

Article

Energy- and Resource-Efficient Hydrodynamic Treatment of Spent Water-Based Drilling Fluids for Process-Water Reuse

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Abstract

Spent water-based drilling fluids generated during the construction of technological wells impose substantial environmental, water-management, transportation, and energy burdens. Conventional practices, including storage in temporary pits, prolonged settling, and off-site disposal, do not enable process-water recovery and require repeated handling of suspensions with a high solids content. This study evaluates a pressure-driven cylindrical hydrodynamic disperser as the central component of a compact on-site treatment system. Unlike conventional mechanical mixers, the disperser contains no driven shaft within the active chamber. Particle–reagent contact is intensified through controlled jet shear, vortex-induced redistribution, and the motion of freely moving steel balls. Field-derived drilling fluids containing 30–40 wt.% solids, with densities of 1.12–1.17 g/cm³, pH values of 7.4–8.2, and median particle sizes of 15–50 μm, were treated at velocity gradients of 500–1500 s^{−1} for 60–180 s using Superfloc N-300 dosages of 0–100 g/t. The optimal operating conditions were $G = 1300 \text{ s}^{-1}$, $\tau = 150 \text{ s}$, and $D = 50 \text{ g/t}$. Under these conditions, the separation efficiency reached 91–93%, the residual suspended-solids concentration decreased to 120–130 mg/L, process-water recovery reached 80%, sludge volume decreased by 40–60%, and specific energy consumption was approximately 0.30 kWh/m³. More intensive treatment increased the separation efficiency to 94–95% but resulted in a less favorable balance among energy consumption, reagent dosage, and resource recovery. Compared with mechanical mixing, the selected treatment system reduced flocculant consumption by 37.5%, treatment time by more than threefold, and specific energy consumption by 40%. These results support the use of modular on-site systems for process-water recirculation and reduced sludge-transport requirements at remote drilling sites.

Keywords: spent drilling fluids; hydrodynamic separation; process-water recovery; sludge-volume reduction; energy efficiency



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1. Introduction

Spent drilling fluids and drill cuttings are complex multicomponent waste streams containing water or base fluid, clay minerals, drilled-rock particles, weighting materials, and residual functional additives. Their high solids content, broad particle-size distribution, and colloidal stability hinder rapid solid–liquid separation and complicate their safe handling [1–3]. Waste-management strategies must therefore consider the fluid composition, solid-phase characteristics, environmental risks, and the potential recovery of reusable water and solid materials [4–6].

This problem is particularly significant at geographically dispersed technological-well sites, where spent drilling fluid and sludge may accumulate in temporary pits or transported to remote storage and disposal facilities. These practices increase transportation requirements, the number of handling operations, freshwater consumption, and the volume of waste requiring long-term management [7–9]. Compact on-site treatment is therefore important not only for environmental protection but also for reducing logistical demands and resource consumption.

Treatment performance should not be evaluated solely in terms of clarification efficiency. A technically viable treatment process must also minimize reagent consumption and treatment time, recover a sufficiently large liquid fraction, reduce the volume of residual sludge, and avoid a disproportionate increase in pumping-energy demand. This integrated formulation is necessary when the treatment unit is intended to operate within the resource circuit of a drilling site.

Established treatment routes include gravitational settling, mechanical mixing with coagulants or flocculants, centrifugation, hydrocyclone separation, filtration, stabilization, and multistage physicochemical treatment [10,11]. These methods can achieve substantial solids removal, but individual routes may require long residence times, high reagent consumption, mechanically complex equipment, or additional dewatering stages. Their suitability therefore depends on the required water quality, solids properties, plant capacity, and local disposal constraints.

Hydrodynamic cavitation and high-shear flow reactors offer an alternative process-intensification mechanism because pressure gradients, jets, vortices, and localized turbulent dissipation can improve particle dispersion and particle–reagent contact without installing a driven agitator in the active chamber [12–15]. Previous studies have mainly focused on pollutant degradation, cavitation-assisted treatment, or enhanced mixing. The combined effects of hydrodynamic intensity and flocculant dosage on liquid-phase quality, sludge compaction, water recovery, and specific energy consumption remain insufficiently studied for spent drilling fluids.

The present study addresses this gap by treating the cylindrical hydrodynamic disperser as the central process intensification unit rather than as an auxiliary mixer. The scientific contribution comprises: experimental identification of the coupled effects of velocity gradient, treatment time, and flocculant dosage on separation efficiency, residual suspended solids, and sludge compactness; definition of an operating window using separation, reagent, water-recovery, sludge-reduction, and energy criteria; explicit distinction between the maximum attainable separation efficiency and the operationally rational mode; and process-level interpretation of the results for on-site water recirculation and sludge logistics. The aim was to determine a reproducible operating window for spent water-based drilling fluids and to evaluate whether the recovered liquid and compacted residue provide meaningful resource benefits for distributed drilling sites.

2. Materials and Methods

2.1. Materials

The studied material comprised water-based spent drilling fluids generated during the drilling of technological wells for uranium production operations in southern Kazakhstan. The fluids were collected from operational circulation and settling systems after completion of their primary drilling function. Each composite sample contained an aqueous phase, clay minerals, finely dispersed drilled-rock particles, and residual additives used to control rheological and filtration properties [16,17]. The scope of the present work is deliberately restricted to water-based systems with the characteristics reported in Table 1. Direct transfer of the operating window to oil-based, highly saline, or invert-emulsion fluids is not claimed because those media require separate experimental verification.

Table 1. Physicochemical characteristics of the studied spent drilling fluids.

Indicator	Designation	Units	Value/Range
Mass fraction of solid phase	Φ	%	30–40
Moisture content	W	%	65–70
Density	ρ	g/cm ³	1.12–1.17
pH	pH	–	7.4–8.2
Average particle size	d_{50}	μm	15–50
Appearance	–	–	Gray-brown opalescent suspension

Before each experimental run, the bulk sample was homogenized until no visible stratification remained and was then divided into test portions without dilution. Samples were stored in sealed containers to minimize evaporation and compositional drift. The suspension temperature was measured immediately before and after treatment, and all comparative series were conducted at 22 ± 2 °C. Controlling this parameter was necessary because viscosity, polymer adsorption, and aggregate-formation kinetics are temperature dependent.

Before the experiments, the main physicochemical characteristics of the initial suspension were determined. Table 1 presents the physicochemical characteristics of the tested spent water-based drilling fluids.

The parameters in Table 1 were selected because they directly govern hydrodynamic transport and flocculation. The solids mass fraction and d_{50} determine collision frequency, settling behavior, and the probability of aggregate breakage; density affects hydraulic loading and separation; pH influences polymer adsorption; and moisture content defines the recoverable liquid fraction. The reported ranges characterize the field-derived water-based samples investigated here rather than a universal specification for all spent drilling fluids [18].

The combination of 30–40% solids, a broad d_{50} range, and a moderately alkaline pH explains the limited effectiveness of unaided gravitational settling. Within these bounds, the method is applicable to water-based clay suspensions of comparable composition. For fluids outside this range, preliminary jar tests should be conducted to determine the appropriate flocculant type, dosage, and hydrodynamic operating window before scale-up.

2.2. Experimental Setup and Hydrodynamic Disperser

The experiments were conducted on a laboratory–pilot recirculating unit built around a custom vertical pressure-driven cylindrical hydrodynamic disperser. The process train comprised a feed tank with pre-mixing, a flocculant dosing point, a centrifugal pump, a flow meter, inlet and outlet pressure gauges, the disperser, a conditioning and settling tank, a clarified-water outlet, and a sludge-collection zone. The custom active chamber

contained 2–4 cascades of perforated disks and freely moving steel balls with diameters of 5–8 mm. The peripheral holes were inclined by 20–30°, the hole length-to-diameter ratio was 4–5, the pressure drop per cascade was 20–60 kPa, and the jet velocity through the holes was 0.8–1.5 m/s. The active chamber and wetted lines were fabricated from corrosion-resistant steel.

The pump established recirculation through the disperser, and the required velocity gradient was set by adjusting the suspension flow rate and the measured pressure drop. Downstream separation was performed in a quiescent settling vessel. After reagent–hydrodynamic activation, the suspension entered the vessel, flocculated solids settled under gravity, clarified supernatant was withdrawn from the upper outlet, and compacted sludge was removed from the lower collection zone; no rotating separator was used. The stated treatment time therefore denotes the total controlled recirculation period rather than the single-pass residence time inside the disperser.

For engineering specification and scale-up, the custom laboratory–pilot configuration was benchmarked against the commercially available DSh-100 ball-type drilling-fluid disperser manufactured by JSC Krasnodar Plant NEFTEMASH (Krasnodar, Russia). The manufacturer specifies a nominal throughput of 15 m³/h, a working inlet pressure of 0.6 MPa, overall dimensions of 590 × 515 × 375 mm, a mass of 49 kg, 9.8 mm steel balls, and operation in combination with a centrifugal slurry pump. These values define the closest verified industrial equipment specifications; they were not used to generate or calculate the experimental results obtained with the custom multicascade chamber.

The DSh-100 is an in-line flow-through unit, for which the manufacturer does not specify a nominal batch working volume or a unique feed-pump model. Accordingly, the reference pump duty was defined by the verified operating point of 15 m³/h at 0.6 MPa. The corresponding hydraulic power is 2.50 kW; for an assumed combined pump–drive efficiency of 0.58–0.65, the required shaft power is 3.85–4.31 kW. A 5.5 kW centrifugal slurry pump equipped with a variable-frequency drive was therefore selected as a conservative design option for the modular scale-up configuration. This pump rating is an engineering selection and is not presented as a measured characteristic of the laboratory unit. Figure 1 presents the process-level flowsheet used to define the material route from spent-fluid feed to recovered process water and compacted sludge.

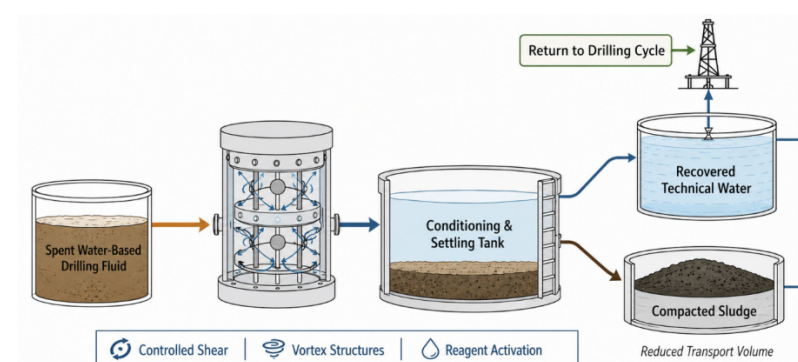


Figure 1. Conceptual process-level route for hydrodynamic treatment of spent water-based drilling fluid, process-water recovery, and compacted-sludge removal.

As shown in Figure 1, spent drilling fluid is first supplied to the hydrodynamic disperser, where controlled shear and vortex structures promote particle–reagent contact. The activated suspension then enters the conditioning and settling stage. The upper liquid fraction is collected for possible return to the drilling-water circuit, whereas the denser lower fraction is removed as compacted sludge. The figure therefore represents the overall

resource loop, while Figure 2 focuses on the apparatus structure and its integration into the experimental line [19].

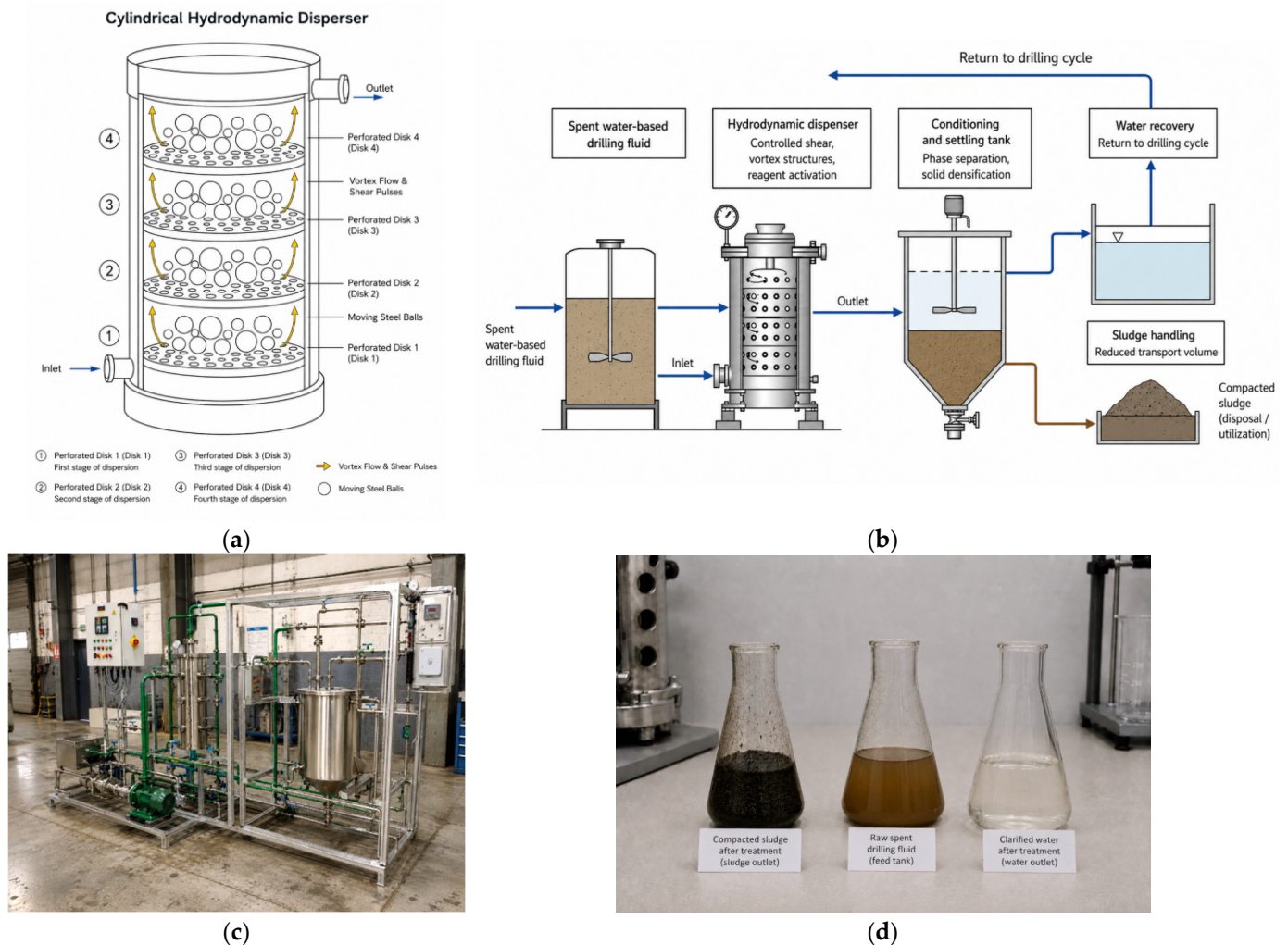


Figure 2. Engineering visualization at four scales: (a) internal arrangement of the cylindrical hydrodynamic disperser with perforated disks and moving steel balls; (b) integration of the disperser into the feed, conditioning, settling, water-return, and sludge-removal route; (c) three-dimensional layout of the modular installation; (d) phase-state representation of untreated slurry, clarified water, and compacted sludge.

Figure 2 presents the apparatus-level engineering schematics: the internal arrangement of the cylindrical disperser and its position within the feed–treatment–settling sequence.

Figure 2 provides a composite engineering representation of the laboratory–pilot concept. It combines the process-line topology, the principal internal flow zones of the cylindrical hydrodynamic disperser, and illustrative phase states used to explain the expected transformation from the untreated suspension to clarified water and compacted sludge. Quantitative confirmation of this transformation is provided by the measured response variables reported in Section 3. As shown in Figure 2c, the proposed modular line comprises seven functional elements: a feed tank with pre-mixing, a metering pump for the Superfloc N-300 (NeftehimInnovation, Krasnoyarsk, Russia) working solution, a cylindrical hydrodynamic disperser, a gravity settling tank, a clarified-water outlet, a compacted-sludge outlet, and a recirculation pump. The hydraulic scheme defines the flow sequence, while the internal view explains the inlet acceleration, jet formation, expansion, vortex redistribution, and ball-assisted mixing zones. Figure 2d illustrates the three process

states used in the interpretation: initial suspension, recovered liquid phase, and compacted solid residue.

Key Design Parameters of the Disperser

Table 2 distinguishes the active-zone parameters used in the custom experimental disperser from the verified manufacturer data and calculated pump duty of the DSh-100 industrial scale-up reference.

Table 2. Active-zone parameters of the experimental disperser and verified industrial scale-up reference.

Parameter	Sym.	Unit	Range/Value
Number of perforated-disk cascades	n	—	2–4
Diameter of steel balls	d_b	mm	5–8
Peripheral-hole inclination angle	α	°	20–30
Hole length-to-diameter ratio	L/d	—	4–5
Pressure drop per cascade	Δp_c	kPa	20–60
Jet velocity through holes	v	m/s	0.8–1.5
Commercial DSh-100 scale-up reference (not an experimental setting)			
Reference unit	—	—	DSh-100
Nominal throughput	Q_{ref}	m ³ /h	15
Working inlet pressure	p_{ref}	MPa	0.6
Overall dimensions (L × W × H)	—	mm	590 × 515 × 375
Reference-unit mass	m_{ref}	kg	49
Steel-ball diameter	$d_{b,ref}$	mm	9.8
Manufacturer-specified feed-pump type	—	—	Centrifugal slurry pump
Nominal batch working volume	—	—	Not applicable: in-line unit
Calculated hydraulic power at reference duty	$P_{h,ref}$	kW	2.50
Selected scale-up motor rating	$P_{m,ref}$	kW	5.5, variable-frequency drive

The first block of Table 2 defines the hydraulically active geometry used in the experiments. The second block provides a traceable industrial boundary for scale-up. The DSh-100 values are manufacturer data, whereas the 5.5 kW motor rating is a conservative engineering selection derived from the verified flow–pressure duty. This distinction prevents commercial reference specifications from being interpreted as unmeasured laboratory parameters.

2.3. Variables and Measured Parameters

Three controlled factors were varied in the experiments: velocity gradient $G = 500, 900, 1100, 1300,$ and 1500 s^{-1} ; treatment time $\tau = 60, 90, 120, 150,$ and 180 s ; and flocculant dosage $D = 0, 25, 50, 75,$ and 100 g/t . The reagent was Superfloc N-300, a commercial nonionic polyacrylamide flocculant supplied by Kemira and prepared as an aqueous working solution immediately before use. Separation efficiency η_{sep} , residual suspended-solids concentration C_{res} , sludge compactness ρ_s , process-water recovery R_w , sludge-volume reduction R_s , and specific energy consumption E_{sp} were the measured response variables. The controlled factors and responses are summarized in Table 3.

Table 3 defines the complete variable system used to evaluate the hydrodynamic treatment process. The controlled factors G , τ , and D characterize the intensity and duration of hydrodynamic action and the reagent input, whereas the response variables describe the resulting separation quality, residue properties, resource recovery, and energy demand. This structure allows the process to be assessed not only by separation efficiency, but also by the residual suspended-solids concentration, sludge compactness, process-water recovery, sludge-volume reduction, and specific energy consumption. Consequently, the opera-

tional optimum is determined as a multicriteria balance between treatment performance, reagent consumption, resource recovery, and energy efficiency rather than by maximizing a single response.

Table 3. Controlled factors and response variables.

Category	Variable	Symbol	Unit
Controlled factor	Velocity gradient	G	s^{-1}
Controlled factor	Treatment time	τ	s
Controlled factor	Flocculant dosage	D	g/t
Response variable	Separation efficiency	η_{sep}	%
Response variable	Residual suspended solids	C_{res}	mg/L
Response variable	Sludge compactness	ρ_s	g/cm ³
Response variable	Process-water recovery	R_w	%
Response variable	Sludge-volume reduction	R_s	%
Response variable	Specific energy consumption	E_{sp}	kWh/m ³

2.4. Analytical and Engineering Expressions

Separation efficiency was calculated using Equation (1):

$$\eta_{sep} = \frac{C_0 - C_{res}}{C_0} \cdot 100, \quad (1)$$

where C_0 is the initial suspended-solids concentration, mg/L, and C_{res} is the residual suspended-solids concentration after treatment and settling, mg/L.

Process-water recovery was calculated using Equation (2):

$$R_w = \frac{V_{rec}}{V_0} \cdot 100, \quad (2)$$

where V_{rec} is the volume of the liquid phase returned, m³; V_0 is the initial volume of the treated suspension, m³.

Sludge volume reduction is defined as

$$R_s = \frac{V_{sl,0} - V_{sl,f}}{V_{sl,0}} \cdot 100, \quad (3)$$

where $V_{sl,0}$ is the initial volume of the sludge phase, m³; $V_{sl,f}$ is the volume of compacted residue after treatment, m³.

Specific energy consumption was estimated as

$$E_{sp} = \frac{\Delta p \cdot Q \cdot t}{3.6 \times 10^6 \cdot V_{treated} \cdot \eta_p}, \quad (4)$$

where Δp is the working pressure drop, Pa; Q is the volume flow, m³/s; t is the duration of treatment, s; $V_{treated}$ is the volume of the treated suspension, m³; η_p is the efficiency of pumping equipment.

2.5. Experimental Workflow

The experimental procedure included three consecutive stages. First, the initial suspension was fed into the cylindrical hydrodynamic disperser, and the required hydrodynamic conditions were established by adjusting the pressure drop and the corresponding velocity gradient. At the second stage, flocculant N-300 was injected into the stream in a given dosage, after which the system was subjected to short-term reagent-hydrodynamic activa-

tion [20]. Finally, the treated suspension was transferred to the settling unit. After settling, the quality of the separated liquid, the residual suspended-solids concentration, and the properties of the solid residue were evaluated [21].

For each mode, the values of G , τ and D were recorded, after which η_{sep} , C_{res} , ρ_s , R_w , R_s and E_{sp} were determined.

Measurement Protocol and Reproducibility of Experimental Data

To ensure reproducibility, each operating condition was defined by a fixed combination of velocity gradient G , treatment time τ , and flocculant dosage D . Before the start of the tests, the initial suspension was stirred until a homogeneous state was reached, after which a representative sample of the specified volume was taken. For each operating condition, the suspension flow rate through the disperser, the operating pressure drop, the suspension temperature, the hydrodynamic treatment time, and the subsequent settling time were recorded.

The residual suspended-solids concentration C_{res} was determined gravimetrically from the dry residue remaining after filtration and drying to constant mass. Suspension and compacted-sludge densities were measured by the volumetric–mass method, and d50 was obtained from particle-size analysis of the homogenized initial suspension. The experimental protocol included three replicates of the treatment for each operating condition ($n = 3$).

2.6. Evaluation Criteria

From an engineering standpoint, the preferred mode was not the condition with the highest separation efficiency, but the condition that best balanced clarified-liquid quality, reagent dosage, treatment time, process-water recovery, sludge-volume reduction, and specific energy consumption. The operational optimum was required to satisfy the following criteria: $\eta_{sep} \geq 90\%$, $C_{res} \leq 130 \text{ mg/L}$, $D \leq 50 \text{ g/t}$, $R_w \geq 75\text{--}80\%$, $R_s \geq 40\%$, and $E_{sp} \leq 0.30 \text{ kWh/m}^3$. This multicriteria definition distinguishes the practically applicable operating range from the single condition that maximizes η_{sep} .

2.7. Methodological Limitations of the Experimental Design

The experimental design was intended to identify an operating window from integral process responses; local velocity fields, turbulent dissipation, and particle trajectories inside the active chamber were not measured directly. The mechanistic interpretation [22] is therefore engineering-based and indirect.

3. Results

3.1. Effect of Velocity Gradient and Treatment Time

The combined effects of velocity gradient and treatment time on separation efficiency and clarified-liquid quality are shown in Figure 3.

Figure 3 shows a monotonic improvement over the investigated range: separation efficiency increases while residual suspended-solids concentration decreases. The response nevertheless approaches a plateau at high hydrodynamic intensity [23], indicating diminishing technological return from additional shear and treatment time. The solid-phase state changed consistently with the plotted response: it was loose and heterogeneous at 500 s^{-1} , partially compacted at 900 s^{-1} , dense and stable at 1100 s^{-1} , uniform and compact at 1300 s^{-1} , and stable and dense at 1500 s^{-1} .

The combined response indicates a qualitative process transition in the range of $1100\text{--}1300 \text{ s}^{-1}$. Separation remained incomplete at $500\text{--}900 \text{ s}^{-1}$, whereas a stable working window developed at $1100\text{--}1300 \text{ s}^{-1}$. The maximum mean separation efficiency of 94%

occurred at 1500 s^{-1} and 180 s, but the 1300 s^{-1} and 150 s mode was preferable under the multicriteria operational definition.

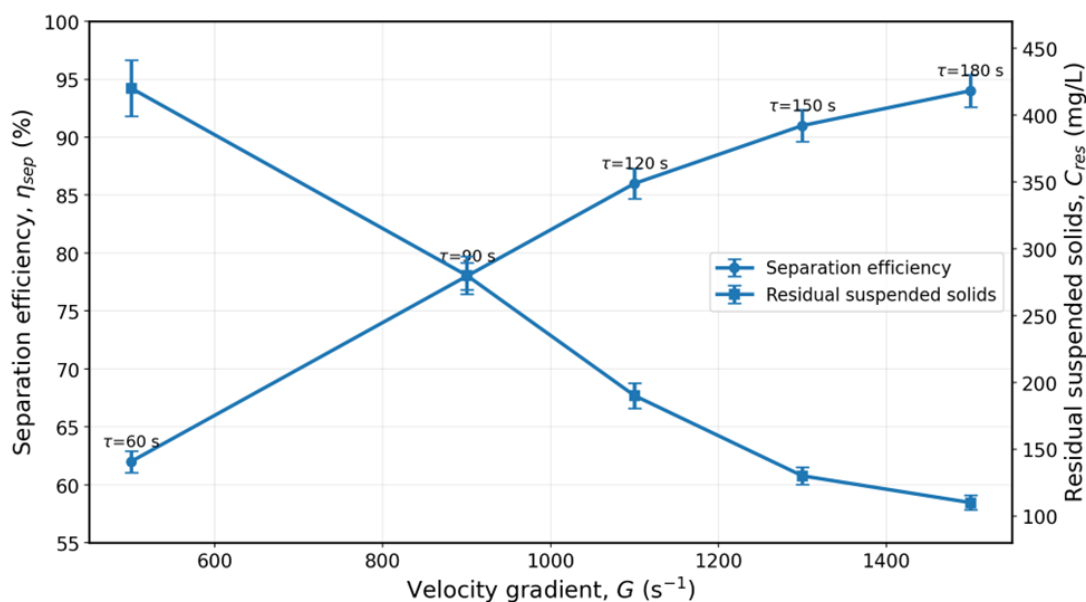


Figure 3. Mean separation efficiency and residual suspended-solids concentration as functions of velocity gradient and treatment time. Error bars are shown based on three replicates for each operating point.

From a practical standpoint, Figure 3 and the observed solid-phase states show that increasing G from 500 to 1300 s^{-1} improves both liquid clarification and residue handling. The transition to a compact, stable solid phase is particularly important for local treatment because subsequent storage and transport depend on residue consistency as well as supernatant quality.

3.2. Effect of Flocculant Dosage on Separation Efficiency

After determining the operating range of hydrodynamic intensification [24], the effect of flocculant dosage was considered. Experimental dependencies for different G values are shown in Figure 4.

Figure 4 shows a reproducible maximum near 50 g/t . The combined hydrodynamic and reagent effects are therefore synergistic only within a limited dosage interval. Numerical values obtained at $G = 1300\text{ s}^{-1}$ are presented in Table 4.

Table 4. Effect of Superfloc N-300 dosage on separation performance and sludge compactness at $G = 1300\text{ s}^{-1}$.

D , g/t	η_{sep} , %	C_{res} , mg/L	ρ_s , g/cm ³	Interpretation
0	84	210	1.04	Flocculant-free treatment
25	89	160	1.07	Initial stable aggregation
50	93	120	1.10	Operational optimum
75	92	125	1.09	Slight decrease in performance
100	90	140	1.08	Excessive flocculant dosage

Table 4 shows that 50 g/t provides the most favorable combination of separation depth, low residual suspended-solids concentration, and high sludge compactness. Increasing the dosage to 75 – 100 g/t does not improve the response and is consistent with partial restabilization or ineffective excess polymer.

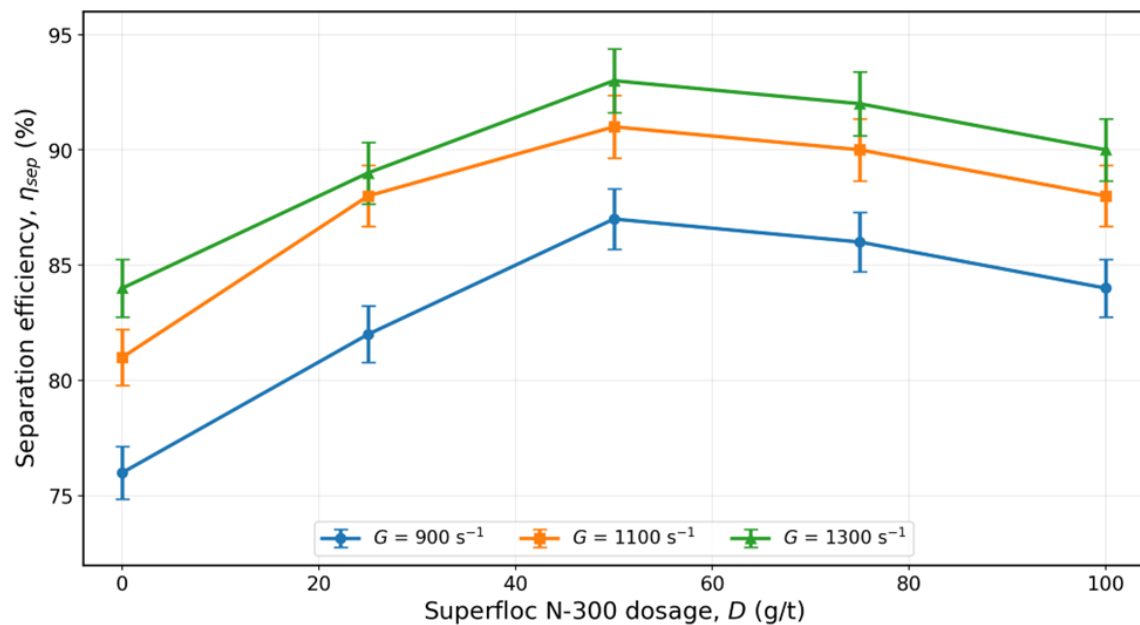


Figure 4. Mean effect of Superfloc N-300 dosage on separation efficiency at three velocity gradients. Error bars are shown based on three replicates for each operating point.

Joint interpretation of Figure 4 and Table 4 identifies 50 g/t as the dosage that simultaneously maximizes separation efficiency and sludge compactness while minimizing residual suspended solids.

3.3. Comparative Assessment of Treatment Routes

To assess the practical value of the proposed technology, the reference routes were evaluated within the same comparative laboratory campaign using the same homogenized spent-fluid matrix, the same measurement methods, and three treatment replicates per operating point. Natural settling, mechanical mixing, chemical treatment, hydrodynamic treatment, and hydrodynamic treatment combined with N-300 therefore represent internal standardized benchmarks rather than values extracted from unrelated literature sources. The comparison in Figure 5 and Table 5 is intended to isolate the effect of the treatment route under a common sample basis.

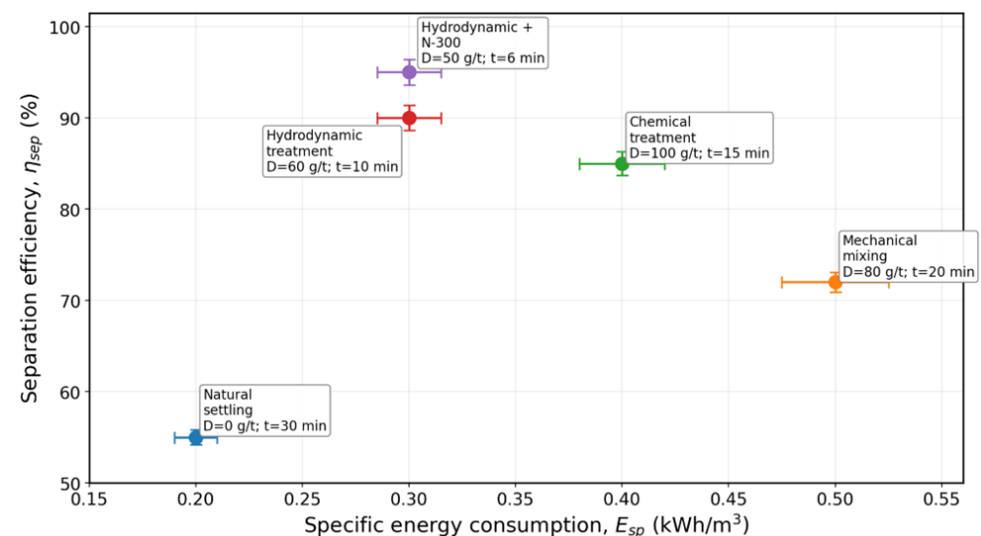


Figure 5. Comparison of treatment routes by separation efficiency and specific energy consumption. Horizontal and vertical error bars are shown based on three replicates for each operating point.

Table 5. Comparison of reference treatment routes and the proposed hydrodynamic route.

Method	η_{sep} , %	Time, min	D , g/t	C_{res} , mg/L	E_{sp} , kWh/m ³
Natural settling	55	30	0	470	0.2
Mechanical mixing	72	20	80	260	0.5
Chemical treatment	85	15	100	180	0.4
Hydrodynamic treatment	90	10	60	130	0.3
Hydrodynamic treatment + N-300	95	6	50	110	0.3

The resulting comparison of separation efficiency and specific energy consumption is presented in Figure 5.

Figure 5 places hydrodynamic treatment, particularly the N-300-assisted mode, in the favorable region of high separation efficiency and moderate specific energy consumption. The advantage is therefore multidimensional rather than attributable to a single performance indicator [25]. Table 5 provides the corresponding numerical comparison.

Relative to mechanical mixing, the combined hydrodynamic/N-300 route reduced flocculant dosage by 37.5%, treatment time from 20 to 6 min, and specific energy consumption from 0.50 to 0.30 kWh/m³ while increasing η_{sep} from 72% to 95%.

Table 5 distinguishes maximum observed process performance from the operational optimum. The values $\eta_{sep} = 95\%$ and $C_{res} = 110$ mg/L represent the highest separation level achieved by the combined route. The operational optimum, however, also requires stable performance, moderate reagent demand, acceptable residence time, limited energy use, and a measurable resource-recovery effect.

The operational optimum was identified sequentially. First, Figure 3 delimited the hydrodynamic working window: increasing G from 1100 to 1300 s^{−1} and τ from 120 to 150 s increased η_{sep} from 86% to 91% and reduced C_{res} from 190 to 130 mg/L, whereas the 1500 s^{−1} and 180 s mode produced only a further three-percentage-point increase in separation efficiency. Second, Figure 4 and Table 4 showed that $D = 50$ g/t gave $\eta_{sep} = 93\%$, $C_{res} = 120$ mg/L, and the maximum measured sludge compactness $\rho_s = 1.10$ g/cm³; larger dosages provided no additional benefit.

Third, calculation with Equation (4) gave $E_{sp} \approx 0.30$ kWh/m³ for $G = 1300$ s^{−1}, $\tau = 150$ s, and $D = 50$ g/t, which satisfied the predefined limits for separation, residual solids, reagent dosage, water recovery, sludge reduction, and specific energy consumption. The selected mode therefore represents a balanced operating condition based on multiple criteria ($\eta_{sep} = 91$ –93%, $C_{res} = 120$ –130 mg/L, $R_w \approx 80\%$, $R_s = 40$ –60%) rather than the condition with the highest η_{sep} alone.

3.4. Resource Implications of Intensified Treatment

The resource value of separation is reflected in both the recovered liquid fraction and the reduced sludge volume [26]. Figure 6 presents these two responses as functions of hydrodynamic intensity.

Figure 6 shows a coupled resource benefit across 1100–1300 s^{−1}: the recoverable liquid fraction increases while the sludge volume requiring transport and disposal decreases [27]. Hydrodynamic treatment therefore functions as a resource-recovery stage rather than only as a clarification step. The greatest simultaneous improvements in water recovery and sludge-volume reduction occurred as the velocity gradient increased from 900 to 1300 s^{−1}. At the operational optimum $G = 1300$ s^{−1}, $\tau = 150$ s and $D = 50$ g/t, the return of process water reached 80%, and the volume of sludge generated was reduced by 40–60%.

This coupled response means that process performance should be evaluated from drilling-site material flows as well as clarified-water quality. Reduced freshwater make-

up and lower sludge logistics are the principal application-level benefits of the selected hydrodynamic treatment mode.

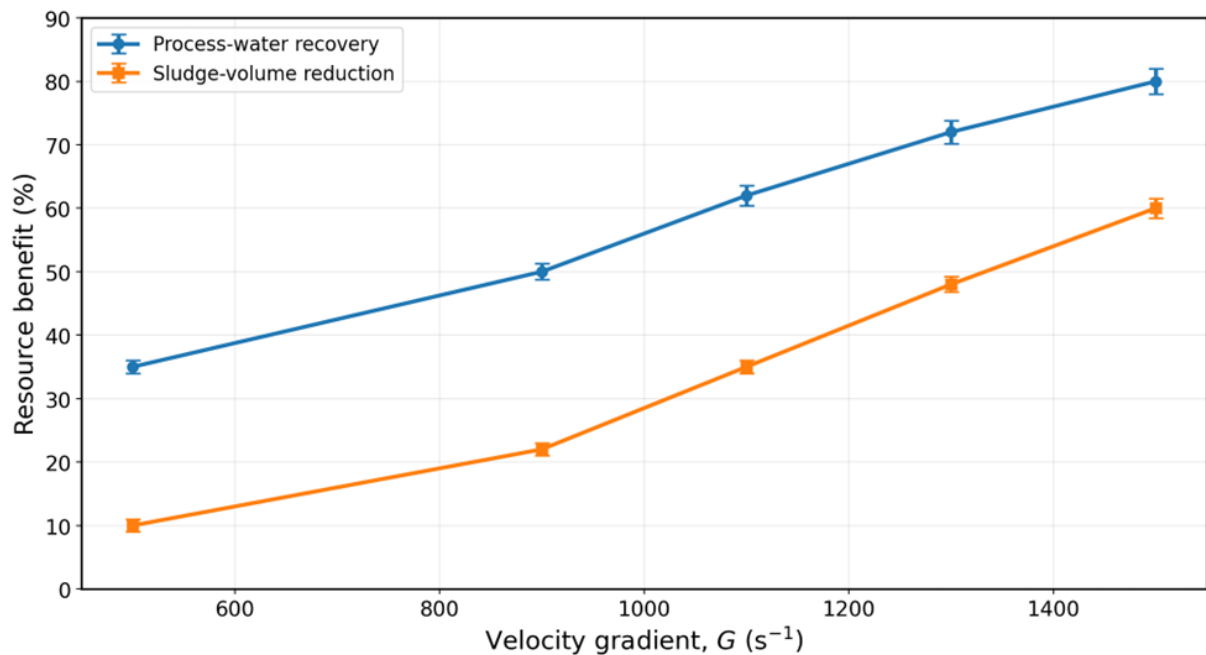


Figure 6. Mean process-water recovery and sludge-volume reduction as functions of velocity gradient. Error bars are shown based on three replicates for each operating point.

3.5. Residual Suspended Solids and Sludge Compactness

To examine residue quality, the effects of N-300 dosage on residual suspended-solids concentration and sludge compactness were evaluated separately, as shown in Figure 7.

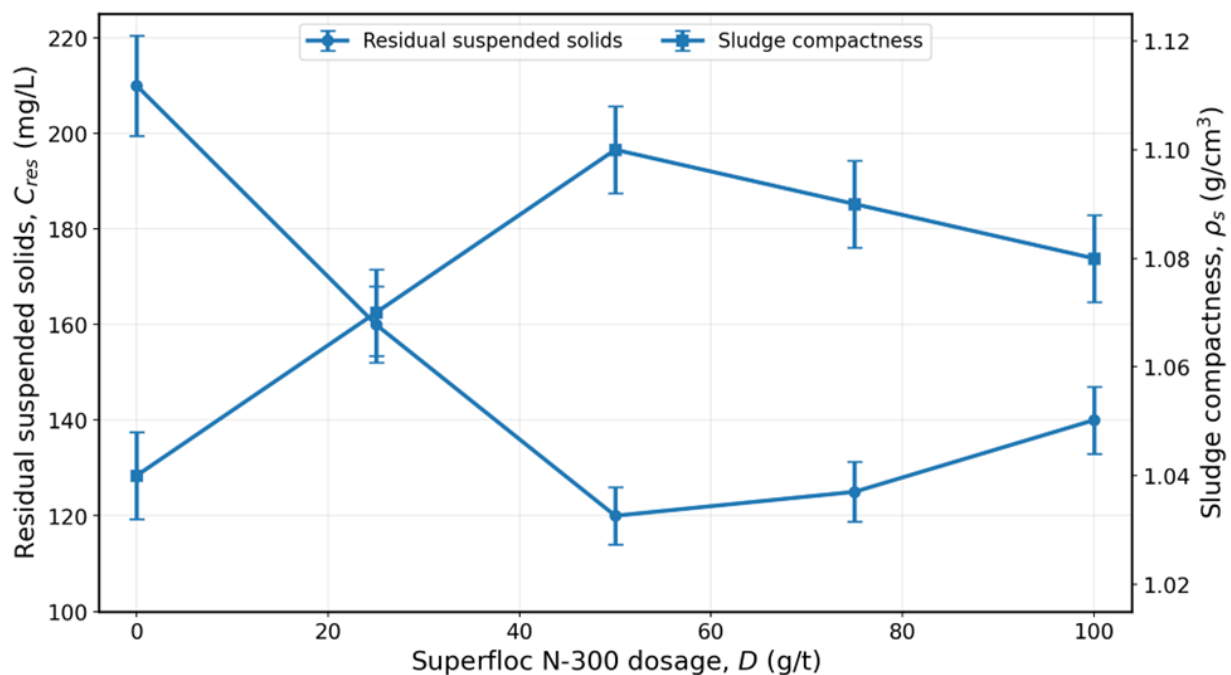


Figure 7. Mean effect of Superfloc N-300 dosage on residual suspended-solids concentration and sludge compactness at $G = 1300 s^{-1}$. Error bars are shown based on three replicates for each operating point.

Figure 7 shows that the minimum C_{res} and maximum ρ_s occur at the same dosage, approximately 50 g/t. This agreement confirms both improved clarified-water quality and formation of the most compact sludge for subsequent handling [28]. The narrow operating window is physically consistent: insufficient dosage produces incomplete floc formation, whereas excessive dosage can restabilize fine particles and impair both the separated water [29] and the solid residue. Table 6 summarizes the resulting optimum operating conditions and process outcomes. The coincidence of the minimum C_{res} and maximum ρ_s at 50 g/t, supports the robustness of the selected reagent dosage.

Table 6. Integrated optimum operating conditions and process outcomes.

Parameter/Outcome	Value
Velocity gradient, G	1300 s^{-1}
Treatment time, τ	150 s
N-300 dosage, D	50 g/t
Separation efficiency, η_{sep}	91–93%
Residual suspended solids, C_{res}	120–130 mg/L
Technical-water recovery, R_w	80%
Sludge-volume reduction, R_s	40–60%
Specific energy consumption, E_{sp}	$\sim 0.3 \text{ kWh/m}^3$

Table 6 summarizes the multicriteria comparison and defines the integrated operational optimum. At $G = 1300 \text{ s}^{-1}$, $\tau = 150 \text{ s}$, and $D = 50 \text{ g/t}$, separation efficiency is 91–93%, residual suspended solids decrease to 120–130 mg/L, process-water recovery reaches approximately 80%, sludge volume is reduced by 40–60%, and specific energy consumption is about 0.30 kWh/m^3 . This condition is an operationally rational region, not the local maximum of a single response.

3.6. Integrated Operating Window of the Process

Comparison of Figures 3–7 identifies an integrated operating window of $G = 1100\text{--}1300 \text{ s}^{-1}$, $\tau = 120\text{--}150 \text{ s}$, and an N-300 dosage of approximately 50 g/t. The process optimum should therefore be interpreted as a bounded multicriteria region rather than as a single maximum-response point.

3.7. Preliminary Techno-Economic Assessment

A preliminary variable-cost assessment was performed to translate the measured water, reagent, sludge, and energy effects into an engineering decision metric. The calculations are intentionally based on models using data on tariffs, transportation distances, disposal costs, labor costs, maintenance, and capital investments. The avoided variable cost per cubic meter of treated suspension was estimated as

$$\Delta C = (E_{ref} - E_{HD})c_e + \rho(D_{ref} - D_{HD})c_f + R_w c_w + V_{s,0} R_s c_s,$$

where c_e is the electricity tariff, c_f is the flocculant price, c_w is the delivered freshwater cost, c_s is the sludge transport and disposal cost, and $V_{s,0}$ is the baseline sludge volume per unit feed.

The following parameters were used for calculations: electricity price USD 0.10/kWh; Superfloc N-300 price USD 3.0/kg; delivered process-water cost USD 1.0/m³; sludge transport and disposal cost USD 20/m³; suspension density 1.15 t/m³; baseline sludge volume 0.30 m³ per m³ of feed; and a 50% sludge-volume reduction. The hydrodynamic route was compared with the mechanically mixed, non-recirculating reference using $E_{sp} = 0.30$

versus 0.50 kWh/m³ and D = 50 versus 80 g/t. Table 7 presents the resulting normalized variable-cost effect.

Table 7. Variable costs of the operational optimum compared to the reference route with mechanical mixing and no recirculation.

Cost Component	Calculation Basis	Avoided Cost, USD/m ³
Electricity	$(0.50 - 0.30) \text{ kWh/m}^3 \times 0.10 \text{ USD/kWh}$	0.02
Flocculant	$1.15 \text{ t/m}^3 \times (0.080 - 0.050) \text{ kg/t} \times 3.0 \text{ USD/kg}$	0.10
Fresh process water	$0.80 \text{ m}^3/\text{m}^3 \times 1.0 \text{ USD/m}^3$	0.80
Sludge transport and disposal	$0.30 \text{ m}^3/\text{m}^3 \times 0.50 \times 20 \text{ USD/m}^3$	3.00
Total, including sludge logistics	Sum of the four components	3.92
Total, excluding sludge logistics	Energy + reagent + water only	0.92

The avoided variable burden is approximately USD 0.92/m³ when only electricity, reagent, and freshwater are considered and USD 3.92/m³ when sludge transport and disposal are included. At the 15 m³/h reference capacity and 2000 operating hours per year, this corresponds to approximately 30,000 m³/year and an indicative annual benefit of USD 27,700 excluding sludge logistics or USD 117,700, including them. The calculation is not a full discounted cash-flow analysis: capital cost, labor, maintenance, wear-part replacement, taxes, financing, and downtime are excluded. Its purpose is to show that the economic result is governed primarily by local water and sludge-logistics costs rather than by pumping electricity alone.

4. Discussion

4.1. Mechanistic Interpretation

The cylindrical hydrodynamic disperser serves as a controlled process-intensification unit rather than as a conventional mixer. Within $G = 1100\text{--}1300 \text{ s}^{-1}$, jet shear, vortex redistribution, local pressure fluctuations, and ball motion create a balance between disrupting weak structures and preserving sufficiently strong flocs for effective settling [30].

Hydrodynamic treatment therefore performs two complementary functions. Initial shear disrupts loose structures and increases particle-surface accessibility to the polymer, whereas the developed flow field promotes collision, bridging, and formation of denser settleable aggregates. The treatment response depends on the spatial distribution of shear and recirculation within the active chamber, not solely on bulk mixing intensity.

The results distinguish an under-activated regime from an over-intensified regime. At insufficient G , particle–polymer contacts and aggregate growth remain limited; at excessive intensity, additional energy provides only marginal improvements in clarification and may increase floc breakage [31]. The optimum is therefore determined by coordination of the hydrodynamic and reagent stages rather than by maximum shear alone.

4.2. Process-Level Advantages

The proposed treatment route improves several operational indicators simultaneously: separation efficiency, reagent dosage, treatment duration, residual suspended solids, process-water recovery, and sludge volume. The benefits are therefore not limited to improved clarification; it also includes lower reagent demand, shorter treatment, reduced specific energy consumption, and a more favorable balance between water recovery and residue reduction [32]. For distributed drilling sites, these effects reduce the load on transport and storage infrastructure and improve water-resource efficiency [33].

These benefits can be observed at three different scales. At the reactor scale, the device intensifies particle–reagent contact. At the process-line scale, it reduces treatment time and

reagent dosage. At the drilling-site scale, it lowers freshwater make-up and the volume of residue transported off site. The suitability of the proposed technology should therefore be evaluated from the combined response of η_{sep} , C_{res} , R_w , R_s , D , and E_{sp} rather than from η_{sep} alone.

4.3. Industrial Applicability and Scale-Up Relevance

Process-water recovery can be achieved without a mechanically complex multistage line; the principal intensification mechanism is the controlled hydrodynamic field [34]. This feature facilitates compact modular deployment near the waste-generation point and integration with the drilling-site water circuit [35].

From the standpoint of industrial implementation, the commercial DSh-100 envelope confirms that a ball-assisted hydrodynamic disperser is available as a compact in-line unit with a nominal throughput of $15 \text{ m}^3/\text{h}$ and a working pressure of 0.6 MPa [18]. The custom multicascade apparatus investigated here is not claimed to be geometrically identical to the DSh-100; the commercial unit is used as a traceable boundary for pump selection, module layout, and subsequent pilot-scale verification. The absence of a rotating shaft inside the active chamber in both concepts reduces the number of mechanically loaded components in direct contact with the abrasive suspension.

Comparison with Previously Reported Treatment Approaches

Comparison with the reference routes shows that the advantage of the proposed scheme extends beyond solid–liquid separation efficiency. Natural settling has the lowest direct energy demand but requires long residence times and provides inadequate clarified-liquid quality. Chemical flocculation can improve separation but uses more reagent and may provide insufficient sludge compaction. Mechanical mixing enhances particle–polymer contact but has a less favorable ratio of treatment time and energy demand to the achieved separation response.

The hydrodynamic route occupies a balanced process region: it does not minimize energy use at the expense of treatment performance, nor does it maximize reagent dosage to obtain marginal clarification gains. Instead, η_{sep} , C_{res} , R_w , R_s , D , and E_{sp} are treated as coupled responses of one operating condition. This distinguishes the method from routes assessed primarily by clarified-liquid quality or final suspended-solids concentration.

The scientific contribution is the experimental demonstration that a controlled hydrodynamic field can act as an independent tool for managing the structural state of a concentrated water-based drilling suspension. The window $G = 1100\text{--}1300 \text{ s}^{-1}$ with $D \approx 50 \text{ g/t}$ coordinates suspension destabilization, floc growth, residual-solids reduction, sludge compaction, and resource recovery.

4.4. Limitations and Future Research

The operating window established here is specific to water-based drilling fluids within the reported solids content, particle-size, density, pH, and temperature ranges. Direct transfer to oil-based or invert-emulsion systems is not justified because continuous-phase polarity, interfacial tension, wettability, demulsifier demand, and oil–solid affinity fundamentally alter aggregation and phase separation [36]. Highly saline fluids also require separate verification because ionic strength can change polymer conformation, adsorption, floc strength, and the dosage response of polyacrylamide-based reagents.

Scaling up introduces additional hydraulic and mechanical constraints. Geometric enlargement alone does not preserve velocity-gradient distribution, pressure-drop partition, residence-time distribution, or ball–particle collision frequency. Pilot design should therefore maintain similarity in flow regime and specific energy input while monitoring abrasive wear of perforated disks and balls, plugging by coarse cuttings, pump cavitation

margin, sediment accumulation in dead zones, shear-induced floc breakage, reagent-dosing lag, and fluctuations in solids loading. Continuous operation will also require a controlled purge strategy and scheduled cleaning of the settling and recirculation circuits.

The present water quality assessment is based principally on residual suspended solids and recoverable liquid volume. Reuse in a drilling-water circuit should additionally be verified by salinity, chloride content, oil and grease, chemical oxygen demand, dissolved metals, microbiological activity, rheological compatibility, and the influence of residual polymer on subsequent drilling-fluid formulation. Future research should combine data-retention analysis, CFD/PIV characterization, continuous pilot testing, deterioration monitoring, and facility-specific life-cycle cost modeling [37].

4.5. Energy and Process Implications

The energy assessment of hydrodynamic treatment should include both direct pumping demand and the associated process effects: shorter treatment time, lower flocculant dosage, reduced transported-sludge volume, and return of process water to the production circuit [38]. At the DSh-100 reference duty of 15 m³/h and 0.6 MPa, the calculated hydraulic power is 2.50 kW. For a combined pump–drive efficiency of 0.58–0.65, the corresponding electrical specific energy is approximately 0.26–0.29 kWh/m³, which brackets the experimentally reported value of about 0.30 kWh/m³. This agreement is an independent engineering consistency check based on a verified industrial flow–pressure duty, not a substitute for a full-scale field energy audit. The comparison with the internal reference routes in Table 5 further shows that the selected hydrodynamic mode uses about 40% less specific energy than mechanical mixing (0.30 versus 0.50 kWh/m³).

4.6. Quantitative Positioning Against Recent Studies

Recent work confirms that compact pressure-driven separation devices can reach high efficiencies, but the relevant performance indicator depends strongly on the treated matrix and separation mechanism. The present results should therefore be compared in terms of their function rather than by a single performance percentage. Optimized hydrocyclone configurations reported in the recent literature commonly achieve approximately 82–94% separation, with selected designs reaching about 93% under experimental conditions; their principal advantages are rapid treatment, compactness, and the absence of internal moving parts, but their pressure drop and fine-particle cut size remain critical [39,40]. Reviews of hydrodynamic-cavitation industrialization similarly emphasize that scale-up must be assessed through capacity, energy demand, reactor durability, and economic efficiency rather than laboratory removal efficiency alone [41].

For chemically assisted water treatment, recent hydrodynamic-cavitation reviews focus mainly on degradation of dissolved persistent pollutants and hybrid advanced-oxidation routes, which are not directly equivalent to solid–liquid separation of high-solids drilling fluids [42]. A 2025 study of ozone fine-bubble treatment of high-viscosity drilling fluid reported a 29% viscosity reduction and 40% oil removal, demonstrating the relevance of bubble-assisted treatment for organic and oil-rich matrices but also confirming that such systems address a different treatment objective from the 91–93% solids-separation efficiency, 80% water recovery, and 40–60% sludge-volume reduction obtained here [43]. Table 8 summarizes the functional comparison.

This comparison places the present contribution in a distinct process niche: it does not compete directly with advanced oxidation for dissolved-organic destruction or with hydrocyclones for de-oiling, but provides a low-specific-energy, reagent-assisted route for recovering water and compacting solids from concentrated water-based drilling waste.

The principal remaining evidence gap is continuous pilot validation with measured wear, maintenance, raw-replicate uncertainty, and site-specific operating cost.

Table 8. Functional positioning of the present process relative to recent treatment studies.

Study/Route	Primary Matrix and Objective	Reported Performance	Direct Comparability
Present study	High-solids water-based spent drilling fluid; solids separation and water recovery	η_{sep} 91–93%; R_w 80%; R_s 40–60%; $E_{\text{sp}} \approx 0.30 \text{ kWh/m}^3$	Direct reference
Recent hydrocyclone studies [40]	Produced-water and dispersed-phase separation	Typical optimized values ≈ 82 – 94% ; selected designs $\approx 93\%$	Partial: different phase system and centrifugal mechanism
HC industrialization review [41]	Pilot/full-scale process intensification	Capacity, durability, and economic efficiency identified as scale-up criteria	Conceptual: industrialization criteria
HC + advanced oxidation review [42]	Dissolved persistent pollutants	Removal/degradation performance depends on hybrid chemistry and energy input	Low: different contaminant class
Ozone fine-bubble drilling-fluid treatment [43]	High-viscosity/oil-bearing drilling fluid	29% viscosity reduction; 40% oil removal	Partial: relevant matrix, different target responses

4.7. Regulatory Status of Recovered Water and Conditions for Reuse

The recovered liquid is intended for closed-loop reuse within the drilling process; it is not presented as potable water or as an effluent suitable for external discharge. Under the Ecological Code of the Republic of Kazakhstan, wastewater discharge requires the applicable environmental permit and permit-specific monitoring of the discharge and receiving environment [44]. The current Water Code also treats wastewater disposal and special water use as regulated activities [45].

Because the samples originated from uranium-production drilling operations, any reuse decision must also include radiation monitoring in accordance with the current sanitary and epidemiological requirements for radiation safety [46]. The present study measured residual suspended solids, recovered-water volume, density, and pH, but did not quantify dissolved salts, organic load, petroleum hydrocarbons, metals, radionuclide activity, or microbiological indicators. Accordingly, the term “recovered process water” denotes a candidate internal-reuse stream and does not constitute a claim of regulatory compliance [47,48]. Table 9 defines the minimum verification matrix required before closed-loop reuse, external discharge, or final sludge management.

Table 9 shows that the measured clarification response is sufficient to establish process performance but not regulatory suitability. Closed-loop reuse requires compatibility testing against the subsequent drilling-fluid formulation, whereas external discharge requires a separate permit-based compliance program. For the uranium-production context, radionuclide activity must be included in both water and sludge characterization before field implementation [49].

Table 9. Minimum verification matrix for recovered-water reuse, external discharge, and compacted-sludge management.

Management Pathway	Minimum Verification Set	Decision Purpose	Status in the Present Study
Closed-loop technical reuse	TSS/turbidity; pH; TDS/salinity; chloride and sulfate; hardness; COD/TOC; oil and grease; dissolved metals; radionuclide activity; microbiological indicators; residual-polymer and rheological compatibility	Protect downstream drilling-fluid formulation, equipment, personnel, and the internal water circuit	Residual suspended solids, pH, density, and recovered volume were evaluated; the remaining parameters require verification
External discharge	Permit-specific emission limits; discharge flow metering; receiving-water monitoring; toxicity or other indicators required by the permit	Demonstrate compliance with the environmental permit and receiving-water quality requirements	Not evaluated; no external-discharge compliance is claimed
Compacted-sludge management	Moisture and density; leachability; hydrocarbons; dissolved or total metals; radionuclide activity; site-specific waste classification	Select the transport, storage, treatment, or disposal route	Volume reduction and compactness were evaluated; hazardous and radiological classification remains pending

5. Conclusions

This study defines an operating window for local treatment of spent water-based drilling fluids using a cylindrical hydrodynamic disperser as the main process-intensification unit. Overall process performance is governed by the coordinated selection of velocity gradient, treatment time, and flocculant dosage rather than simply by maximizing the hydrodynamic intensity.

At $G = 1300 \text{ s}^{-1}$, $\tau = 150 \text{ s}$, and $D = 50 \text{ g/t}$, the operational optimum yielded $\eta_{\text{sep}} = 91\text{--}93\%$, $C_{\text{res}} = 120\text{--}130 \text{ mg/L}$, $R_w \approx 80\%$, $R_s = 40\text{--}60\%$, and $E_{\text{sp}} \approx 0.30 \text{ kWh/m}^3$. More intensive treatment increased the separation efficiency to 94–95% but did not improve the overall balance between energy consumption, reagent demand, and resource recovery. The 50 g/t dosage also produced the minimum C_{res} and maximum sludge compactness. Relative to mechanical mixing, the combined route reduced flocculant dosage by 37.5%, treatment time by more than threefold, and specific energy consumption by 40%.

The simultaneous recovery of process water and reduction in sludge volume make the proposed method an integral part of the drilling-site resource cycle rather than merely a clarification process. The DSh-100 reference duty of $15 \text{ m}^3/\text{h}$ at 0.6 MPa provides a traceable scale-up boundary, and a 5.5 kW variable-frequency pump is a conservative specification for a future modular pilot unit. The illustrative economic model indicates avoided variable burdens of approximately USD $0.92/\text{m}^3$ without sludge logistics and USD $3.92/\text{m}^3$ when the central sludge-transport assumption is included; investment decisions require site-specific tariffs, raw operating records, and full CAPEX/OPEX analysis.

The main scientific result is the demonstrated distinction between maximum separation efficiency and an operationally rational multicriteria region. The controlled hydrodynamic field couples phase separation, water recovery, sludge compaction, reagent demand, and specific energy consumption within a single technological regime. This provides a quantitative basis for designing compact treatment modules for concentrated water-based drilling waste.

The proposed technology can therefore reduce the water and logistics intensity of drilling operations, subject to continuous pilot validation, complete water quality characterization, and site-specific regulatory assessment.

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