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Review

A Review of Research Progress on Intelligent Cyclone–Filtration-Integrated Equipment for High-Suspended-Solids Mine Water Treatment

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Abstract

Mine water treatment remains a long-term challenge due to high suspended solids, wide particle size distributions, and inflow variability, all of which stress solid–liquid separation systems. Hydrocyclones and filtration often fail not from insufficient capacity, but from the inability to handle dynamic influent behavior. This review integrates existing studies and reinterprets mine water treatment as a system performance issue, focusing on maintaining operability under fluctuating conditions. Evidence shows that high-solids mine water behaves as a concentrated multiphase flow, where particle interactions and flow changes lead to gradual shifts in separation behavior. For example, hydrocyclone efficiency ranges from 85 to 95%, and pressure drop increases by 0.5–5 kPa/h under continuous operation. Wear, clogging, and flow redistribution develop together, impacting the operational window of integrated treatment units. Key gaps remain in system performance under fluctuating loads and reliable performance under high-solids loading. The complexity of these interactions often leads to significant operational risk and performance variability in real-world conditions. Future research should focus on dynamic control strategies, multi-stage pre-separation, and advanced filtration designs to enhance system performance, long-term stability, and adaptability in real mining environments. Emerging technologies and new system configurations may further improve efficiency and reduce operational failure risks under extreme conditions.

Keywords: mine water treatment; high suspended solids; system stability; integrated separation filtration

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1. Introduction

Mine water is continuously generated during mining activities and represents a distinct class of industrial wastewater with pronounced operational complexity [1]. Compared with conventional industrial effluents, mine water is typically characterized by high-suspended-solids concentrations, heterogeneous particle composition, wide particle size distributions, and pronounced temporal variability linked to mining operations [2–4]. These characteristics impose substantial solid–liquid separation loads and challenge the stability of treatment processes operating over long periods. In underground and semi-underground mining environments, treatment systems must function within constrained spatial conditions while maintaining continuous operation and high reliability, which further amplifies the sensitivity of the system to influent disturbances [5,6].

In engineering practice, hydrocyclone separators and filtration systems remain the most commonly deployed process components for mine water treatment [7]. Under relatively stable influent conditions, such configurations can provide effective removal of suspended solids and meet discharge requirements. Field experience shows that when suspended-solids concentrations increase abruptly, particle characteristics shift, or flow rates fluctuate, system performance can deteriorate rapidly, often manifested by reduced separation efficiency and accelerated clogging or fouling in filtration units [8,9]. These operational failures are rarely attributable to the insufficient capacity of individual units; they are more frequently associated with a mismatch between the dynamic characteristics of influent conditions and the fixed structural design and operating envelopes of the treatment equipment [10].

Hydrocyclone separation combined with filtration has therefore received increasing attention in space-constrained mine water applications due to its compact footprint and high volumetric throughput. Hydrocyclones enable rapid removal of coarse particles and high-suspended-solids loads within limited space, thereby reducing stress on downstream filtration barriers. Recent studies indicate that under elevated-solids concentrations and non-Newtonian flow conditions, hydrocyclone separation behavior is highly sensitive to solids loading and operating parameters, directly linking influent variability to unit-level stability [11]. Despite this recognition, most existing work remains focused on geometric optimization of hydrocyclones or improvements in filter media and cleaning strategies, while integrated analyses of hydrocyclone–filtration systems under dynamically varying mine water conditions remain limited. Classical hydrocyclone theory continues to provide the fundamental basis for defining feasible operating windows, yet its extension to system-level stability under fluctuating influent conditions remains insufficiently explored [12].

When hydrocyclones and filtration are deployed together for high-suspended-solids mine water, their relationship is not a simple upstream downstream sequence [13]. The separation outcome of the hydrocyclone directly reshapes the particle size spectrum and solids flux delivered to the filter, thereby redefining the operating load envelope of the downstream unit [14]. Under elevated-solids loading, filter head loss buildup and solids breakthrough tend to accumulate faster, and they become immediate determinants of whether continuous operation can be sustained [15]. As a result, even if individual devices perform well under controlled tests, field operation may still drift into system-level imbalance driven by localized overload and flow redistribution [16]. This observation highlights the need for a system-level perspective to clarify the functional roles of hydrocycloning and filtration, and specifies their coordination strategy under fluctuating influent conditions (Figure 1).

Mine water inflow exhibits pronounced temporal variability and compositional drift, which undermines long-term consistency when regulation relies primarily on operator experience [16,18]. For filtration, the triggering logic and intensity of backwashing materially affect solids' release and performance recovery, and they determine the usable operating window in the subsequent cycle [19]. In industrial equipment, PLC-based logic is widely adopted for sequential control and interlock protection, because it offers explicit, verifiable switching rules and dependable actuation [20]. However, much of the existing discussion on automation and intelligence remains conceptual, and it rarely defines an engineering minimum set that separates mandatory control functions from optional enhancements in integrated mine water equipment [21,22], limiting the role of system stability in supporting SDG 6 and SDG 12, while also constraining its contribution to SDG 9 in terms of infrastructure resilience and industrial system innovation.

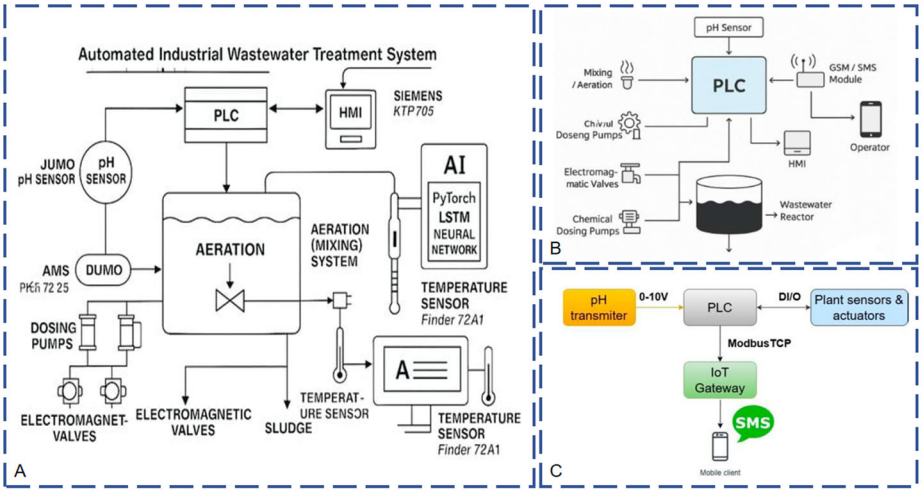


Figure 1. Integrated hydrocyclone–filtration wastewater treatment system with automatic control. (**A**) Conceptual diagram illustrating system-level automatic control objectives and feedback logic; the control logic shown is intended for conceptual demonstration only and does not represent a site-specific engineering design. (**B**) Overall architecture of the wastewater treatment system, showing the arrangement of main functional units and flow paths. (**C**) Interfaces between key components, highlighting hydraulic connections, control signals, and information exchange [17].

On this basis, this review adopts stable system operation as the central objective, synthesizing recent progress on hydrocycloning and filtration for high-suspended-solids mine water while shifting the evaluation target from standalone unit performance to stability and maintainability of the operating chain [23]. In engineering terms, system stability refers to the ability of the integrated hydrocyclone–filtration unit to operate within defined operational envelopes, characterized by bounded pressure-drop growth, controlled-solids split ratio between overflow and underflow streams, and recoverable filtration resistance development. This paper starts from influent variability, formulates the bidirectional constraints between hydrocycloning and filtration, and summarizes representative integrated architectures and their load allocation logic, including the role of bypass and sludge discharge pathways in preserving steady operation [14]. Building on these insights, a minimum closed-loop control framework is proposed to map essential monitoring variables to essential control actions, enabling implementable guidance for system design and equipment selection [19].

2. Literature Review Methodology

To ensure the comprehensiveness and scientific validity of this literature review, this study conducted a systematic screening and analysis of relevant literature within the field. This review primarily utilized databases such as Web of Science, Scopus, and Google Scholar, employing keyword searches and systematic literature-screening procedures. The literature covered in this review spans the period from 2006 to 2026, encompassing research advancements over the past two decades; notably, literature published within the last five years accounts for over 90% of the retrieved material, while earlier literature was selected only if it constituted foundational, classic works within the field. Inclusion criteria for literature comprised peer-reviewed research articles, monographs, and conference papers addressing relevant themes, such as mine water treatment, high-suspended-solids concentrations, and water treatment technologies. Exclusion criteria included non-peer-reviewed literature, works unrelated to the subject matter, and documents published more than 20 years ago—as well as those published 5 to 15 years ago that have largely been superseded by more recent research—or literature lacking sufficient data. For the selected

literature, this study comprehensively evaluated factors such as journal impact factors and citation counts to ensure the authority and quality of the review's content.

3. Mechanisms of Fine Particle Separation in Swirling Flow and Filtration

3.1. Characteristics and Flow Regimes of High-SS Mine Water

The engineering complexity of high-suspended-solids mine water originates from the particulate system itself [24]. As shown in Table 1, influenced by geological conditions and mining operations, mine drainage typically exhibits significant variability in terms of pH, suspended solids, dissolved metals, and sulfate concentrations. Unlike conventional industrial wastewater, mine water contains particles spanning several orders of magnitude, with irregular morphologies and pronounced density contrasts [25–27]. During active mining, the solids volume fraction commonly remains at a high level, with solid concentrations typically ranging from 1% to 10%, forcing the influent to behave as a concentrated multiphase suspension dominated by interparticle interactions. The suspension's rheology can be described by Bingham or Herschel–Bulkley models ($\tau = \tau_0 + \mu_k\gamma$ or $\tau = \tau_0 + K(\gamma)\hat{}n$), with yield stresses reported between 50 and 300 Pa. Transport and separation processes are constrained by bulk rheological responses, with Reynolds numbers typically between 1 and 100, indicating laminar to transitional flow, and Froude numbers affecting sedimentation stability [28]. Transport and separation processes are therefore constrained by bulk rheological responses [29,30].

Table 1. Typical physicochemical characteristics of mine wastewater reported in the literature.

Parameter	Typical Range	Notes	Reference
TSS	1–100 $g \cdot L^{-1}$	Can exceed tens $g \cdot L^{-1}$ during peak inflow	Wei et al. (2018) [31]
pH	2–9	Acidic in sulfide oxidation systems	Hao et al. (2025) [32]
Fe	1–500 $mg \cdot L^{-1}$	Dominant dissolved metal	Jin et al. (2020) [33]
Mn	0.1–50 $mg \cdot L^{-1}$	Often persistent after neutralization	Du et al. (2025) [34]
Sulfate	200–3000 $mg \cdot L^{-1}$	From pyrite oxidation	Butler et al. (2018) [35]
Total dissolved solids	500–5000 $mg \cdot L^{-1}$	Varies by geology	Wei et al. (2018), Du et al. (2025) [31,34]

In field operations, this intrinsic complexity is not static; instead, it is continuously reshaped by irregular drainage conditions. Changes in mining rhythm, switching of active working faces, and adjustments in drainage strategies can rapidly alter solids concentration, particle size distribution, and volumetric flow rate [24]. These disturbances typically overlap, producing multi-dimensional inlet variability that cannot be captured by conventional design envelopes. As a result, treatment units are forced to operate under persistently unsteady Operational Boundaries, in which inlet characteristics fluctuate on timescales comparable to or shorter than the internal hydraulic response time. Internal flow fields, vortex structures, and separation interfaces therefore remain in a quasi-transient state and are unable to stabilize. Under such operating regimes, parameter settings derived from steady-state assumptions or long-term averaged feed properties systematically underestimate disturbance intensity and fail to represent real operating windows, leading to chronic performance mismatch and elevated operational risk [25].

From a separation mechanism perspective, high-solids loading fundamentally alters particle transport behavior. Frequent collisions, transient aggregation, and repeated

re-dispersion dominate the particulate dynamics, making single-particle force balances inadequate [28,36,37]. Particle trajectories are jointly controlled by local concentration gradients and collective migration patterns, while turbulent structures reorganize transport pathways. Consequently, separation boundaries evolve in time rather than remaining fixed, giving rise to fluctuating capture loads and unstable separation sharpness [29].

As summarized in Table 2, these effects render hydrocycloning and filtration processes inherently dynamic in high-SS mine water treatment. Separation efficiency, cut size, and fouling behavior depend on both instantaneous inlet conditions and the evolving internal structure of the suspension. When propagated across integrated treatment systems, moderate unit-level fluctuations may accumulate and amplify, ultimately manifesting as process instability, accelerated fouling, and loss of separation controllability.

Table 2. Key characteristics of high-SS mine water and their implications for separation and filtration behavior.

Key Characteristic	Representative Quantitative Range	Effect on Separation Behavior	Effect on Filtration Behavior
High-solids concentration	Suspended solids typically 1–100 $g \cdot L^{-1}$ (occasionally higher in peak inflow)	Particle interactions dominate, separation boundaries become unstable	Rapid resistance buildup and reduced recoverability
Broad particle size distribution	Particle size commonly 1–500 μm, with significant fine fraction <10 μm	Diffuse cut size and increased fine particle misplacement	Simultaneous surface and internal clogging
Non-dilute rheology	Apparent viscosity often 2–10× that of water depending on solids loading	Deviation from classical flow assumptions	Nonlinear head loss growth
Strong temporal variability	Solids concentration fluctuations often >50% within short operating periods	Time dependent and history sensitive separation performance	Unsteady fouling dynamics and fluctuating operating margins

3.2. Particle Motion and Classification Mechanism in the Cyclone Separation Process

Hydrocycloning is widely applied in the treatment of high-suspended-solids mine water because it can provide high throughput pre-separation within a compact and robust unit, which is particularly suited to space-constrained underground or near shaft installations, as illustrated in Figure 2. Its widespread adoption is not only a consequence of structural simplicity but also reflects its ability to tolerate large fluctuations in flow rate and solids loading that commonly occur in mining operations. From a mechanistic perspective, particle motion inside a hydrocyclone cannot be attributed to a single dominant force. Instead, particle migration emerges from the combined action of centrifugal acceleration generated by swirling flow, hydrodynamic drag imposed by the carrier fluid, and turbulent shear arising from strong velocity gradients. These effects act simultaneously and interact with each other, forming a complex force balance that governs particle trajectories rather than a simple deterministic pathway.

For engineering interpretation, the overall separation performance of a hydrocyclone is commonly characterized by the cut size, d_{50}, which can be expressed in a simplified empirical form as follows:

$$d_{50} = K\left(\frac{\mu}{\rho_p - \rho_f}\right)^{\frac{1}{2}}\left(\frac{D_c}{V_i}\right) \quad (1)$$

where d_{50} denotes the cut size corresponding to a 50% probability of reporting to either the overflow or underflow stream; K is an empirical constant dependent on cyclone geometry and operating conditions; μ represents the dynamic viscosity of the carrier fluid; ρ_p and ρ_f denote the particle density and fluid density, respectively; D_c is the cyclone body diameter; and V_i is the inlet velocity.

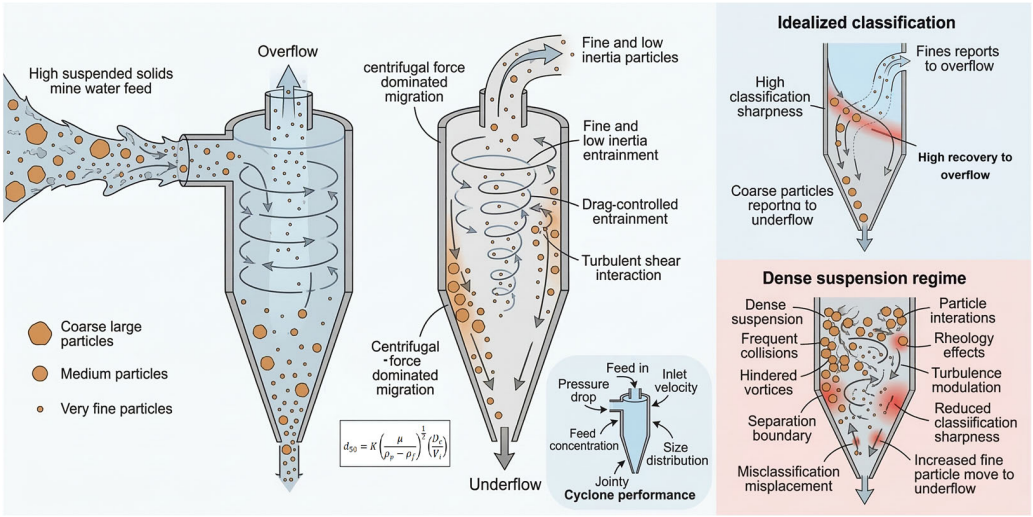


Figure 2. Particle motion and classification mechanism in hydrocyclone separation.

Under idealized conditions, this coupled force environment leads to a characteristic classification pattern. Larger or denser particles experience stronger outward radial migration and are preferentially driven toward the outer vortex region, where they move downward along the wall and eventually discharge through the underflow. Finer or lower-density particles are more strongly coupled to the fluid motion and therefore tend to follow the inner vortex upward, exiting with the overflow stream [38]. Classical hydrocyclone performance prediction has long relied on empirical or semi-empirical formulations, particularly the Plitt model and the Nageswararao model, which are widely used in industrial simulation studies [39,40]. However, these models were developed mainly from calibration datasets under relatively dilute slurry and near-steady operating conditions, and they represent cyclone performance through fitted relationships for variables such as cut size, flow split, and classification sharpness, rather than through explicit treatment of particle–particle interactions, suspension rheology, or turbulence modulation. Their predictive capability under high-solids mine water conditions is therefore limited unless additional calibration or correction is introduced [29,41]. This general description, while conceptually useful, represents only a limiting case.

As the solids fraction increases, particle–particle interactions become increasingly frequent, and the suspension departs from dilute behavior. At high-solids concentrations, the suspension may depart markedly from dilute-slurry behavior, and traditional empirical models such as the Plitt and Nageswararao formulations may no longer predict separation efficiency reliably without recalibration [39,40]. Dense suspension rheology begins to influence local flow resistance, and particle interference disrupts the orderly separation implied by single-particle motion. These models fail to account for the yield-like behavior of the suspension and the increased turbulence effects, which significantly affect the separation sharpness. Under such conditions, the effective separation boundary becomes diffuse, classification sharpness deteriorates, and the probability of fine particle misplacement increases markedly [29].

The internal flow field structure plays a decisive role in determining whether these deviations remain manageable or evolve into persistent instability. Key features such as

the position and extent of the recirculation region, the axial velocity distribution along the cyclone axis, and the strength and coherence of local vortex structures jointly define the separation environment. Small shifts in these features can significantly alter residence time distributions and radial migration paths, thereby amplifying the sensitivity of separation performance to upstream disturbances [38]. In practical systems, operating pressure drops for hydrocyclones treating high-suspended-solids suspensions, typically falling within 50–200 kPa, and variations within this range can significantly influence centrifugal intensity and classification behavior. Such variations are difficult to represent using classical empirical formulations because they do not explicitly account for suspension rheology, turbulence modulation, or particle–particle interactions under high-solids loading [42]. In practical operation, fluctuations in feed concentration or particle size distribution can therefore trigger disproportionate changes in overflow quality, even when nominal operating parameters remain unchanged.

The pressure drop across a hydrocyclone can be approximated using a conventional hydraulic loss relationship:

$$\Delta P = \xi \frac{\rho V_i^2}{2} \tag{2}$$

where ΔP represents the pressure drop across the hydrocyclone; ξ is the dimensionless loss coefficient determined by cyclone geometry and internal flow structure; ρ denotes the fluid density; and V_i is the inlet velocity.

For this reason, the engineering objective of cyclone design and operation has gradually shifted away from the pursuit of peak separation efficiency under idealized conditions. Instead, greater emphasis is placed on the ability of the system to accommodate disturbances, suppress excessive fine particle carryover, and maintain acceptable performance across a broad range of realistic operating scenarios [43]. This shift is reflected in recent reviews that frame cyclone optimization as a problem of coordinated trade-offs rather than single parameter tuning, highlighting scalability issues in applying traditional models under high-solids conditions. Geometry selection, operating conditions, energy demand, and classification sharpness are increasingly treated as interdependent variables that must be balanced against each other rather than optimized in isolation [38,44]. In practice, improvements in separation sharpness often require higher inlet pressures or stronger swirl intensity, which can increase hydraulic losses and energy demand, highlighting the need to balance separation efficiency with operational stability [45].

Within this context, feed particle size distribution has emerged as a critical control factor. Experimental and numerical studies consistently indicate that changes in size distribution can strongly reshape the grade efficiency curve and shift the effective cut size, often exerting a first-order influence on fine particle outcomes [46]. Broad or bimodal distributions intensify particle interference, while an increased fine fraction modifies local viscosity and turbulence, complicating separation behavior. These effects persist even when average solids concentration remains constant, highlighting that bulk indicators alone are insufficient for predicting cyclone performance under high-solids conditions, while techniques such as high-speed PIV and X-ray tomography support validation of dense-suspension models.

It is important to recognize the limits of the current modeling approaches when interpreting these phenomena. Computational fluid dynamics and related simulation tools are highly valuable for diagnosing internal flow topology and identifying relative trends associated with geometric or operational changes. However, under dense suspension conditions, turbulence modulation, particle collision effects, and dispersion closures remain strongly model dependent. As a result, quantitative predictions of separation efficiency

and fine particle misplacement often carry significant uncertainty and typically require validation against independent experimental measurements or field observations [47].

To improve interpretability, particularly for fine particle behavior, recent work has attempted to explicitly incorporate specific misclassification phenomena into modeling frameworks. One example is the representation of fishhook behavior (non-monotonic separation efficiency for fine particles), which seeks to capture the anomalous increase in fine particle recovery to the underflow observed under certain operating conditions [48]. While such approaches offer valuable insights into the mechanisms underlying fine particle misplacement, their applicability remains constrained by assumptions regarding particle interactions and flow structure. Consequently, they are best viewed as complementary diagnostic tools rather than fully predictive substitutes for experimental or operational evidence.

3.3. Load Evolution and Clogging Mechanisms in Filtration Processes

In contrast to hydrocyclone separation, filtration units in mine water treatment serve as the final control barrier for effluent quality, which means that their hydraulic condition directly determines whether the overall system can maintain stable operation under variable loading conditions, as illustrated in Figure 3. Once the filtration stage loses hydraulic stability, upstream separation performance becomes largely irrelevant from a compliance perspective. Filtration must therefore be understood as an inherently time-dependent process, as solids retention continuously alters the internal structure of the filter medium and, in turn, the available flow paths through which water can pass. This makes it particularly sensitive to cumulative loading effects and fluctuating influent. This temporal evolution distinguishes filtration from upstream classification processes and makes it particularly sensitive to cumulative loading effects.

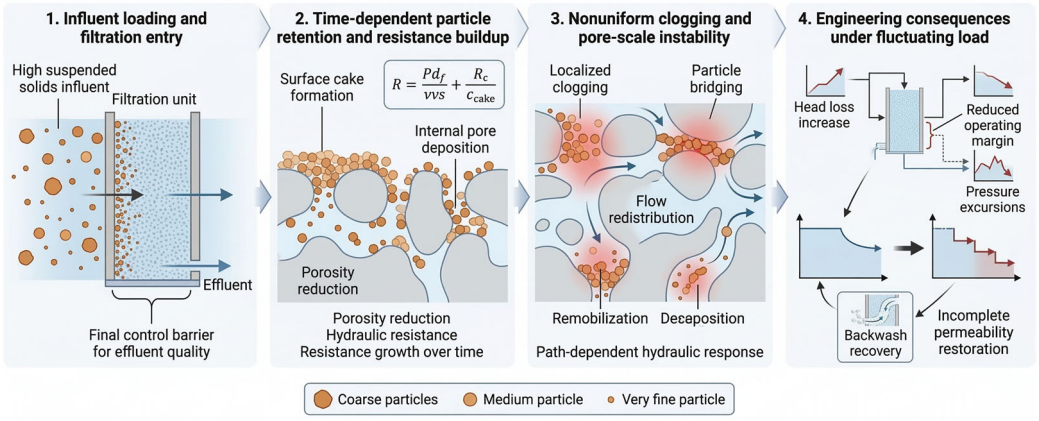


Figure 3. Dynamic clogging mechanisms and hydraulic response in high-solids filtration.

The filtration rate is commonly described using the classical resistance model:

$$\frac{dV}{dt} = \frac{A\Delta P}{\mu(R_m + R_c)} \tag{3}$$

where $\frac{dV}{dt}$ denotes the volumetric filtration rate; A is the effective filtration area; ΔP represents the pressure difference across the filter medium; μ is the dynamic viscosity of the fluid; R_m denotes the intrinsic resistance of the clean filter medium; and R_c represents the resistance of the cake layer formed by deposited particles.

Under high-suspended-solids conditions, particles are deposited rapidly both on the surface of the filter medium and within pore throats. Reported particle deposition rates range from 5 to 20 g $m^{-2} \cdot h^{-1}$ [49], which accelerates clogging and reduces filter

permeability over time [50,51]. As deposition proceeds, the effective porosity decreases and hydraulic resistance increases steadily, leading to a persistent rise in head loss and a progressive narrowing of the operating margin. Even when influent quality remains within nominal design limits, this gradual resistance buildup reduces the system's ability to absorb additional disturbances. When influent load fluctuates, which is common in mine drainage systems, the spatial pattern of permeability loss can change significantly. Instead of developing uniformly across the filter bed, resistance growth may become strongly localized. Regions exposed to higher seepage velocities or locally elevated solids flux experience accelerated clogging, which explains the sudden pressure drop excursions and step-like capacity losses frequently observed in practice [52,53].

At the scale of the porous medium, resistance growth cannot be described solely as a monotonic process of pore filling. Hydraulic resistance typically increases at rates of 0.5–5 $kPa \cdot h^{-1}$, especially under fluctuating flow conditions and varying solids loading [54,55]. Multiple retention and removal mechanisms often coexist and interact over time. At the inlet face, cake formation can dominate early stages of filtration, imposing an additional resistance layer that controls overall head loss. Deeper within the bed, however, deposited particles may be subject to erosion or remobilization as local shear conditions evolve, especially under fluctuating flow rates. These internal rearrangements can partially reopen blocked pathways while simultaneously promoting deposition elsewhere, resulting in a resistance trajectory that reflects the balance between accumulation and redistribution rather than simple clogging progression [56].

Pore scale observations provide further insight into why filtration behavior under high suspended solids often appears abrupt and nonlinear. Experimental studies have shown that clogging can develop through the formation of particle-bridging structures that span across pore spaces. Once such bridges form, they can expand rapidly, capturing additional particles and triggering an abrupt collapse in permeability. This mechanism explains why filtration systems may operate seemingly stably for extended periods before experiencing sudden failure events. It also accounts for the strong path dependence observed under load swings, where the same average influent conditions can lead to very different hydraulic responses depending on the sequence and magnitude of prior disturbances [55].

These characteristics imply that filtration performance under high suspended solids is governed as much by the kinetics of resistance growth as by the instantaneous removal efficiency. Designs that focus primarily on initial filtration performance or nominal removal rates risk overlooking the cumulative and irreversible aspects of clogging. For mine water applications subject to repeated fluctuations in solids' load and flow rate, filtration design should therefore prioritize the rate at which resistance develops and the extent to which permeability can be recovered through cleaning or backwashing operations [57,58]. Emphasizing resistance evolution and recoverability provides a more realistic basis for ensuring long-term stability and addressing scalability issues than relying on short-term performance metrics alone. The progressive linkage between particle deposition, hydraulic resistance growth, and flux instability is schematically summarized in Figure 4.

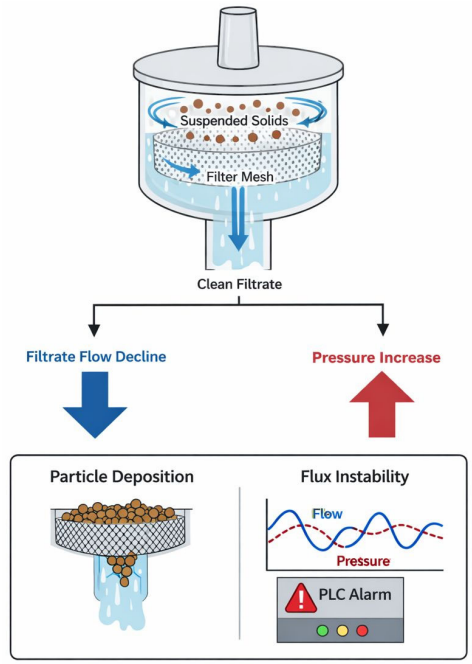


Figure 4. Schematic illustration of deposition-driven instability in cyclone–filtration systems.

3.4. Implications of Mechanistic Understanding for Integrated System Design

From a mechanistic perspective, the hydrocyclone and the filtration process form an interconnected chain of risks, rather than a simple upstream–downstream relationship, as shown in Figure 5.

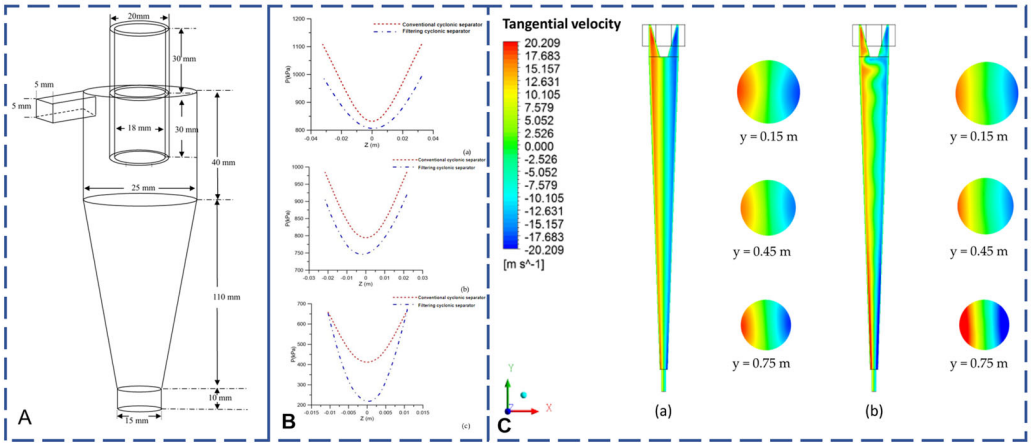


Figure 5. Coupled cyclone–filtration interactions under high-suspended-solids conditions. (**A**) Schematic diagram of a multi-outlet membrane-type hydrocyclone [59]. (**B**) Pressure profiles comparing conventional and filtering hydrocyclones at different axial positions: (**a**) y = 0.15 m, (**b**) y = 0.45 m, and (**c**) y = 0.75 m. (**C**) Water tangential velocity field in the yz plane: (**a**) conventional hydrocyclone and (**b**) filtering hydrocyclone [60].

Hydrocyclone performance determines the solids spectrum delivered to the filter, and the filter then becomes the first unit to expose instability once the upstream buffering fails, typically manifested by rapid pressure-drop growth, accelerated filtration resistance development, or abnormal solids breakthrough. Recent work on hydrocyclone-derived swirling membrane filtration concepts demonstrates that strong rotational shear can suppress particle deposition on porous surfaces, indicating that hydrodynamic design and load management are therefore central to maintaining bounded pressure-drop growth and controlled-solids loading, rather than relying solely on media selection [60]. For integrated

equipment, the design target is therefore not peak unit efficiency but a stable load handoff that maintains solids loading and pressure drop development within defined operational envelopes, keeping the filter away from irreversible clogging regimes, consistent with hydrocyclone pretreatment being used primarily to protect downstream membrane elements from clogging under elevated suspended solids [61]. This interpretation is consistent with filtering hydrocyclone concepts, where separation and permeation are structurally coupled to reshape the solids split and reduce downstream burden, emphasizing that architecture choices can function as a stability lever rather than a packaging decision [62].

4. Structure and Engineering Implementation of Integrated Swirl Flow and Filtration Equipment

4.1. Engineering Motivation and Overall Approach of Integrated Structural Design

In high-TSS mine water treatment, the dominant engineering constraint is often not whether individual unit operations can meet nominal compliance targets, but whether the overall system can sustain a sufficiently wide reliability window under the combined effects of influent variability and long-term continuous operation requirements [63]. In this review, high-TSS mine water refers to conditions where suspended-solids concentrations typically exceed 1–10 $g \cdot L^{-1}$ and may reach several tens of $g \cdot L^{-1}$ during peak inflow events. In coal-mining drainage systems, total-suspended-solids concentrations of several thousand $mg \cdot L^{-1}$ have frequently been reported, with measured values reaching up to 5400 $mg \cdot L^{-1}$ under high-TSS conditions [64]. However, when mine water is discharged to receiving surface waters, environmental regulations impose significantly stricter limits on effluent quality. For example, the Chinese Integrated Wastewater Discharge Standard (GB 8978-1996) specifies a suspended-solids limit of 70 $mg \cdot L^{-1}$ for mining and mineral processing wastewater under the Grade-I discharge standard, while pH is required to remain within 6–9 [65].

Under these regulatory constraints, treatment systems must operate with a sufficiently wide reliability margin to accommodate fluctuations in influent characteristics. In practice, even when hydrocyclones and filtration units are each capable of achieving acceptable performance under controlled conditions, their series operation under fluctuating loads tends to compress the margin between normal operation and failure. This compression becomes the primary source of operational risk in high-solids environments, where disturbances are frequent and recovery times are long.

These challenges are further intensified in underground or semi-underground deployments. In such settings, available footprint, access for maintenance, and space for installing redundant units are all severely constrained. As a result, treatment systems often rely on a limited number of compact units operating close to their design limits. Under these conditions, distributed treatment trains are more likely to convert local upsets into plant-wide shutdown events, because there is insufficient buffering capacity to isolate disturbances or reroute flow during transient failures [24]. What might be a manageable deviation at the level of a single unit can therefore propagate rapidly across the system, leading to loss of overall operability [66].

As water reuse requirements increase and discharge standards become stricter in mining operations, treatment systems are increasingly required to operate for extended periods under high-solids loading and elevated recycle ratios. In such regimes, short-term transients that would previously have been absorbed without consequence now translate directly into increased operational expenditure, unplanned downtime, and heightened environmental risk [3,67]. Continuous operation under these conditions leaves little room for error, and the cumulative impact of repeated minor disturbances can be as damaging as rare extreme events.

Field experience has consistently shown that when hydrocyclones and filters are configured as fully separate units in series, transient losses in pre-separation performance are transmitted to the filtration stage with minimal attenuation. Sudden increases in fine particle carryover or short-term shifts in particle size distribution can rapidly accelerate head loss development in the filter, triggering clogging-driven trips and forcing premature cleaning or shutdown. In this configuration, the filtration unit effectively bears the full consequence of upstream instability.

Against this background, the overall approach of integrated structural design is motivated by the need to reduce this direct coupling. Rather than relying solely on active control or oversized downstream capacity, structural integration aims to passively shave load peaks within the hydraulic path and functional zoning of the equipment. By shortening internal flow pathways and deliberately reshaping recirculation patterns, integrated designs seek to dampen the transmission of upstream disturbances and lower the effective coupling gain from hydrocyclone to filter. In this way, structural integration becomes a means of enhancing system robustness under realistic operating variability, rather than merely a compact packaging solution [68].

4.2. Typical Integrated Configurations and Their Structural Characteristics

Most integrated treatment units for high-TSS mine water continue to follow a backbone arrangement in which hydrocyclone separation precedes filtration (Table 3). Within this general framework, however, decisive structural differences arise from how tightly the two functions are coupled. Key design dimensions include whether the cyclone and filtration sections share a common pressure vessel, whether inlet and outlet interfaces are merged or kept separate, and how effectively the underflow discharge region is isolated from the filter feed zone [69]. These structural choices determine not only footprint and layout feasibility but also the degree to which upstream disturbances are transmitted or attenuated before reaching the filtration stage.

Table 3. Typical integrated hydrocyclone–filtration configurations and their structural characteristics.

Configuration Type	Structural Coupling Feature	Representative Studies	Reported Operational Outcomes/ Comparative Metrics	Main Advantage	Key Structural Risk
Conventional series arrangement	Cyclone and filtration units installed as independent modules	Wills & Finch, (2016) [70]	Cyclone removes 40–80% coarse solids, reduces filtration load	Clear separation, flexible control	Large footprint, limited buffering
Shared pressure vessel integration	Cyclone and filter housed within a common shell	Liu et al. (2024) [14]	Reduces system footprint by 30%, improved hydraulic continuity	Compact, fewer external pipes	Stronger internal coupling, less isolation
Tightly coupled integrated design	Minimal hydraulic distance between cyclone underflow and filter feed	Ekechukwu et al. (2024) [71]	15–25% increase in throughput, mitigates membrane fouling	Short flow paths, high density	Internal short-circuiting under fluctuating loads
Filtering hydrocyclone-based design	Filtration elements embedded within swirling flow	Vieira et al. (2005); César et al. (2025) [72,73]	Intercepts fine particles early, reduces filtration burden by 20–40%	Early capture, load redistribution	Higher complexity, limited operational data

Integrating the cyclone and filter chamber within a single pressure shell offers clear advantages under underground deployment constraints. A shared vessel can substantially reduce the number of external manifolds, valves, and interconnecting pipes, simplifying installation and lowering the risk of leakage or mechanical failure in confined

spaces. At the same time, this level of physical integration reduces the availability of external control points. As a consequence, controllability must be regained through internal design measures, including stricter flow guidance, well-defined internal boundaries, and explicit anti-short-circuit features that prevent unintended mixing between functional zones [68]. Without such measures, compactness can be achieved at the expense of operational robustness.

A critical vulnerability in tightly integrated designs arises when the boundary between the cyclone underflow-handling zone and the filter feed zone is insufficiently defined. This can lead to localized short-circuiting, where solids are unintentionally recycled back into the filtration zone, increasing the risk of clogging and energy inefficiency. If this boundary becomes ambiguous, local recirculation structures can form that re-entrain coarse solids or high-concentration slurry back into the filtration side. Under fluctuating loading conditions, such internal short circuits can rapidly nullify the buffering function of pre-separation, exposing the filter to solids loads it was not intended to handle. This failure mode is particularly problematic because it may not be evident from external measurements until accelerated head loss or clogging has already occurred.

To address these challenges, several unconventional structural designs, such as the one shown in Figure 6, have been proposed, aiming to reshape the interaction between swirling flow and filtration. Filtering hydrocyclones and filtration-enabled cyclone geometries introduce screening or permeation functions directly within the swirling field, allowing separation and filtration to proceed in parallel rather than strictly in series [13,62]. By intercepting fine particles earlier and redistributing solids within the vortex, these concepts aim to reduce the burden on downstream filtration while maintaining acceptable energy demand. Although such designs are still evolving, they illustrate how internal architecture can be used to reshape solids partitioning rather than merely compress existing unit operations into a smaller footprint.

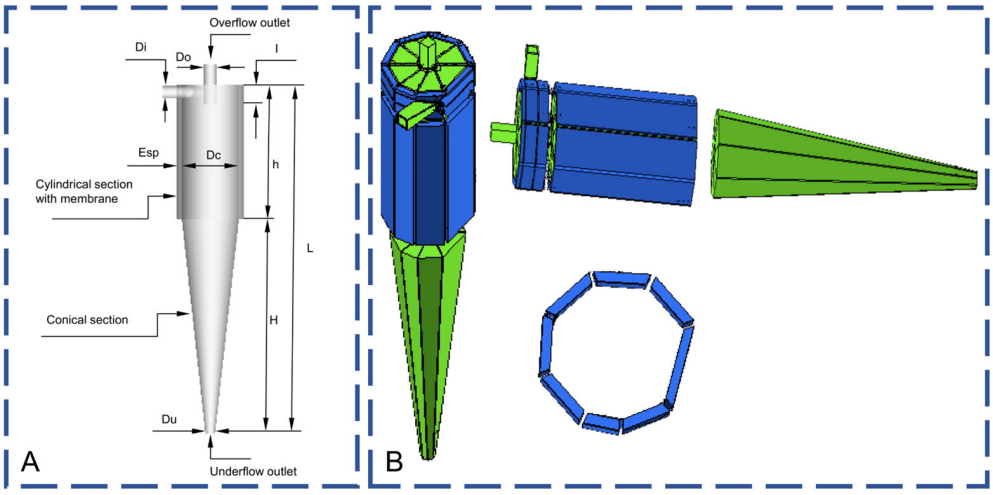


Figure 6. Filtering cylindrical hydrocyclone configuration. (**A**) Structural schematic of a filtering cylindrical hydrocyclone (HciF), presented as a conceptual design rather than an experimentally validated configuration. (**B**) Schematic representation of the filtering cylindrical hydrocyclone, also intended for conceptual illustration [13].

Related work coupling swirling hydrodynamics with membrane filtration has further demonstrated that shear intensity and near-wall turbulence structures exert a strong influence on particle deposition and fouling kinetics [60]. Elevated rotational shear can delay the formation of stable deposits and promote periodic detachment, thereby modifying resistance growth behavior without relying solely on material selection or chemical cleaning. These findings provide testable mechanistic levers for internal channel and surface

design in integrated equipment, linking flow field characteristics directly to long-term filtration performance.

Despite these advances, experience under highly variable loading conditions suggests that robustness often benefits from maintaining explicit functional zoning within integrated systems. Designs that clearly separate underflow discharge, filter feed, and cleaning loops using baffles, flow directors, and defined bypass routes tend to exhibit more predictable behavior. By reducing unintended interactions between zones, such arrangements limit the number of effective control degrees of freedom, making it easier to manage scalability issues and ensuring more predictable performance under fluctuating loads. In this sense, structural clarity, rather than maximal compactness, becomes a key determinant of stable operation when treating high-TSS mine water under realistic field conditions.

4.3. Engineering Implementation of Wear-Resistant and Anti-Clogging Structures

Under high-TSS mine water conditions, wear and erosion are not spatially uniform, and the damage pattern is typically governed by where particles repeatedly impact and where energy is dissipated most intensely [74]. Experimental and numerical studies indicate that erosion rates in hydrocyclone wall regions exposed to high particle impact may reach 10^{-6}–10^{-4} $kg \cdot m^{-2} \cdot s^{-1}$, depending on particle concentration, velocity, and slurry properties. In engineering terms, this corresponds roughly to wall material losses in the order of 0.05–1 mm per year under moderate conditions, while highly abrasive slurries may produce erosion rates approaching 1–5 mm per year [75]. In practical hydrocyclone and integrated channel layouts, near-wall regions in the conical section, the underflow outlet, and sharp turning channels are consistently high-risk zones, because particles concentrate toward the wall while the flow field imposes strong curvature and velocity gradients. The consequence is not only material loss, but also gradual geometric deformation in locations that are hydraulically sensitive.

Wall degradation then feeds back into separation behavior. As the surface roughness evolves and local profiles drift, the near-wall boundary layer and secondary flow structures are altered, which can change the effective residence time distribution and local mixing intensity. This creates a performance trajectory that often drifts slowly at first, appearing manageable in routine operation, and then destabilizes rapidly once small geometric changes push the internal flow field across a sensitivity threshold [76]. In this context, wear resistance cannot be treated as a purely mechanical durability problem. It must be evaluated together with hydrodynamic sensitivity, because the operational consequence of wear is defined by how strongly small wall changes perturb classification and discharge behavior.

Recent numerical and experimental work has provided a more actionable basis for engineering implementation by quantifying erosion distributions inside hydrocyclones [77]. This enables targeted reinforcement rather than uniform overdesign. Vulnerable regions can be equipped with structural redundancy and replaceable liners so that wear is managed as a planned maintenance event. In industrial practice, liner materials such as polyurethane, high-chromium cast iron, and alumina ceramics are widely used. Compared with mild steel, these materials typically provide several fold improvements in erosion resistance depending on slurry properties and particle impact velocity. Crucially, this can be achieved without materially increasing pressure demand, because the goal is to protect hydraulically critical surfaces while preserving the intended flow topology.

At the spigot and sand discharge path, geometric details are equally decisive, not only for wear but also for blockage and misclassification. The discharge path is a stability hinge. If the spigot region becomes partially obstructed or its effective diameter drifts, studies have shown that even a 10–20% reduction in effective spigot diameter can significantly alter

the underflow split ratio and increase fine particle misplacement; also, the underflow split changes, the internal recirculation pattern shifts, and fine particle carryover can increase. Accordingly, spigot structure optimization has been shown to improve discharge stability within a practical operating envelope, which directly supports stable operation under realistic fluctuation conditions [78].

For integrated units, the engineering principle is to treat wear and anti-clogging as a combined strategy rather than isolated material upgrades. The objective is to identify hotspots, reduce local scour where it triggers hydraulic sensitivity, and ensure that unavoidable degradation is directed toward components designed to be replaceable. The actual service life of such equipment varies significantly, influenced by factors such as material selection and operational intensity. Steel liners operating in high-solids slurry environments may require replacement within several months, polyurethane liners typically operate for approximately 6–18 months, and ceramic liners can remain in service for one to three years in industrial hydrocyclone applications [79]. Through such design strategies, failures can be transformed from catastrophic and system interrupting events into maintainable and predictable degradation modes, which is a prerequisite for long-duration operation under highly variable mine water conditions.

4.4. Self-Cleaning Mechanism and System Operation in Coordination

Whether the filtration stage can sustain continuous operation under fluctuating loads depends less on the peak aggressiveness of individual cleaning actions than on whether cleaning behavior is predictable, triggerable, and recoverable within the overall operating cycle [11]. In high-TSS mine water systems, filtration inevitably operates close to fouling thresholds, meaning that cleaning must be treated as an integral part of normal operation rather than an exceptional intervention. Cleaning actions are typically triggered when the pressure drop across the filter exceeds 20–40 kPa or when the pressure-drop growth rate reaches 0.5–2 kPa/h. If cleaning actions occur in an ad hoc manner or rely solely on conservative safety margins, they tend to erode operational stability by introducing unnecessary interruptions and hydraulic disturbances.

From a mechanistic standpoint, cleaning strategies must manage a dynamic trade-off between preserving filtration flux and avoiding fouling rebound. Aggressive cleaning can temporarily restore permeability but may also accelerate irreversible fouling or structural degradation of the medium. Conversely, insufficient cleaning allows resistance to accumulate until recovery becomes incomplete. Simple timer-based triggering schemes are poorly suited to this balance, because they are insensitive to actual fouling state and often amplify energy consumption and wash water demand without proportionate gains in net production [80].

For membrane and fine filtration systems, experimental and operational studies indicate that embedding hydraulic backwash and chemical-enhanced cleaning within a unified sequence optimization framework can improve overall water recovery and slow the accumulation of irreversible fouling [81,82]. Hydraulic backwash and chemical-enhanced cleaning can typically restore 60–90% of the initial permeability, depending on particle characteristics and the degree of cake consolidation. Rather than treating these actions independently, coordinated sequencing allows each step to operate within its effective window, reducing unnecessary chemical exposure and limiting excessive shear that may destabilize deposited structures. This approach emphasizes consistency and recoverability over maximal instantaneous cleaning intensity.

Adaptive control studies further suggest that robustness to loading variability improves when cleaning triggers are linked to online state variables and continuously corrected during operation [83]. Under conditions characterized by strong water quality

transients and shifting particle characteristics, the sensitivity of performance decay to cleaning parameters becomes a critical factor. If this sensitivity is not explicitly assessed, a cleaning cycle that appears stable under nominal conditions can fail rapidly when exposed to abnormal loads or atypical particle populations [84].

In integrated equipment, self-cleaning cannot be considered in isolation. Cleaning actions must be synchronized with hydrocyclone underflow discharge behavior and bypass logic. Cleaning typically occurs every 2–8 h, depending on the load and fouling rate. If coordination is lacking, transient-flow switching induced by cleaning can re-inject concentrated solids or hydraulic disturbances into the filtration zone, undermining the intended recovery and potentially triggering secondary instability [85]. Effective self-cleaning in integrated systems therefore relies on temporal and hydraulic coordination across unit boundaries, ensuring that recovery actions stabilize rather than destabilize the coupled separation process.

4.5. The Impact of Structural Integration on System Stability

Performance assessment of integrated treatment units should shift away from peak separation efficiency and toward the concept of a stable operating window [86,87]. In this context, stability refers to the range of operating conditions, under a given level of influent variability, within which pressure drop, solids' discharge behavior, and effluent quality remain jointly controllable. This framing recognizes that under high-TSS mine water conditions, short-term efficiency gains are less relevant than the ability to sustain predictable operation without triggering runaway resistance growth or unplanned shutdowns [88].

When the hydrocyclone stage provides sufficient buffering capacity, fluctuations in solids' concentration and particle size distribution are partially absorbed upstream. As a result, the filtration stage operates more frequently within a comparatively stable loading regime. This reduction in load volatility directly lowers clogging risk and reduces the frequency and intensity of cleaning actions. Such effects have been observed in engineered systems where hydrocyclones are explicitly deployed as a pre-removal step to protect downstream filtration elements, confirming that upstream buffering can be translated into tangible gains in operational stability.

To convert structural synergy into practical operability, integrated equipment must embed protection logic and interlocks around observable variables rather than relying solely on nominal setpoints. Process dynamics, including transient shifts in pressure drop, discharge behavior, and internal flow patterns, should be treated as primary inputs to control strategy design rather than as secondary disturbances to be corrected after the fact [23]. This approach aligns structural design with operational logic, ensuring that the system responds to early indicators of instability rather than to fully developed failures.

For implementation, monitoring and state classification play a critical role because they translate latent instability precursors into triggerable actions [89]. Online identification of abnormal hydrocyclone discharge states, such as the onset of roping (a dense, unstable underflow discharge regime), enables timely activation of warning, bypass, or load-shedding measures for the filtration stage [90]. In parallel, data-driven prediction of key internal hydrodynamic states offers a practical pathway to replace experience-based adjustments with state-scheduled operation, further extending the stable operating window without increasing structural complexity [91,92].

5. Progress in the Application of Automation and Intelligent Control in Integrated Equipment

5.1. Control Objectives and Management Boundaries Under Operational Fluctuations

In high-solids mine water applications, once hydrocyclone separation and filtration are physically integrated, uncertainty is not eliminated; instead, it becomes concentrated in rapid-operating state drift and the accumulation of time-dependent risk [93]. Structural integration reduces buffering redundancy at the system level, which means that deviations propagate more quickly through the hydraulic path. Under these conditions, the dominant engineering challenge is not the sophistication of control algorithms, but the ability to respond with low latency, recognize emerging risks at an early stage, and apply protective actions that are stable and repeatable over long operating periods [94].

When suspended-solids concentration, particle size composition, and flow rate fluctuate in a coupled manner, deviations in pressure drop and filtration flux typically emerge earlier than changes in effluent quality [95]. These hydraulic indicators act as leading signals of instability, while effluent quality often lags due to internal storage and mixing effects. In industrial monitoring practice, pressure and flow sensors used for hydrocyclone–filtration systems are typically sampled at 1–10 Hz, which is sufficient to capture hydraulic fluctuations while maintaining signal stability in slurry environments. As a result, control objectives should be framed around equipment safety, recoverability, and disturbance tolerance rather than peak single-pass separation performance or short-term quality optimization [96]. Prioritizing recoverability ensures that transient excursions do not escalate into irreversible fouling or structural damage, which would impose disproportionate operational penalties.

From an operations-governance perspective, this shift requires the explicit definition of a safe operating window. Such a window can be described using a limited set of observable and enforceable boundaries, including allowable pressure-drop growth rates, acceptable frequencies of cleaning or backwash triggering, and bounded disturbance ranges for purge and bypass actions [97]. These boundaries transform abstract stability concepts into operational constraints that can be monitored, audited, and enforced consistently across shifts and operating conditions. In practical control architectures, these variables are commonly monitored through pressure, flow, and turbidity sensors with PLC response delays typically maintained within 1–5 s, allowing protective actions such as valve switching or cleaning initiation to be executed before instability escalates.

In practice, automation creates value by translating experience-based judgement into rule-based state decisions and fixing them as an auditable logic chain [98–100]. Rather than replacing operators, this approach standardizes responses to recurring situations and reduces variability in decision making. Recent wastewater research increasingly frames anomaly management and resilient control around sensor data quality, early diagnosis, and fault-tolerant operation as the foundation for compliance stability. These elements emphasize reliability and interpretability over optimization complexity.

In parallel, digital transformation and data platformization are pushing operations from reactive maintenance toward condition-driven maintenance. This transition makes interlock protection strategies and maintenance policies easier to formalize, standardize, and replicate across different operating contexts [101]. For mine sites characterized by dust, humidity, and strong electromagnetic interference, reliability must be treated as a hard constraint. Under such conditions, industrial-grade sensors with protective housings and redundant measurement channels are typically preferred to ensure reliable signal acquisition and prevent control failure caused by sensor drift or temporary data loss [102].

5.2. Minimum Perceptual Layer and PLC Rule-Based Closed-Loop Control

The sensing layer of an integrated hydrocyclone–filtration unit should not aim for exhaustive measurement coverage; rather, it should be configured around the principle of risk observability [103]. In high-solids mine water treatment, many failure modes emerge first as hydraulic or discharge anomalies rather than as immediate violations of effluent quality targets. Accordingly, sensor selection should prioritize variables that respond early to load shifts and internal state drift, allowing control actions to be triggered before instability becomes irreversible (Table 4).

Table 4. Key monitored variables and corresponding control actions in an integrated hydrocyclone–filtration system.

Monitored Variable	Indicative System State	Primary Control Action	Control Objective
Cyclone pressure drop	Rapid change in feed load or internal flow resistance	Adjust feed or activate bypass	Prevent separation instability
Underflow discharge state	Onset of abnormal regimes such as roping	Regulate spigot or discharge flow	Maintain stable solids removal
Overflow turbidity or solids proxy	Increased fine particle carryover	Reduce filtration load or trigger protection	Protect downstream filtration
Filter pressure-drop growth rate	Accelerating clogging and reduced recoverability	Initiate backwash or cleaning sequence	Avoid irreversible fouling
Persistent abnormal state	Sustained deviation beyond defined limits	Degraded operation or protective shutdown	Ensure equipment safety and recoverability

On the hydrocyclone side, a limited set of measurements is often sufficient to capture these early indicators. Inlet and outlet pressure difference provides a rapid proxy for changes in feed load and internal flow resistance, while underflow discharge state reflects the stability of solids removal and the onset of abnormal regimes such as roping. Overflow turbidity or solids-related proxies further indicate whether fine particle carryover is increasing beyond the intended buffering capacity of the cyclone [104]. Together, these variables provide a compact yet responsive representation of upstream separation state without requiring direct measurement of particle size distribution in real time.

On the filtration side, the pressure-drop trajectory and flux decay rate more directly reflect clogging accumulation and the changing marginal benefit of cleaning actions. Rather than relying on absolute pressure drop thresholds alone, tracking the rate of change enables earlier recognition of accelerating resistance growth and diminishing recoverability. This temporal information is critical for distinguishing between reversible fouling that can be managed through routine cleaning and irreversible clogging that requires protective intervention [105]. When site data infrastructure is improved, soft sensing and data fusion approaches can be used to supplement hard measurements, combining multiple indirect signals to stabilize state classification for particle or water quality variables that are otherwise difficult to measure reliably. Hybrid PLC–machine-learning control architectures have been reported in full-scale water treatment applications to improve filtration performance and operational stability [106].

At the same time, while deep-learning methods for wastewater-process modeling have matured at the methodological level, their deployment in integrated equipment remains constrained by the need for explicit variable boundaries, consistent data quality, and strict governance frameworks [94]. In practice, data-driven models are most effective when embedded within clearly defined operational envelopes, where their outputs support state recognition and parameter adjustment rather than direct actuation. This positioning preserves interpretability and prevents model extrapolation from undermining operational safety.

PLCs therefore remain the backbone of rule-based closed-loop control in integrated equipment. Their value lies in determinism, auditability, and tight coupling with mechanical actions such as valve switching, pump control, and cleaning execution [107]. Standardized PLC programming languages and structures provide a reusable engineering grammar for implementing sequential control, interlocks, and protective logic, which reduces migration cost and operational inconsistency across different systems and sites [108]. In water automation case studies, the PLC combined with a supervisory monitoring layer is commonly used to unify threshold decisions, action sequencing, and alarm management into a single execution chain, minimizing randomness introduced by manual intervention and ad hoc operator judgement [109].

Within this framework, a minimal closed loop for a hydrocyclone–filtration integrated unit can be defined using a small number of rule sets. These include triggering cleaning actions based on pressure drop evolution rather than fixed schedules, coordinating purge and bypass flows during cleaning to prevent disturbance reinjection, and executing protective shutdown or degraded operation when abnormal states persist beyond defined limits [110]. By constraining control logic to a compact, transparent rule base, such a loop provides reliable stabilization under fluctuating loads while remaining compatible with incremental data-driven enhancements.

5.3. Operational Boundaries and Incremental Value of Data-Driven and Intelligent Control

At a higher level of operational regulation, data-driven methods are most effective when positioned as support tools for setpoint tuning and maintenance decisions, rather than as replacements for interlocks and sequential control logic [111]. In high-solids mine water treatment, safety and recoverability depend on deterministic protective actions, thus limiting the role that adaptive or probabilistic models can directly play in execution. Within this boundary, data-driven approaches add value by refining decisions made within predefined operating envelopes, not by redefining those envelopes on the fly.

Anomaly-detection research in water systems has produced several usable frameworks that align with this role. Hybrid architectures combining representation learning with time-series prediction have been shown to improve alarm accuracy and timeliness under multivariate noise and complex operating regimes [112]. These methods are particularly useful for filtering spurious signals and highlighting deviations that are consistent across multiple variables, thereby supporting earlier and more reliable state recognition without increasing false alarm rates.

Digital twin-based monitoring has also advanced rapidly in recent years. By aligning mechanistic models, data-driven representations, and measurement streams, digital twins provide a unified framework for fault detection and state tracking across unit operations [113]. In integrated hydrocyclone–filtration systems, such alignment is valuable for contextualizing local anomalies within the broader process state, helping operators distinguish between transient disturbances and structural degradation. For filtration-related units in particular, predictive modeling of pressure drop and transmembrane pressure has been widely adopted to quantify fouling rates and assess cleaning effectiveness, providing finer grained evidence to support cleaning trigger policies [114].

In mine water treatment contexts where operating regimes are not easily repeatable and data distributions drift over time, practical intelligence gains typically arise from two specific capabilities. One is the transition from fixed schedule maintenance toward condition-driven decisions, thereby reducing both unnecessary over-cleaning and the risk of sudden clogging-induced losses [115]. The other is the expansion from single-threshold logic to multivariable consistency checks, thus helping to suppress false actions caused by individual sensor drift or temporary measurement faults [17]. These capabil-

ities directly address common operational pain points without introducing additional control complexity.

Experience from integrated control studies further suggests that maintainability is improved when learning models and PLC-based control are combined in a clearly partitioned manner. Learning models are most effective when used to provide recommendations, validation, or confidence assessment, while PLCs retain responsibility for execution, sequencing, and protection [116]. Accordingly, the intelligent development path for hydrocyclone–filtration-integrated equipment should emphasize robustness and maintainability. Progress should be guided by constraints related to data quality, model generalization, and edge deployment cost, rather than by the pursuit of algorithmic novelty alone [101].

6. Current Status of Engineering Applications and Performance Evaluation Comparison

6.1. Engineering Application Scenarios and Typical Operating Modes

Based on published engineering cases and application reports, integrated hydrocyclone–filtration units are primarily deployed in underground pretreatment systems or compact surface installations, where space limitations and continuous drainage requirements dominate design choices [117]. In these applications, the main objective is to reduce high-suspended-solids loading to a manageable level while maintaining uninterrupted mine water removal, rather than achieving peak separation efficiency under isolated or idealized test conditions. The integrated configuration is therefore valued for its ability to operate as a robust front-end treatment step within constrained layouts, supporting downstream processes or direct discharge compliance.

In typical operating scenarios, these units are required to function over extended periods under influent conditions that vary with mining activities, such as changes in production rhythm, working face relocation, or intermittent inflow surges. Solids concentration, particle characteristics, and flow rate often fluctuate simultaneously, placing sustained stress on both separation and filtration functions. Under such conditions, reliability and the presence of controllable failure modes become the dominant evaluation criteria, because unplanned shutdowns or unstable operation directly affect mine safety and production continuity [118].

Compared with laboratory-scale systems, engineering installations place significantly greater emphasis on predictable behavior under non-steady operating conditions. Short-term improvements in removal efficiency are less valuable than the ability to absorb disturbances, recover from transient overloads, and degrade gracefully when limits are exceeded. This shift in emphasis requires both structural design and operational strategies to prioritize long-term stability, maintainability, and clear protective responses over short-term performance metrics that are difficult to sustain in the field.

6.2. Representative Plant-Scale Case Study

Hydrocyclone-based separation systems have been applied at full-scale wastewater treatment plants to improve solids separation in high-suspended-solids environments. A representative example is the installation at the Kochi Municipal Wastewater Treatment Plant in India, which processes 100,000 m^3/day of wastewater. Hydrocyclones were used as a pretreatment stage before biological treatment, where influent wastewater with a suspended-solids concentration of 1500 mg/L was treated to reduce the solids loading on downstream clarifiers. The hydrocyclone units, operating at an inflow pressure of 4 bar, successfully reduced the suspended-solids concentration to 250 mg/L, enhancing the overall settling efficiency and reducing the solids carryover. The system has been in

operation for 18 months, with stable performance observed, including minor fluctuations in pressure drop and overflow turbidity. Long-term operational data showed that the underflow solids were reduced by 45%, leading to significant savings in sludge disposal costs [119].

Another example is the ArcelorMittal Industrial Wastewater Treatment Plant in Belgium, which treats 50,000 m^3/day of industrial effluent with high oil and grease content. In this setup, hydrocyclones were integrated with electrocoagulation to treat the wastewater. Over a 12-month period, the system demonstrated 65% removal of suspended-solids and improved organic contaminant removal by 55%, compared to conventional single-stage treatment systems. This integrated approach also resulted in a 25% reduction in chemical usage for the downstream electrocoagulation stage. The capital expenditure (CAPEX) for the hydrocyclone unit was approximately €180,000, with annual operational costs (OPEX) of €40,000 for maintenance, energy consumption, and chemical savings. The combined system achieved a payback period of approximately 2 years [120].

These case studies demonstrate that hydrocyclone-based separation systems can significantly improve operational stability and performance in large-scale industrial and municipal wastewater treatment applications. The integration of hydrocyclones into multi-stage treatment systems not only enhances solids removal efficiency but also provides significant economic benefits by reducing chemical usage, energy consumption, and overall operational costs.

6.3. Performance Differences Under Different Technological Approaches

Engineering experience indicates that integrated hydrocyclone–filtration units adopting different structural configurations and operating strategies exhibit systematic and repeatable differences in performance. These differences are not limited to separation efficiency metrics; they extend to energy consumption, wear progression, and the breadth of stable operation under variable loading, typically reflected by bounded pressure-drop growth and controlled-solids split ratios. As a result, the choice of technological approach has a direct impact on how the system behaves over time rather than only on its short-term treatment outcome.

Some designs prioritize high-front-end-solids removal by operating hydrocyclones at elevated separation intensity. This strategy can effectively reduce the solids burden delivered to downstream filtration, particularly under moderate and stable influent conditions. However, both an intensified swirling flow and higher pressure drop are typically accompanied by increased energy demand and accelerated wear in hydraulically sensitive regions. Over extended operation, these effects tend to compress the stable operating window defined by acceptable pressure-drop growth and solids loading limits, making system performance more sensitive to disturbances and increasing the likelihood of maintenance-driven interruptions [121].

In contrast, other approaches deliberately operate hydrocyclones at reduced loading and separation intensity, accepting lower peak solids removal in exchange for improved robustness. In these configurations, greater emphasis is placed on maintaining filtration stability, expressed by gradual pressure drop development and predictable resistance growth behavior. Although the immediate separation efficiency may be lower, the system response to influent fluctuations is often more gradual, with slower degradation and clearer recovery pathways. This operating philosophy has been associated with improved long-term sustainability and reduced risk of abrupt failure under realistic mining conditions [122].

These contrasting behaviors highlight the limitations of evaluating integrated systems using single efficiency indicators. Peak removal efficiency or nominal cut size (particle size corresponding to 50% separation probability) alone provides little insight into how a system

will perform under sustained variability. Instead, engineering evaluation benefits from metrics that capture buffering capacity; sensitivity to disturbance; and rates of performance degradation, such as pressure-drop growth rate, solids split ratio stability, and recoverable filtration resistance development. Such indicators better reflect the operational value of integrated hydrocyclone–filtration units and support more informed trade-offs between short-term efficiency and long-term stability.

6.4. Engineering Trade-Offs Regarding Energy Consumption, Land Use, and Operation and Maintenance Requirements

From an engineering perspective, evaluation of integrated hydrocyclone–filtration equipment must simultaneously consider energy consumption, footprint, and operation and maintenance requirements. Structural integration can significantly reduce overall system size, external piping length, and auxiliary equipment, which is particularly advantageous in underground or space-constrained installations. However, under high-suspended-solids loading, integrated configurations often operate at elevated hydraulic intensity, and energy demand may increase accordingly, which can exacerbate issues related to energy inefficiency and system wear. These challenges are particularly evident when dealing with fluctuating load conditions in mine water treatment [2,123]. As a result, practical engineering solutions rarely pursue absolute minimization of power consumption. Instead, they favor stable operation within an acceptable energy envelope that can be sustained over long periods without compromising reliability.

These trade-offs are closely linked to how compactness is achieved. Designs that rely on aggressive flow acceleration or tight internal passages may reduce footprint but tend to amplify sensitivity to load fluctuations and wear. Conversely, slightly larger internal volumes and gentler flow transitions can improve robustness at the cost of marginally higher space requirements. In practice, engineering preference often leans toward configurations that balance compactness with tolerance to variability, recognizing that moderate increases in footprint may yield disproportionate gains in operational stability.

At the operational level, structural complexity and control strategy strongly influence ease of use and maintainability. Integrated systems with clear state indicators, transparent control logic, and limited tuning parameters are more likely to remain serviceable in mining environments characterized by harsh conditions and variable staffing. In contrast, designs that depend heavily on fine-tuning or frequent parameter adjustment place higher demands on operator expertise and maintenance resources, which can limit scalability and increase the risk of performance degradation in dynamic mining environments. Such dependence can limit field adaptability and increase the risk that performance degrades when operating conditions deviate from design assumptions [124].

To enable consistent engineering evaluation and cross-comparison, a minimal standardized performance metric set is defined here, including (i) specific energy consumption per unit treated water ($kWh \cdot m^{-3}$) to reflect hydraulic intensity; (ii) footprint per unit capacity ($m^2 \cdot (m^3 \cdot h^{-1})^{-1}$) to represent spatial efficiency; (iii) pressure-drop growth rate ($kPa \cdot h^{-1}$) as an indicator of resistance accumulation and stability; (iv) solids split ratio stability between overflow and underflow streams to characterize separation robustness; and (v) recoverable filtration resistance after cleaning cycles to quantify maintainability. Together, these metrics capture the essential trade-offs among energy demand, spatial constraint, and long-term operational stability in integrated systems.

6.5. Common Problems Revealed in Engineering Applications

Across reported engineering applications, several common challenges remain evident. Under extremely high suspended-solids conditions, imbalanced internal load distribution can still occur, leading to localized overloads despite overall integration. This issue is

especially problematic because it can result in localized short-circuiting, where solids bypass key separation zones, which exacerbates clogging and operational instability. In addition, the limited accumulation of long-term operational data constrains the depth of performance assessment, making it difficult to fully characterize degradation pathways and lifetime behavior.

Moreover, the absence of unified evaluation criteria across projects introduces uncertainty into cross comparison of different technical solutions. Differences in performance metrics, reporting practices, and operating contexts complicate efforts to generalize conclusions from individual cases. These issues do not indicate the inherent superiority or inferiority of specific approaches but rather reflect the scalability challenges and the need for systematic standardization in future engineering practice to better accommodate fluctuating loads and varying solids concentrations. They also reflect that integrated hydrocyclone–filtration systems remain in a phase of experience accumulation, highlighting clear needs for continued refinement and standardization in future engineering practice.

7. Conclusions and Perspectives

This paper takes high-suspended-solids mine water as a typical complex engineering system and systematically reviews the research progress of hydrocyclone–filtration-integrated equipment from the perspectives of separation mechanism, structural form, operation control, and engineering application. Existing studies and engineering practices show that optimizing only a single unit or an isolated parameter cannot ensure long-term stable operation under variable mining conditions. Only through overall design and coordinated regulation of hydrocyclone separation and filtration at the system-level can their functional complementarity be transformed into practical engineering advantages. Integrated equipment combining load reduction, fine separation, and operation regulation has become the core development direction for high-suspended-solids mine water treatment facilities.

Mechanically, particle systems under high-suspended-solids conditions exhibit obvious multiphase coupling and strong time-varying characteristics. Both hydrocyclone separation and filtration processes evolve dynamically with changes in particle interaction, flow field structure, and resistance distribution. Therefore, equipment performance should not be evaluated only by steady-state separation efficiency or design points; more attention should be paid to anti-disturbance ability, fluctuation resistance, and overload recovery capacity. Existing relevant mechanism studies can exert engineering value only when they are effectively applied to structural design and operation strategies. At the structural and operational levels, the core value of integrated equipment lies in expanding the safe operating range of the system. Through flow path optimization, anti-wear and anti-clogging structure design, and coordination of self-cleaning, backwashing, and bypass functions, stable operation under large load fluctuations is guaranteed. The design focuses more on operational predictability and controllable performance degradation rather than maximizing instantaneous separation efficiency. The automation and control system shortens response time and reduces manual dependence through key parameter regulation and protection interlock strategies. Data-driven and intelligent methods can further improve state identification, maintenance planning, and operational stability within a controllable range without reducing reliability and interpretability. Their further development would also benefit from data-sharing frameworks and open-access operational repositories, which can support the accumulation of long-term operational data and improve reproducibility and sustainability across applications.

Looking forward, continued progress in integrated hydrocyclone–filtration systems is likely to depend less on incremental gains in unit efficiency and more on advances in

system-level integration. Priorities include clearer definitions of stability-oriented evaluation metrics, accumulation and sharing of long-term operational data, and further standardization of design and control practices across applications. By aligning mechanistic understanding, structural design, and operational governance within a unified framework, integrated equipment can better meet the demands of high-suspended-solids mine water treatment, supporting safe, stable, and sustainable mining operations over extended time horizons.

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