establishes kinetic intensification rather than a complete tungsten recovery route. Transfer to tailings, grinding residues, or spent catalysts also depends on gangue dissolution, impurity loading, filtration, alkali make-up, and conversion of soluble tungstate into a defined product.

Cavitation-assisted uranium mobilization was investigated for MgF_2 slag and low-grade ore using acoustic and hydrodynamic configurations [15]. Recovery from the slag increased from approximately 72–78% without cavitation to 84–87% under cavitation-assisted nitric acid leaching. The incremental benefit was greater for coarser or incompletely liberated material and diminished after sufficient particle size reduction, indicating that renewed phase accessibility governed the response. Practical implementation would additionally require radiological containment, aerosol and fines control, equipment durability, acid management, and evaluation of the downstream ion exchange or solvent extraction burden.

Gold systems provide stronger evidence of coupled gas–liquid–solid intensification. The Jetleach reactor generated opposing high-velocity pulp jets within an oxygen-

pressurized chamber and increased recovery from refractory ores and tailings by approximately 8–15 percentage points relative to conventional agitation [16,17]. Treatment of a tailings concentrate also reduced oxygen consumption by about 50% and lowered cyanide demand while increasing recovery. Improved gas dispersion, slurry contact, particle collision, and interfacial renewal are consistent with the reported response, although the absence of a noncavitating impinging-jet control at comparable mixing power prevents attribution to cavity collapse alone. Process performance also depends on cumulative passes, dry solids throughput, working inventory, pumping and compression energy, activated carbon management, elution, and residual cyanide treatment.

Average gold-recovery gains cannot be transferred independently of feed mineralogy. Liberated particles, sulfide inclusions, surface coatings, and gold associated with carbonaceous matter respond differently to short high-shear exposure. An increase of approximately 10 percentage points may represent faster dissolution of an accessible fraction rather than progressive liberation of refractory gold. Mineralogical characterization, size-resolved deportment, diagnostic leaching of residues, and evaluation of carbonaceous matter are therefore required to identify the affected fraction and the exposure beyond which additional treatment no longer improves recovery.

As an adjacent boundary case rather than core recovery evidence, controlled HC has reduced toxic-metal concentrations in metallurgical residual effluents [42]. Such treatment may provide solution conditioning or polishing, but its demonstrated function remains detoxification unless the removed metals are subsequently concentrated through adsorption, precipitation, electrodeposition, membrane separation, or another defined recovery step.

Lower-severity gold routes, including biocyanidation, provide relevant benchmarks because faster extraction is advantageous only when assessed against an equivalent product and treatment duty [43]. A more integrated secondary-resource case involved gold-bearing dump tailings treated through an HC-assisted thiourea carbon-in-leach process [44]. Sulfur dioxide stabilized thiourea, HC intensified gas–slurry contact, and activated carbon captured dissolved gold. Recovery reached 93.5% under the reported conditions, with thiourea consumption of 0.57 kg t^{-1} and sulfur dioxide addition of 8 kg t^{-1}. The result reflects the combined effects of acid pretreatment, redox control, sulfur dioxide, cavitation, recirculation, and carbon adsorption. Carbon loading, elution, product purity, sulfur balance, reagent recycling, and continuous solids handling determine whether the route provides an advantage over cyanidation or alternative lixiviants.

Closed-loop washing with ethylenediaminetetraacetic acid (EDTA) combined with HC removed Pb, Zn, Cd, and Cu from sewage sludge while recycling process water and part of the chelator and preserving much of the nutrient value [45]. Average removals were approximately 35% for Pb, 68% for Zn, 47% for Cd, and 45% for Cu. Phosphorus and potassium were largely retained, and plant-available phosphorus increased. Repeated batches, solution reuse, residual-solid leachability, nutrient retention, and potential fertilizer use were evaluated within the same sequence, providing comparatively complete flowsheet-level evidence.

Important limitations remained: approximately 46% of the EDTA was lost and required replenishment, total nitrogen decreased, plant yield did not improve, and the mobilized metals were not isolated as defined products. The demonstrated outcome is therefore stronger for closed-loop decontamination and sludge valorization than for circular recovery of the extracted metals. Suitability for land application depends on leachability, chemical speciation, bioavailability, ecotoxicity, nutrient performance, contaminant accumulation, and regulatory compliance rather than total metal concentration alone.

Across these systems, flowsheet relevance depends on chemical severity, selectivity, product formation, and residual-stream quality rather than on mobilization rate alone.

4.3. Spent Catalysts: Coating Liberation and Selective Recovery

Spent automotive, selective catalytic reduction (SCR), and refinery catalysts contain Pt, Pd, Rh, W, V, Mo, Ni, Co, and Al in complex oxide, sulfide, and supported phases. Conventional recovery combines thermal or mechanical pretreatment with acidic, alkaline, chlorinating, pressure-assisted, biological, solvent extraction, precipitation, or ion exchange stages [46–49]. These routes provide the relevant benchmark because HC-assisted processing must retain recovery and product quality while reducing thermal severity, reagent demand, comminution, or downstream separation burden.

Spent hydrodesulfurization catalysts illustrate why dissolution and selectivity must be considered together. Conventional routes can mobilize Mo, V, Ni, Co, and Al, but solution complexity, selective separation, and reagent regeneration often govern overall performance [50–53]. Sulfuric acid and physicomechanical treatments can improve phase exposure while increasing fines generation and impurity dissolution [54,55]. Alkaline conditions may favor Mo and V dissolution while retaining more Ni and Co in the solid, whereas acidic conditions can transfer Al, P, S, Ni, and Co into the liquor. Intensified surface renewal is beneficial only when it preserves the partition required by the subsequent separation route.

A hybrid sonoelectrochemical–HC process used a submerged convergent jet with an outlet of approximately 0.2 mm at about 60 MPa to condition spent three-way catalysts before 20 kHz sonoelectrochemical dissolution [56]. The hydraulic stage primarily promoted mechanical deconstruction and transfer of the catalytic coating from cordierite, while ultrasound and electrochemistry governed subsequent dissolution. Reported Pd and Pt concentrations increased by approximately 9% and 34%, respectively, and about 40% of the platinum-group metals was recovered within one hour, compared with less than 10% without HC pretreatment. The result supports mechanical coating liberation, but the extreme pressure, partial recovery, unresolved stagewise energy demand, uncertain preservation of the support, and incomplete balance of platinum-group metals preclude direct extrapolation to an industrial route.

A related procedure used diverging submerged jets at approximately 40 MPa and 0.5 L min^{-1} over 200 cycles to detach oxide agglomerates rich in Ti and W from spent automotive or SCR catalyst material [57]. The recovered primary particles were approximately 16–25 nm, and their composition and second-life photocatalytic performance were evaluated. Inclusion of second-life photocatalytic performance extends the endpoint beyond coating removal alone, but the use of 200 cycles raises concerns over continuous productivity. Liberation yield per pass, total solids throughput, energy consumption, nozzle lifetime, cordierite breakage, separation of detached fines, and consistency of the recovered fraction determine whether direct reuse can compete with roasting and leaching. The same high-pressure conditions also impose constraints associated with pump efficiency, pressure containment, nozzle erosion, support fragmentation, and contamination by wear products.

Spent SCR catalysts provide a demanding conventional comparison. Soda roasting followed by water leaching, pressure leaching, and other hydrometallurgical routes can achieve high W and V recovery but require substantial thermal or chemical severity and careful impurity control [58–61]. HC-assisted processing would provide a meaningful advantage only if it reduced roasting temperature, pressure, alkali concentration, treatment time, or support comminution without compromising W/V selectivity. Direct reuse of a coating rich in Ti and W and dissolution of W or V into a purified product are distinct objectives and require different measures of yield, purity, and functional performance.

The available catalyst evidence therefore supports HC most strongly as a mechanical and interfacial conditioning operation integrated with established recovery stages. The principal unresolved issues are single-pass productivity, equipment durability, selective liberation or dissolution, and transfer of the recovered coating or metals into a defined product.

4.4. Batteries and Electronic Wastes: Emerging Evidence and Gaps

Battery and electronic wastes combine high strategic value with demanding established recovery routes. Waste printed circuit boards and end-of-life electronics can undergo physical liberation, acid or oxidative leaching, solvent extraction, precipitation, ion exchange, and electrochemical recovery [62,63]. Lithium-ion battery recycling includes reductive acid leaching, selective recovery of Li, Co, Ni, and Mn, direct regeneration, and separation of current collectors and graphite [64–67]. Fluorinated electrolytes, binders, mixed chemistries, Al and Cu contamination, variable state of charge, and stringent product specifications define the constraints that any HC stage must satisfy.

Direct evidence for pressure-driven HC remains scarce. Cavitation studies involving battery particles have examined fragmentation, surface damage, and leaching enhancement, including nickel–manganese–cobalt oxide materials and an intensified route based on methanesulfonic acid and a biogenic reductant [68,69]. These studies establish that battery particles respond to cavitation-assisted contact, but their results cannot be transferred automatically between acoustic and pressure-driven devices because energy delivery, bubble fields, solids suspension, exposure frequency, and erosion differ.

Graphite flotation provides a plausible preconcentration function for battery black mass, but representative-feed validation must address graphite purity, cathode-active-material loss, binder and current-collector carryover, and metal recovery from the non-floating fraction [41]. The available evidence does not demonstrate intensified cathode dissolution.

Black mass is not a uniform feed. Lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), lithium cobalt oxide (LCO), lithium iron phosphate (LFP), and mixed-chemistry streams differ in target value, redox behavior, acid demand, and impurity tolerance, while production scrap and end-of-life material differ in electrolyte content, aging products, binder condition, and current collector carryover. Safe discharge, casing removal, controlled shredding, electrolyte management, drying, and preliminary separation may also dominate the system boundary before HC is applied. An HC stage would need to replace or reduce one of these burdens. Meaningful process gains would include improved wetting or deagglomeration at unchanged chemistry, lower temperature or reagent demand for an equivalent product, or greater selective recovery without additional co-dissolution of Al, Cu, Fe, or other impurities.

The relevant endpoints depend on the intended route. Purified salts, precursor-grade mixed hydroxides, lithium carbonate, regenerated cathode material, separated graphite, and recovered metallic foils impose different compositional and functional requirements. Rate enhancement must therefore remain evident after impurity removal, precipitation or crystallization, direct regeneration, and recycle of acid, reductant, and wash water.

Electronic wastes offer plausible HC functions in delamination, solder liberation, coating removal, and selective conditioning before leaching, but direct recovery from representative waste printed circuit boards remains insufficiently demonstrated. Excessive attrition may generate inseparable polymer–metal fines, increase undesirable base-metal dissolution, complicate filtration, and introduce wear contamination. Feed characterization must account for polymers, metallic foils, solders, flame retardants, particle size distribution, and precious-metal carriers.

Battery and electronic-waste processing remains insufficiently established as an HC application. Graphite separation provides a concrete entry point, while direct leaching with pressure-driven HC, selective downstream recovery, repeated solution recycle, and product-grade regeneration still require demonstration under representative feed variability.

4.5. Downstream Metal Separation and Product Recovery

Downstream HC evidence is concentrated in copper cementation and preparation of liquid emulsion membranes. Other separation technologies provide the benchmarks needed to determine whether an upstream gain in dissolution or conditioning survives purification and product formation.

Cavitation-enhanced dispersion intensified copper cementation from aqueous waste streams using iron powder [70]. Improved particle dispersion, removal of passivating deposits, and renewal of the iron surface can accelerate copper deposition and improve reductant utilization. Relevant endpoints include the mass, purity, morphology, filterability, and subsequent use of the cemented copper, together with Fe consumption, residual Cu, dissolved Fe, and fines generated through particle attrition. Depletion of copper from solution is valuable only when the recovered solid can be separated and used or refined.

Rare-earth and multi-metal hydrometallurgy illustrates the selectivity burden created by intensified leaching [71]. Greater dissolution may increase extractant loading, neutralization demand, impurity precipitation, or the number of separation stages when gangue and competing metals enter solution simultaneously. Purified product yield per unit feed or reagent can therefore be more informative than gross leach extraction.

HC has also been used to prepare liquid emulsion membranes for extraction of Co(II), Cr(VI), and Pb(II) [72–74]. Fine and relatively uniform droplets increase interfacial area and can shorten emulsification compared with conventional mixing. Relevant performance variables include electrical energy, emulsion stability, swelling, rupture, phase disengagement, extractant and surfactant inventory, stripping efficiency, and reuse over repeated cycles. Feed-phase removal becomes recovery only after transfer to the internal phase, stripping, and conversion into a defined product.

Membrane technologies provide additional routes for concentrating critical metals [75]. Compatibility with HC-derived liquors depends on suspended fines, colloids, organic matter, ionic strength, pH, and residual extractants. Upstream particle disruption can increase fouling, stabilize unintended emulsions, occlude precipitates, or slow phase separation, whereas effective detachment and classification may improve clarification and filtration.

Liquors derived from spent automotive catalysts require selective recovery of Pt, Pd, and Rh from concentrated chloride, acidic, or impurity-rich media. Solvent extraction and related separation sequences provide established benchmarks [76,77]. Upstream coating detachment or dissolution is beneficial only when the resulting liquor does not increase extractant consumption, phase-disengagement time, crud formation, or precious-metal loss. Product purity, recovery through stripping and precipitation, and extractant regeneration determine whether the upstream improvement persists.

Mine-tailings liquors present comparable constraints. Comparative extraction of rare earth elements demonstrates differences among acidic, solvating, and mixed extractant systems in selectivity and reagent demand [78]. Nickel recovery from industrial wastes likewise depends on feed composition, precipitation or extraction chemistry, and competing metals [79]. Lower-toxicity lixiviants and separation media may reduce specific hazards, but environmental performance remains dependent on concentration, reagent recycle, product specification, and residue management [80].

The preferred intensity of an upstream HC stage may therefore be lower than that producing maximum gross dissolution. Co-dissolved Al, Fe, Ca, Si, or support material can consume neutralizing agents, load extractants, generate gelatinous precipitates, contaminate crystallized products, or increase membrane fouling. Paired analyses of feed, leachate, intermediate phases, product, and residual streams are required to identify the condition that maximizes recoverable rather than merely solubilized yield.

Representative application evidence is consolidated in Table 3 by linking each resource or process context to the HC-enabled function, the main demonstrated outcome, and the principal boundary of the available evidence.

Table 3. Representative application evidence for HC-enabled functions in circular hydrometallurgical processing.

Resource or Process Context	HC-Enabled Function	Main Demonstrated Outcome	Principal Evidence Boundary	Ref.
Contaminated soils	Washing, fractionation, and preconcentration	Metal mobilization and reduction of the fine-particle burden	HC contribution and downstream recovery of enriched fines remain unresolved	[35–37]
Graphite flotation benchmark	Nanobubble-assisted particle conditioning	Higher recovery and faster flotation kinetics	Transferability to heterogeneous battery black mass remains unverified	[41]
Scheelite and uranium-bearing materials	Leaching intensification	Faster dissolution and increased target extraction	Cavitation effects remain partly confounded by acoustic, hydraulic, and particle-size effects	[14,15]
Gold ores and tailings	Gas–liquid–solid contact intensification	Higher recovery and, in selected cases, lower oxygen or reagent demand	HC was not isolated from jet mixing, oxygenation, or chemical stabilization	[16,17,44]
Metal-bearing sewage sludge	Chelant-assisted washing and metal mobilization	Partial metal removal with retention of residue-valorization potential	Mobilized metals were not recovered as characterized products	[45]
Spent automotive catalysts	Coating liberation and washing	Recovery of catalyst-bearing and oxide-rich fractions	High pressure or repeated passes limit demonstrated process productivity	[56,57]
Copper-bearing aqueous streams	Cementation intensification	Improved iron dispersion and renewal of reactive surfaces	Product quality and complete metal balances remain insufficiently reported	[70]
Co(II)-, Cr(VI)-, and Pb(II)-containing extraction systems	Liquid-emulsion-membrane preparation	Rapid formation of fine dispersed phases for metal extraction	Stability, stripping, reuse, and final product recovery remain incomplete	[72–74]

Note: Evidence boundaries identify the principal limitation affecting interpretation of each application. References grouped within the same row denote evidence relevant to the same application category and do not necessarily represent independent replications or directly comparable experiments. Reported outcomes are concise syntheses and should not be interpreted as directly comparable across feeds, process duties, or operating conditions.

5. Whole-Flowsheet Performance, Loop Closure, and Scale-Up

Application-level improvements become flowsheet-relevant only when they remain advantageous through product recovery, solution recirculation, residue management, and sustained operation. Flowsheet-level performance requires material, chemical, water, and energy inventories linked to productivity, product specification, and operability. Compar-

isons must be made at equivalent target recovery and product quality rather than at equal clock time, nominal residence time, or maximum local treatment intensity.

5.1. Circularity, Resource Use, Productivity, and Residue Fate

Whole-route recovery is determined by the mass of target entering the process and the mass isolated in a defined product. Target and major non-target elements should therefore be tracked across the feed, concentrate, leachate, intermediate phases, recovered product, washings, purge streams, and residual solids. Mass closure and analytical uncertainty are particularly important when fine-particle loss, adsorption, precipitation, retained solution, or incomplete sampling can distort apparent extraction or recovery.

Selectivity governs whether intensified contact reduces or increases the downstream burden. Greater surface accessibility may accelerate target dissolution while also exposing gangue, catalyst supports, binders, current collectors, or other impurity-bearing phases. The resulting liquor may require more neutralization, extractant inventory, precipitation stages, washing, or product purification. Selectivity ratios, impurity transfer, product purity, and the severity of subsequent separation operations are therefore more informative than target extraction alone.

Chemical inventories include lixiviants, reductants, oxidants, gases, collectors, frothers, chelators, surfactants, pH-control agents, washing chemicals, regenerants, and neutralization reagents. Consumption should be normalized to both dry feed and recovered target, with make-up, entrainment, adsorption, degradation, and purge losses included. A lower reagent concentration does not necessarily reduce the total chemical burden when it requires greater solution volume, additional treatment passes, or more extensive downstream neutralization.

Closed-loop operation is constrained by impurity accumulation as much as by nominal reagent recovery. Dissolved gangue, corrosion and wear products, suspended fines, degraded reagents, organics, and counter-ions can progressively alter viscosity, interfacial tension, cavitation inception, extraction selectivity, precipitation, filtration, and product quality. Repeated-cycle testing should therefore quantify performance retention, reagent make-up, pH control, impurity accumulation, gas demand, purge composition, and product consistency over enough cycles to reveal the limiting species [45,72–74]. Stable performance over one or two recycle steps does not establish sustained closure when chloride, sulfate, fluoride, phosphate, silica, organics, or wear metals continue to accumulate.

The EDTA–HC sludge process illustrates partial loop closure: repeated solution reuse and nutrient retention strengthened the valorization case, but chelator loss and the absence of separate metal products remained unresolved [45]. Comparable accounting is required across resource classes. Gold routes require balances for lixiviant make-up, gas supply, activated carbon, elution, and residual-lixiviant destruction [17,44]. Catalyst routes require reagent recovery, selective metal separation, and support qualification [57]. Battery routes require acid and reductant recycle, fluoride and phosphorus control, current-collector separation, and product-grade recovery [69].

Water demand extends beyond slurry preparation to washing, dilution, phase disengagement, equipment cleaning, and product purification. HC may improve dispersion or washing while producing stable fine suspensions that require greater clarification or filtration. Net water withdrawal, recycle fraction, purge quality, moisture retained in solids, and dissolved target or reagent carried into the residue should therefore accompany extraction data. Where complete water closure is impractical, a quantified recycle ratio combined with a defined purge-treatment route provides a more credible circular strategy than an unsupported claim of zero discharge.

Solid–liquid separation closes the physical loop between solution and product or residue. Fines generated by HC can retain mother liquor, increase washing demand, slow settling, impair filtration, and transfer dissolved target or reagent into residual solids. Filterability, settling rate, cake moisture, wash efficiency, and dissolved-metal loss are therefore part of the flowsheet balance. Agglomeration, seeded precipitation, classification, or alternative separation equipment may be required when the desired product or residue is excessively fine. Any associated chemical and energy demands must be included within the system boundary.

Residue fate provides the final test of material closure. Cleaned coarse fractions, purified gypsum, regenerated graphite, recovered catalyst supports, treated sludge, and stabilized tailings may retain value or reduce disposal requirements [38,39,41,45]. Reuse, however, depends on leachability, functional or mechanical performance, contaminant release, mineral stability, aging behavior, and conformity with the intended application. Total elemental concentration alone is insufficient because particle size reduction may lower the bulk concentration while increasing surface reactivity and contaminant mobility. Residual complexants, surfactants, acid-generation or neutralization potential, and long-term release behavior determine whether a solid is reusable, requires stabilization, or remains hazardous [38,39,45,80].

A controlled purge is often more realistic than complete closure. Purging can prevent accumulation of salts, organics, degradation products, or wear metals, but the purge composition and treatment route determine whether the burden is reduced or merely transferred. Selective recovery, reagent regeneration, crystallization of manageable salts, or stabilization of a smaller concentrated residue may still improve circular performance when reductions in freshwater use, chemical demand, and residual mass are quantified.

Energy assessment must include hydraulic or electrical power, pump efficiency, pressure drop, flow rate, gas compression, temperature history, treatment time, solids concentration, and effective passes. Specific energy should be expressed relative to dry feed and recovered target and interpreted against any reduction in grinding, heating, gas consumption, residence time, or downstream purification. A short nominal residence time can conceal repeated recirculation, a large working inventory, and substantial pumping or compression demand. Conversely, moderate hydraulic energy may be justified if it replaces roasting, pressure digestion, fine grinding, or prolonged high-temperature treatment. Direct quantitative comparison across studies remains limited because energy inputs are reported inconsistently and are rarely normalized to dry-feed throughput or recovered product.

Productivity complements recovery by linking the result to equipment use. High percentage recovery from a dilute feed may still correspond to little recovered metal per unit reactor volume, time, or energy. Relevant measures include target mass transferred into a reduced concentrate mass, recovered product per unit feed and time, dry solids processed per pass, and purified product per unit membrane area, solvent inventory, or electrode area. Single-pass productivity and cumulative recovery must remain distinct because high recovery after many exposures may not translate into practical throughput.

The apparent advantage also depends on the baseline. A large relative improvement from poor conventional performance may remain technically inadequate, whereas a modest gain at high baseline recovery may be valuable if it reduces mass pull, chemical demand, impurity transfer, or equipment size. The strongest comparator is the best practical reference route operated to the same product specification. Incremental benefit can then be assessed through recovery, selectivity, residence time, chemical and water inventories, energy, productivity, and residual burden rather than through a single optimum value.

Environmental and economic interpretation must remain consistent with data maturity. Preliminary inventories can identify dominant pressure, heating, reagent, or separation

demands, but detailed life-cycle or techno-economic conclusions are unreliable when product recovery, equipment life, recycle, purge treatment, and residue fate remain unknown. Measured process inventories should be separated explicitly from assumed industrial values. Incomplete inventories should limit the strength of circular or industrial claims.

5.2. Scale-Up, Operability, and Minimum Reporting

Scale-up is function-specific. Leaching intensification depends on solids suspension, active-zone exposure, renewal frequency, and gas–liquid and liquid–solid contact. Bubble-assisted separation depends on bubble population and particle-contact history. Ejector washing depends on impact, entrainment, and classification; cementation on reductant dispersion and surface renewal; and emulsion preparation on droplet-size distribution and stability. Geometric enlargement alone does not preserve local pressure history, gas fraction, particle stress, slip, or residence-time distribution.

Single-pass and cumulative performance must be reported separately. Flow-through or recirculating operation should be characterized through treated volume or dry solids per pass, recycle ratio, number and frequency of effective exposures, working inventory, bypass or dead volume, and time to the reported endpoint. High cumulative recovery may otherwise conceal low single-pass conversion, limited throughput, or excessive specific energy. Batch experiments can establish a response but do not by themselves demonstrate continuous productivity.

Feed variability can alter both cavitation behavior and equipment performance. Solids loading, particle size distribution, density, viscosity, moisture, gas content, ionic composition, and surface-active species influence pressure loss, cavity formation, particle motion, erosion, blockage, and pump stability. Tailings, catalysts, ashes, sludges, and battery-derived feeds also vary with source, aging, storage, and pretreatment. Claims of transferability therefore require representative feed lots and appropriate mineralogical, phase, and physical characterization.

Long-duration operation reveals constraints that short laboratory tests cannot capture. Pressure and flow stability, temperature rise, gas entrainment, pump efficiency, throat or nozzle erosion, corrosion, solids accumulation, blockage, cleaning frequency, sedimentation, particle attrition, and product consistency should be monitored over extended exposure. Wear can alter the active geometry and introduce Fe, Cr, Ni, or other contaminants, while fines accumulation can modify the cavitation regime and downstream separation. Start-up, shutdown, off-specification conditions, unsuccessful treatment windows, and maintenance requirements define practical limits and should be reported rather than excluded from the performance record.

Parallel devices, staged treatment, replaceable active elements, and classified or low-solids side streams may preserve the intended function more effectively than simple geometric enlargement. Their success must nevertheless be demonstrated through stable throughput, exposure uniformity, product consistency, pressure containment, maintenance frequency, and durability. The architecture selected for scale-up is less important than preservation of the required process function under representative operating conditions.

Minimum reporting must correspond to the level of the claim. Mechanistic studies require resource and fluid properties, active-zone geometry, pressure and flow references, evidence that cavitation occurred, treatment history, appropriate controls, and analytical uncertainty. Bench-scale process claims additionally require kinetics, selectivity, particle or surface changes, mass balances, product characterization, chemical and water inventories, energy, and throughput. Pilot, circularity, or industrial claims further require representative feed variability, recycle and purge behavior, residue fate, long-duration operability, equipment wear, maintenance, and campaign-level uncertainty.

Hydraulic reporting requires more than a nominal operating pressure or cavitation number. The equation used, vapor-pressure treatment, reference velocity, upstream and downstream pressure locations, temperature, flow rate, and active geometry must be stated. A single nominal cavitation number cannot characterize spatially varying, particle-laden, or gas-containing flow without the underlying measurements. Pressure fluctuations, acoustic signals, direct observation, erosion patterns, and validated flow analysis may provide supporting evidence, but no single diagnostic identifies the metallurgically active mechanism.

Instrumentation must reflect the treatment history. Pressure sensors located far from the restriction can miss local losses, and time-averaged values can conceal fluctuations in gas–liquid or solids-laden flow. Sensor locations, acquisition frequency, calibration, and uncertainty should be specified for pressure, flow, temperature, power, gas supply, and sampling. Small differences in extraction or recovery cannot be assigned confidently to HC when their magnitude approaches the uncertainty of the hydraulic or analytical measurements.

Solids sampling requires particular care because settling, classification, recirculation, and particle breakage can make grab samples unrepresentative of the reactor inventory. Feed, intermediate, product, and residue samples should be collected through validated or mass-proportional procedures, with moisture and retained solution included in the balance. For valuable metals at low concentration, feed heterogeneity and analytical uncertainty may approach the reported improvement. Replicate runs, uncertainty propagation, and independent mass-balance closure are therefore integral to scale-up evidence rather than optional statistical additions.

The cumulative requirements summarized in Table 4 distinguish the minimum information needed for mechanistic interpretation, bench-scale process validation, and pilot or integrated flowsheet claims.

Table 4. Minimum reporting requirements for mechanistic, bench-scale, and pilot or integrated studies of hydrodynamic cavitation in circular hydrometallurgical flowsheets.

Reporting Domain	Mechanistic Interpretation	Bench-Scale Process Validation	Pilot or Integrated-Flowsheet Claim
Resource and fluid basis	Feed origin and composition; relevant mineralogy or phase structure; particle-size distribution; solids loading; key fluid properties; temperature	Representative feed preparation and variability; complete lixiviant, reagent, and gas composition; initial and final stream properties	Feed provenance and campaign variability; representative sampling; inventory and stream-distribution data
HC system and treatment history	Active-zone geometry; pressure and flow reference locations; pressure drop; flow rate; temperature; evidence of cavitation; treatment time or number of passes	Treated volume; recirculation ratio; gas addition; power and energy input; throughput; cumulative exposure	Device scale and number; parallel or staged arrangement; control strategy; duty cycle; start-up, shutdown, and off-specification operation
Controls and measurement quality	Appropriate noncavitating hydraulic control; sensor location, calibration, and acquisition frequency; replicates; analytical uncertainty	Comparator at equivalent process duty; validated sampling; run-to-run reproducibility; uncertainty propagation	Campaign-level variability; independent material-balance closure; reporting of unstable or unsuccessful operating periods

Table 4. *Cont.*

Reporting Domain	Mechanistic Interpretation	Bench-Scale Process Validation	Pilot or Integrated-Flowsheet Claim
Process response and material outputs	Direct measurement of the claimed bubble, particle, surface, transport, or interfacial response	Kinetics and selectivity; particle or surface changes; target and impurity balances; product and residue characterization	Feed-to-product recovery; product specification; liquid- and solid-stream accounting; sustained performance consistency
Resource use, circularity, and operability	Defined experimental boundary; chemical, gas, water, and electrical inputs relevant to the claimed response	Specific energy and throughput; chemical and water inventories; reagent utilization; preliminary wear, fouling, or blockage observations	Recycle and purge behavior; reagent and water make-up; residue fate; wear, corrosion, maintenance, durability, and long-duration productivity

Note: Requirements are cumulative from left to right. Function-specific metrics that are not applicable should be explicitly identified and their omission justified. Hydraulic reporting should state the governing equation, vapor-pressure treatment, reference velocity, pressure-measurement locations, temperature, flow rate, active geometry, and treatment history; nominal pressure or a single cavitation number alone is insufficient. Material balances should account for moisture, retained solution, suspended fines, and the relevant target and impurity streams.

6. Evidence Coverage and Research Priorities

Evidence coverage remains uneven across functions and resource classes. Support is strongest for discrete operations involving surface renewal, gas–liquid contact, particle conditioning, washing, coating liberation, cementation, or phase preparation. Integrated feed-to-product validation is much less developed, and practical operability is often documented more clearly than causal attribution or endpoint completeness.

The largest gaps concern heterogeneous battery black mass, waste printed circuit boards, rare-earth magnets, red mud, complex slags, metallurgical dusts, and multimetal residues. These feeds combine difficult liberation, variable phase composition, impurity-sensitive downstream recovery, and substantial residual masses. Graphite flotation and cavitation-assisted battery-particle studies identify plausible integration points, but pressure-driven HC routes connecting representative feed preparation, selective dissolution, product-grade recovery, solution recycle, and residue management have not yet been demonstrated [41,62,64,69]. Comparable gaps remain for electronic wastes and rare-earth-bearing residues.

Independent replication is limited. Several application clusters derive from individual research groups, closely related reactor families, or repeated development of the same experimental configuration. Further optimization within one device does not necessarily improve transferability when feed characteristics, pressure history, mixing power, exposure frequency, and diagnostic methods remain unchanged. Cross-laboratory testing of common feeds, comparison of different geometries at equivalent process duty, shared reporting conventions, and access to hydraulic and analytical data would provide stronger evidence than additional optimization of isolated recovery percentages.

Function-specific development begins with mechanistic screening to determine whether wetting, external transport, gas supply, surface deposits, particle aggregation, coating adhesion, or phase dispersion controls performance. Controlled bench experiments then compare cavitating and noncavitating hydraulics and establish kinetics, selectivity, chemical demand, and energy. Integrated laboratory flowsheets add purification, product formation, solution recycle, and residue qualification, while pilot campaigns address representative-feed variability, throughput, control, equipment wear, maintenance, and long-duration operation. Negative results remain informative when they identify condi-

tions that increase impurity transfer, reagent consumption, fines generation, equipment damage, or downstream separation burden.

Decision-relevant experiments determine whether HC can reduce grinding, temperature, lixiviant concentration, gas demand, treatment inventory, or downstream purification while preserving recovery and product specification. Comparisons based only on equal treatment time or maximum extraction provide limited guidance.

Compatibility with downstream separation remains critical. Intensified dissolution may generate colloids, dissolve additional gangue, increase extractant loading, impair membrane performance, complicate precipitation, or contaminate regenerated materials. The HC operating window should therefore be evaluated together with solvent extraction, membrane separation, precipitation, crystallization, cementation, or direct regeneration rather than optimized independently at the leaching stage [75–80]. The optimum hydrodynamic intensity may be lower than that producing maximum dissolution when selectivity and product recovery are included.

Priorities vary across resource classes but converge on selective function-specific treatment, validation on representative feeds, product-grade recovery, controlled management of liquid and solid streams, and sustained operability without excessive impurity transfer, fines generation, or equipment wear. The corresponding resource-specific evidence gaps, priority validation experiments, and advancement criteria are summarized in Table 5.

Table 5. Resource-specific evidence gaps and priority validation experiments for hydrodynamic cavitation in circular hydrometallurgical flowsheets.

Resource Class	Decision-Critical Gap	Priority Validation Experiment	Advancement Criterion
Tailings and slimes	Selective preconcentration is not yet linked consistently to grade–recovery balance, water use, and residue management	Continuous HC-assisted conditioning or preconcentration on representative feeds with complete fraction and water balances	Lower downstream feed mass at maintained target recovery, with water demand and residue quality quantified relative to the matched reference process
Spent catalysts	Selective liberation or dissolution remains limited by high pressure, repeated passes, incomplete recovery, and equipment wear	Matched HC and noncavitating tests including single-pass yield, product recovery, support integrity, energy, and wear	Maintained target recovery and product quality with lower specific energy, chemical or comminution demand, or fewer treatment passes, with equipment wear quantified
Metal-bearing sludges	Metal mobilization is not completed by chelator regeneration, isolated metal recovery, and safe residue qualification	Repeated-cycle washing with chelator and water recycle, metal recovery, and residue testing	Stable repeated-cycle operation with quantified metal recovery, chelator and water make-up, and residual-metal content in the qualified solid
Fly ash and mineral residues	Matrix upgrading is not sufficiently connected to contaminant concentration, water recycle, and long-term solid qualification	Closed-loop washing or fractionation with contaminant capture, purge control, and solid characterization	Quantified contaminant concentration or removal with maintained solid recovery or reuse quality and documented water demand and purge generation
Battery black mass	Pressure-driven HC lacks representative validation across graphite separation, selective metal recovery, impurity control, and recycle	Chemistry-specific testing on heterogeneous black mass with product-grade recovery and solution recycle	Higher or maintained graphite or metal recovery and product purity without increased impurity transfer, reagent or water demand, or residual-stream generation relative to the matched reference

Table 5. *Cont.*

Resource Class	Decision-Critical Gap	Priority Validation Experiment	Advancement Criterion
Electronic wastes	Delamination and liberation may generate inseparable polymer–metal fines and downstream contamination	HC-assisted liberation followed by classification, metal recovery, and nonmetal-fraction characterization	Higher selective liberation or metal recovery with maintained product purity and separability and quantified fines generation
Rare-earth and complex metallurgical residues	Feed variability and impurity-sensitive recovery prevent transferable operating windows	Function-specific studies linking HC exposure to selectivity, solid–liquid separation, purification, and product formation	Higher target recovery with quantified impurity rejection, product quality, solid–liquid separation performance, and residual-stream generation

Note: Priority experiments should use representative feeds and compare cavitating and noncavitating operation at equivalent process duty. Advancement requires that the local HC benefit persists through product recovery, liquid-stream management, and residue handling. Where applicable, advancement should be assessed against a matched reference process using absolute values and/or relative changes in these metrics.

7. Conclusions

Current evidence supports HC as a targeted process module rather than a generally superior hydrometallurgical platform. The most defensible contributions involve transport and gas–liquid intensification in selected leaching systems, particle conditioning and washing, coating liberation from spent catalysts, copper cementation, and preparation of separation media. Evidence remains strongest for discrete operations and substantially weaker for integrated feed-to-product recovery.

Flowsheet relevance depends on the persistence of the local gain through purification and product recovery. The target and major impurities must be included in complete material balances, while recirculating solutions, purge streams, and residual solids require defined management routes. HC is most credible when it replaces, reduces, or enables a more burdensome operation rather than adding an energy-intensive recirculation step to an otherwise unchanged flowsheet.

Integrated validation remains limited for heterogeneous battery, electronic, rare-earth, slag, dust, and multi-metal feeds. Independent replication, long-duration solids handling, closed-loop operation, equipment durability, and product-grade recovery remain the principal development needs. Progress depends on matched hydraulic controls, complete material balances, representative-feed testing, and explicit uncertainty. Under these conditions, HC may contribute to selective secondary-resource recovery and residue valorization without compromising the material-accounting requirements of circular hydrometallurgy.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The author declares no conflicts of interest.

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