

Review

Hydrodynamic Cavitation in Water and Wastewater Treatment: A Critical Review of Applications, Reactor Design, and Process Function

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Abstract

Hydrodynamic cavitation has attracted increasing attention in water and wastewater treatment because it can generate localized shear, pressure fluctuations, interfacial renewal, and reactive species in relatively simple continuous-flow devices. This review critically examines its main application domains, including microbial disinfection, cyanobacterial bloom control, organic micropollutant degradation, real wastewater treatment, sludge pretreatment for energy recovery, and hybrid process configurations. Rather than treating hydrodynamic cavitation as a single treatment mode, the discussion compares applications in relation to reactor design, matrix characteristics, treatment target, operating conditions, and assigned process function. The analysis shows that performance depends strongly on the interaction among device geometry, treated matrix, process configuration, and evaluation metrics. The same nominal process may therefore act as direct treatment, pretreatment, mass-transfer intensifier, oxidant-activation module, or support to downstream biological and polishing steps. The most consolidated evidence concerns microbial disinfection, sludge pretreatment, and several classes of organic contaminants, whereas PFAS treatment, field-scale validation, and system-level assessment remain less mature. Overall, hydrodynamic cavitation is best interpreted as a process-intensification platform rather than as a universally applicable stand-alone solution. Further progress will require more transparent assessment criteria, more comparable metrics, stronger validation in real matrices, more controllable reactors, and more rigorous energy, techno-economic, and scale-up evaluation.

Keywords: hydrodynamic cavitation; water treatment; wastewater treatment; process intensification; advanced oxidation processes; reactor design; sludge pretreatment; scale-up

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1. Introduction

Over the past two decades, hydrodynamic cavitation has gained increasing relevance in water and wastewater treatment. Interest in this technology arises from its ability to generate, in relatively simple devices compatible with continuous operation, localized conditions characterized by high shear, microjets, pressure fluctuations, interfacial renewal, and formation of reactive species. These effects have supported its investigation across a broad range of applications and have extended its relevance beyond the narrower field of advanced oxidation processes.

The current application range includes microbial disinfection, cyanobacterial bloom control, degradation of organic micropollutants, treatment of real wastewaters, and sludge pretreatment for energy recovery. Such breadth, however, also makes a unitary interpretation of the process insufficient [1,2]. As the target, matrix, reactor, and operating conditions change, both the dominant mechanism and the role assigned to the treatment may change. In some systems, mechanical effects are central. In others, radical-driven transformation prevails. In still others, the main contribution lies in mass-transfer intensification, matrix conditioning, or improved downstream treatability. Under the same technological label, hydrodynamic cavitation therefore includes applications that differ in process logic, performance criteria, and maturity of evidence [3].

This heterogeneity is particularly relevant for sustainable water and wastewater management. Hydrodynamic cavitation is often proposed as a means to reduce chemical demand, improve process efficiency, support water reuse, enhance sludge valorization, or intensify existing treatment trains. These potential advantages are important for resource-efficient treatment systems, but they cannot be inferred from pollutant removal alone. Claims of environmental benefit require attention to final matrix quality, residual toxicity, energy demand, chemical consumption, operational stability, and transferability to real matrices and larger-scale systems.

In this perspective, the relevance of hydrodynamic cavitation to sustainable development lies not in generic process intensification, but in its potential contribution to more resource-efficient, lower-chemical-demand, and better-integrated water and wastewater treatment systems.

A critical reading of the field therefore requires applications, devices, matrices, and process strategies to be considered together [1–4]. Parent compound reduction, microbial inactivation, biodegradability enhancement, methane-yield increase, biomass destabilization, and dewaterability improvement are not equivalent indicators. Similarly, performance measured in model solutions cannot be transferred automatically to real wastewaters, natural blooms, or complex sludge matrices. The value of hydrodynamic cavitation depends on whether the treatment function assigned to the reactor is consistent with the matrix, the target, the selected performance metrics, and the position of the unit within the overall treatment train.

Review Approach, Novelty, and Limitations

This work was prepared as a critical narrative review rather than as a quantitative meta-analysis. The literature was identified through searches of major scientific databases and publisher platforms, including Scopus, Web of Science, ScienceDirect, and Google Scholar, followed by cross-checking of references in relevant review articles and primary studies. The literature coverage includes foundational studies from the early development of hydrodynamic cavitation in water treatment and more recent contributions up to 2026, with emphasis on reactor configuration, operating conditions, treatment target, matrix complexity, performance metrics, energy demand, and process integration.

Studies were considered when they addressed hydrodynamic cavitation in water treatment, wastewater treatment, sludge processing, hybrid advanced oxidation processes, microbial or algal control, nutrient management, reactor modelling, or scale-up. Priority was given to peer-reviewed studies reporting reactor type, operating conditions, treated matrix, and treatment performance. Studies focused exclusively on acoustic cavitation were not treated as core evidence, except where they provided direct comparison with hydrodynamic cavitation or formed part of hybrid configurations. Contributions with insufficient process information, limited relevance to aqueous treatment systems, or only marginal connection to hydrodynamic cavitation were not used as central evidence.

The novelty of this review lies in the interpretive organization of the field around process function rather than application listing alone. Hydrodynamic cavitation is examined as a platform whose significance changes according to reactor design, matrix characteristics, treatment objective, operating conditions, and evaluation metric. This perspective makes it possible to distinguish cases in which the process is more convincing as a direct treatment from those in which its main value lies in pretreatment, mass-transfer intensification, oxidant activation, matrix conditioning, or support to downstream biological and polishing steps.

The qualitative evidence-maturity assessment used in this review is based on four main criteria: breadth of the experimental base, consistency of reported outcomes, availability of data from real or complex matrices, and comparability or transferability of the adopted metrics. The assessment is intended only as an interpretive aid for cross-domain comparison. It is not a formal scoring system and does not imply strict quantitative equivalence among application areas that differ in treatment objective, matrix type, reactor configuration, and performance indicator.

The main limitation of this review follows from the heterogeneity of the available literature. Many studies differ simultaneously in reactor geometry, operating pressure, cavitation regime, matrix composition, treatment time, oxidant dose, and evaluation metric. This prevents robust quantitative comparison across all application domains. For this reason, the emphasis is placed on process interpretation, evidence maturity, recurring limitations, and research priorities rather than on pooled numerical ranking.

Table 1 provides a comparative overview of the main application domains addressed in this review, highlighting the prevailing role of hydrodynamic cavitation, the most informative performance metrics, and the qualitative maturity of the available evidence.

Table 1. Comparative overview of the main application domains of hydrodynamic cavitation in water and wastewater treatment.

Application Domain	Prevailing Role of HC	Key Metrics	Evidence Maturity
Bacterial disinfection ¹	Direct treatment/intensification	Log reduction; energy per order; number of passes	■■■■
Viral disinfection ²	Direct treatment/intensification	Infectivity reduction; number of passes; effective exposure within the loop	■■■
Cyanobacterial bloom control ³	Selective destabilization/physiological control	Buoyancy loss; sedimentation; regrowth; toxin release	■■■
Pharmaceuticals ⁴	Treatment intensification	Parent compound removal; TOC/COD; mineralization; toxicity	■■■
Antibiotics ⁵	Treatment intensification	Parent compound removal; TOC/COD; mineralization	■■■
Endocrine-disrupting Compounds ⁶	Radical-based intensification	Parent compound removal; TOC/COD; reactor–cavitation response	■■
PFAS ⁷	Radical/interfacial intensification	Defluorination; fluorine balance; intermediates; energy demand	■
Phenols and chlorophenols ⁸	Direct treatment/hybrid systems	Pollutant removal; TOC/COD; operating window	■■■
Pesticides and herbicides ⁹	Direct treatment/hybrid systems	Pollutant removal; TOC/COD; energy–performance trend	■■■
Chlorinated solvents and volatile aromatics ¹⁰	Direct treatment/interfacial intensification	Pollutant removal; energy demand; gas-phase effects	■■

Real wastewaters: biodegradability enhancement ¹¹	Pretreatment	BOD/COD; COD; TOC; downstream treatability	■ ■ ■
Real wastewaters: intensification of oxidative processes ¹²	AOP intensification/hybrid systems	COD; TOC; colour; reagent consumption; specific energy	■ ■ ■
Real wastewaters: polishing and reuse ¹³	Polishing/water reconditioning	Residual COD/TOC; colour; toxicity; reuse suitability	■ ■
Sludge pretreatment for anaerobic digestion ¹⁴	Line pretreatment	SCOD; methane yield; net energy balance	■ ■ ■ ■
Sludge dewaterability Improvement ¹⁵	Matrix conditioning/support to hybrid systems	CST; SRF; cake solids; water content	■ ■
NH ₄ ⁺ management/removal in concentrated streams ¹⁶	Mass-transfer intensification	NH ₄ ⁺ removal; energy demand; reactor-dependent performance	■ ■

Note: Evidence maturity is expressed qualitatively on a four-level scale, from ■ to ■■■■. The classification is based on breadth of evidence, consistency of outcomes, availability of real- or complex-matrix data, and comparability or transferability of metrics. The scale is used only as an interpretive aid and does not represent a formal quantitative ranking or strict equivalence among application domains. ¹ In bacterial disinfection, evidence is broad but strongly dependent on reactor configuration, microbial target, water matrix, and energy metric. ² In viral disinfection, performance depends strongly on effective exposure to cavitational active regions, making treatment time alone insufficient. ³ In cyanobacterial bloom control, excessive severity may promote lysis, toxin release, and deterioration of liquid-phase quality; natural-bloom evidence remains less uniform. ⁴ For pharmaceuticals, parent compound removal may overestimate treatment depth when mineralization, residual toxicity, and final matrix quality are not assessed. ⁵ For antibiotics, performance is highly sensitive to reactor geometry and auxiliary oxidants, and cavitation alone is often only partially effective for stable compounds. ⁶ For endocrine-disrupting compounds, the evidence base remains narrower and is still dominated by model compounds and radical-assisted systems. ⁷ For PFAS, parent compound transformation cannot be equated with class destruction; defluorination, fluorine balance, intermediates, and energy demand remain essential. ⁸ For phenols and chlorophenols, deeper treatment often requires hybrid configurations, and the useful operating window may differ from the most intense cavitation regime. ⁹ For pesticides and herbicides, response is strongly contaminant-specific, and cavitation often initiates rather than completes degradation. ¹⁰ For chlorinated solvents and volatile aromatics, interfacial effects and localized pyrolytic contributions make results less easily generalizable. ¹¹ In biodegradability-oriented wastewater pretreatment, the main benefit is often improved downstream treatability rather than direct oxidative removal. ¹² In hybrid oxidative treatment of real wastewaters, comparability remains limited because matrix composition, reactor design, reagent dose, and performance criteria often vary simultaneously. ¹³ In polishing and reuse applications, treatment value depends strongly on the position of the cavitation unit within the overall treatment train. ¹⁴ In sludge pretreatment for anaerobic digestion, maximum disintegration does not necessarily coincide with the best net outcome; the key criterion is energy input versus methane gain. ¹⁵ In sludge dewaterability improvement, disintegration alone may produce contradictory effects, and the strongest evidence usually involves hybrid conditioning. ¹⁶ In NH₄⁺ management from concentrated streams, mass transfer and reactor design are central, but the evidence remains less extensive and less comparable than in other sludge-line applications.

Previous studies and recent reviews indicate that hydrodynamic cavitation cannot be interpreted independently of reactor design, matrix characteristics, treatment target, and assigned process function [5–8]. This interpretation is consistent with broader assessments of hydrodynamic cavitation as a process platform whose apparent performance depends on the coupling among mechanical effects, radical or oxidative pathways, mass-transfer intensification, matrix conditioning, and integration within the treatment train [9–11].

2. Microbial Disinfection of Water

Microbial disinfection is one of the hydrodynamic cavitation applications with the broadest experimental base. The literature covers Gram-negative and Gram-positive bacteria, model viruses, seawater, and several reactor families, including orifice plates, Venturi devices, vortex diodes, cavitating jets, and rotational reactors [12]. These studies demonstrate genuine disinfection potential [13], but they do not support device-independent or matrix-independent conclusions [14]. Observed performance depends on the microbial target, reactor configuration, collapse quality, number of effective events, number of passes, and characteristics of the treated water [12–14].

2.1. Inactivation Mechanisms

Microbial inactivation results from the combined action of mechanical and chemical effects. Cavity collapse generates microjets, pressure waves, shear stresses, and strong local velocity gradients that may damage cell walls, alter membranes, and reduce microbial viability [15]. Under more severe conditions, structural damage may extend to cell lysis. Oxidizing species generated during cavitation may also contribute to inactivation, especially when the process is combined with external oxidants or embedded in hybrid configurations [16].

The relative importance of these mechanisms depends on the reactor and the target. In bacteria, mechanical action may dominate when collapse is concentrated in locally aggressive regions [17], whereas other systems show a combined contribution of structural damage and oxidative stress. Viral inactivation is even more dependent on effective exposure. Results obtained with the MS2 bacteriophage indicate that infectivity reduction may involve capsid damage, repeated passage through cavitational active zones, and, in some configurations, reactive species formation. Total treatment time alone is therefore an incomplete descriptor of disinfection performance.

2.2. Microbial Target and Effective Exposure

Microbial response varies substantially across targets. In bacterial systems, *Escherichia coli* is generally more sensitive than Gram-positive bacteria, largely because of differences in cell wall structure [18]. This limits direct extrapolation from *E. coli* to more resistant microorganisms. Even within bacterial systems, the required cavitation regime is target-dependent [19]. For *Legionella pneumophila*, the available evidence suggests that rapid pressure drop under conditions close to supercavitation may play an important role [20].

For viruses, the number of passages through the cavitator is particularly important. Infectivity reduction depends on the cumulative probability that viral particles cross regions where cavitation events are sufficiently effective. This strengthens the need for metrics based on pass number, active-zone exposure, or reactor-specific event frequency, rather than on nominal treatment time alone.

2.3. Reactor Configurations

The main reactor families used for disinfection are orifice plates, Venturi devices, vortex diodes, cavitating jets, and rotational reactors of the rotor–stator or rotor–rotor type [13,21–23]. This distinction is not merely geometric. Each configuration generates cavitation through a different hydraulic mechanism and presents a specific balance among collapse intensity, active volume, pressure loss, regime stability, energy demand, and scale-up potential.

Orifice plates are simple, inexpensive, and useful as baseline devices, but their performance is often associated with localized cavitation, high energy dissipation, and

limited active volume [21,22]. Venturi devices generally provide smoother pressure recovery and more stable cavitation, although their effectiveness remains highly sensitive to throat diameter, converging–diverging geometry, and diffuser angle [23]. Vortex diodes are relevant because significant bacterial reductions may be achieved at relatively low pressure drops, provided that the internal swirling-flow structure is maintained. Cavitating jets generate locally aggressive collapse regions and can be highly effective against both Gram-negative and Gram-positive bacteria, although energy balance and transferability to larger treated volumes require careful evaluation [24].

Rotational reactors represent a more advanced development line. In rotor–stator and rotor–rotor systems, the fluid undergoes rapid sequences of constriction, expansion, and high shear, increasing the number of cavitation events experienced by each fluid element. Reported advantages include shorter disinfection times, improved event distribution, and closer proximity to continuous operating conditions. Their relevance lies in the possibility of enlarging the active zone and making disinfection less dependent on highly localized collapse.

2.4. Operating Parameters and Matrix Quality

Reactor configuration cannot be separated from operating conditions. Reactor pressure, pressure drop, flow rate, number of passes, throat or hole dimensions, rotor–stator clearance, and fluid properties all contribute to defining the cavitation regime and the resulting disinfection performance [25]. Pressure and pressure drop influence cavity inception, growth, and collapse intensity, but their effect is not linear. Increasing pressure may improve inactivation only within a useful operating window; beyond that range, additional energy input may increase faster than the microbiological benefit.

Process time and pass number are equally important, especially in recirculating systems. In these configurations, microbial or viral inactivation depends on the cumulative probability that the target repeatedly crosses cavitationally active regions. Treatment time should therefore be interpreted together with treated volume, loop configuration, pass frequency, and reactor-specific exposure.

Initial microbial concentration also affects the apparent inactivation response. Higher starting concentrations may require longer exposure or a larger number of effective events to achieve the same log reduction, whereas low initial concentrations may make performance appear more favorable if detection limits are not carefully considered. Operating temperature can modify vapour pressure, viscosity, gas solubility, microbial susceptibility, and collapse intensity. Its effect is therefore process-specific and should not be treated as a secondary parameter.

pH further influences disinfection performance, particularly in hybrid systems. It may affect cell-surface properties, oxidant speciation, radical stability, and microbial susceptibility to oxidative stress. Matrix composition adds an additional level of complexity. Results obtained in simple water cannot be directly transferred to seawater or real waters, where salinity, suspended solids, natural organic matter, inorganic ions, and mixed microbial communities may alter both the cavitation field and target susceptibility. In disinfection studies, microbial data must therefore be interpreted together with hydraulic conditions, process time, pH, temperature, initial concentration, and water composition.

2.5. Hybrid Systems, Energy Efficiency, and Comparative Limitations

Cavitation-based disinfection becomes especially relevant when integrated with complementary treatments. Evidence from seawater, thermal systems, and oxidant-assisted configurations indicates that hydrodynamic cavitation can reduce chemical demand or increase the rate of inactivation [26]. In these cases, the benefit does not derive only from cavity collapse. It also depends on improved contact between microorganisms and reactive species, interfacial renewal, enhanced oxidant distribution, and preliminary weakening of biological structures.

Energy assessment remains central. Comparisons across reactor configurations are often weakened by non-uniform metrics, including energy per treated volume, energy per order, log reduction at fixed treatment time, and quantities referred to as pass number [13,26]. Available evidence often suggests favorable performance for vortex diodes and rotational reactors, but robust comparison remains difficult when reactor geometry, treated volume, experimental loop, matrix composition, and performance criteria vary simultaneously.

The most stable conclusion in this domain is that disinfection performance is strongly reactor- and matrix-dependent. Collapse quality, active-zone distribution, exposure frequency, operating conditions, and water composition directly shape the observed inactivation. By contrast, energy comparability across devices, transferability to real matrices, and scale-up criteria remain less consolidated.

3. Cyanobacterial Bloom Control and *Microcystis aeruginosa*

Cyanobacterial proliferation in surface waters affects water quality, ecological stability, drinking-water management, and public health, particularly when toxin-producing species are involved. Hydrodynamic cavitation has therefore been investigated not only as a means of damaging cyanobacterial biomass, but also as a process able to destabilize blooms within the water column. Most available studies focus on *Microcystis aeruginosa*, whose intracellular gas vesicles regulate buoyancy and promote accumulation in surface layers [27]. This feature is important because bloom control does not necessarily require complete cell destruction. In several cases, a useful outcome may consist of buoyancy loss, aggregation, and sedimentation, provided that liquid-phase quality is not worsened by excessive cell lysis.

The critical issue in this application is that hydrodynamic cavitation can produce different and not always equally desirable outcomes [28]. Under moderate conditions, the dominant effect may be selective destabilization of the bloom, with reduced buoyancy and enhanced separation potential. Under more severe conditions, the process may cause extensive physiological damage, membrane disruption, and lysis. Immediate biomass reduction is therefore an incomplete performance indicator. In cyanobacterial systems, treatment value depends on the balance between biomass control, toxin release, dissolved organic matter formation, regrowth potential, and the availability of downstream removal or polishing steps [27,28].

3.1. Mechanisms and Treatment Pathways

The action of hydrodynamic cavitation on cyanobacterial biomass results from coupled mechanical and chemical effects. Cavity collapse generates microjets, pressure waves, local velocity gradients, and shear stresses that may alter the cell surface, weaken membranes, and damage sensitive intracellular structures [29]. In *M. aeruginosa*, the most characteristic target is the gas vesicle. Its deformation or collapse reduces buoyancy and promotes loss of stability in surface accumulations. This mechanism supports a selective-

destabilization pathway, in which the process facilitates aggregation and sedimentation without necessarily maximizing cell destruction.

A second pathway is associated with more serious physiological damage. Several studies report reduced photosynthetic activity, impairment of photosystem II, pigment loss, growth inhibition, membrane damage, and, at higher severity, cell lysis. This pathway may be useful when rapid suppression of cell viability is required or when a downstream step is available to manage released intracellular material. It is not, however, automatically preferable. More aggressive treatment may increase dissolved organic load, pigment release, and toxin-related risk, thereby worsening the final water-quality profile despite apparent biomass reduction [27–29].

3.2. Reactor Type, Operating Conditions, and Hybrid Configurations

Reactor type and operating window directly shape cyanobacterial response. Jet cavitation and swirling-jet systems tend to promote buoyancy loss and sedimentation, whereas more severe configurations may shift the process toward structural disruption and lysis. The outcome depends on pressure-field structure, active-zone distribution, collapse regime, exposure time, initial biomass concentration, temperature, and post-treatment irradiation conditions [30]. Operating pressure also shows a non-linear effect: increasing pressure may improve treatment efficacy only up to a useful range, beyond which the additional benefit may no longer increase proportionally [31].

This non-linearity is particularly important because the most intense treatment is not necessarily the most suitable one. Short or moderate exposure may be sufficient to impair gas vesicles and reduce regrowth, whereas longer or harsher exposure increases the probability of membrane rupture and intracellular release. Data obtained with field-collected biomass and pilot-scale configurations are therefore especially valuable, because they reduce the gap between simplified cultures and natural bloom conditions. Even in these cases, however, transferability remains limited by bloom composition, particulate matter, natural organic matter, associated microbial communities, and changing environmental conditions.

Hybrid configurations extend the process window but also change the function assigned to hydrodynamic cavitation. Coupling with ozone combines biomass damage with enhanced gas–liquid mass transfer and stronger oxidative pathways, often producing faster reductions in biomass and pigments than cavitation or ozone alone [32]. Coupling with hydrogen peroxide follows a different logic. At moderate doses, it may strengthen physiological inhibition and buoyancy loss without necessarily promoting extensive lysis. These two configurations should therefore not be treated as equivalent. Ozone-assisted systems are more clearly associated with oxidative intensification, whereas hydrogen-peroxide-assisted systems may be more compatible with selective bloom destabilization and subsequent physical removal.

3.3. Water-Quality Implications and Transferability

In cyanobacterial bloom control, performance cannot be judged only from optical-density decrease, visible biomass reduction, or immediate loss of cell viability. The release of intracellular material, pigments, dissolved organic matter, and cyanotoxins may offset the benefit obtained from biomass disruption. The most informative assessments are therefore those that consider buoyancy loss, sedimentation, photosynthetic activity, regrowth, toxin release, and liquid-phase quality together.

This point is central for interpreting the environmental relevance of hydrodynamic cavitation. A treatment that is effective inside the reactor may still be incomplete if the treated matrix subsequently releases dissolved organic matter, supports regrowth, or requires additional polishing before discharge or reuse. Conversely, a less aggressive

treatment may be more appropriate when the objective is to destabilize the bloom and facilitate separation while limiting deterioration of the liquid phase. The process should therefore be evaluated as part of a treatment sequence rather than as an isolated biomass-destruction step.

The main limitation remains transferability to complex natural blooms. Much of the available evidence is based on *M. aeruginosa* cultures or simplified matrices. In natural waters, response may be altered by species composition, suspended particles, organic matter, nutrient status, hydrodynamic conditions, and associated biological communities. The evidence base is promising, but still not uniform under field conditions. In this application domain, the key issue is therefore not biomass reduction alone, but the balance among bloom destabilization, final liquid-phase quality, regrowth control, toxin management, and compatibility with downstream treatment [27–32].

4. Degradation of Pharmaceuticals, Antibiotics, Endocrine-Disrupting Compounds, and PFAS

Persistent organic micropollutants expose the limits of conventional treatment when the objective is not only to reduce bulk organic load, but also to transform compounds that are present at low concentrations, biologically active, poorly biodegradable, and often resistant to biological processes. In this context, hydrodynamic cavitation has been investigated both as a direct treatment and, more frequently, as an intensification step combined with hydrogen peroxide, persulfate, ozone, photocatalysis, or other advanced oxidation processes. The available evidence shows a clear gradient of maturity and effectiveness [33]. Some pharmaceutical compounds undergo appreciable transformation under cavitation alone, whereas more stable antibiotics, endocrine-disrupting compounds, and perfluorinated substances generally require stronger dependence on reactor design, oxidant activation, and hybrid process configuration [33,34].

The criterion used to evaluate performance is decisive [34]. Parent compound disappearance is often reported as the main outcome, but it does not necessarily correspond to mineralization, toxicity reduction, or lower environmental risk. More informative studies also consider TOC reduction, transformation intermediates, toxicity evolution, performance per pass, energy demand, and comparison across reactor configurations. For PFAS, this distinction is even more important, because partial removal of the initial compound cannot be equated with effective destruction unless defluorination, fluorine balance, intermediate formation, and energy cost are also addressed.

4.1. Pharmaceuticals and Real-Water Matrices

The most established pharmaceutical examples include compounds known for persistence in biological treatment, such as carbamazepine, diclofenac, and ibuprofen. In these systems, hydrodynamic cavitation can promote transformation of the parent compound, but the response remains strongly dependent on molecular structure, operating conditions, and process configuration. For particularly recalcitrant compounds, cavitation alone often produces measurable but incomplete degradation, whereas coupling with oxidative processes more clearly increases treatment depth [35].

Diclofenac illustrates the importance of looking beyond parent compound removal. Coupling with heterogeneous photocatalysis has been associated not only with high removal of the initial compound, but also with a significant decrease in TOC [36]. For ibuprofen, degradation depends strongly on pressure and operating conditions, and reported pathways include hydroxylation, demethylation, and fragmentation intermediates [37]. These examples indicate that hydrodynamic cavitation may directly promote molecular

transformation, but treatment significance remains incomplete when mineralization, residual toxicity, and intermediate formation are not considered.

The transition from synthetic water to real matrices further qualifies the role of the process. In municipal wastewaters or biologically treated effluents, hydrodynamic cavitation does not behave as a universal polishing step [38]. More biodegradable molecules may already be removed by biological treatment, whereas more recalcitrant compounds require an additional contribution from cavitation, UV treatment, or other downstream combinations. In these cases, the benefit may lie less in direct micropollutant degradation than in matrix modification, improved accessibility, or enhanced performance of the following treatment stage. The position of the cavitation unit within the treatment train therefore becomes a process variable rather than a simple sequence choice.

4.2. Antibiotics and Endocrine-Disrupting Compounds

Antibiotics provide one of the clearest examples of the link between reactor design and treatment outcome. The available literature includes norfloxacin, chlorotetracycline, tetracycline, ciprofloxacin, and cephalixin, and shows that even relatively modest geometric changes in the restriction element or in the reactor can substantially alter treatment efficiency [39,40]. In these systems, cavitation alone may initiate degradation, but final performance depends more strongly on collapse quality, event distribution, and the presence of auxiliary oxidants.

For fluoroquinolones and tetracyclines, reactor optimization increases parent compound degradation and, in the presence of hydrogen peroxide, persulfate, or other oxidative partners, can move the process toward higher removal levels [41]. Ciprofloxacin data also highlight the interest of vortex-based configurations over more conventional devices [42,43]. These results confirm that pressure drop alone is not a sufficient descriptor of performance. The number, distribution, and usefulness of cavitation events are more relevant for interpreting degradation efficiency. Cephalixin illustrates the opposite limit: when chemical stability is high and the system is not sufficiently intensifying, cavitation alone remains only partially effective, and TOC reduction may be much lower than parent compound removal.

Bisphenol A provides a complementary case because it links kinetic response, radical chemistry, and cavitation-field properties. In persulfate-assisted systems, BPA removal increases markedly, with sulfate radicals playing a dominant role and hydroxyl radicals contributing secondarily [44]. The process therefore acts not only as a source of cavitation events, but also as a means of activating secondary oxidants and modifying the radical system. The correlation between BPA degradation, bubble-volume expansion, and cavitation-related parameters further indicates that chemical performance must be read in relation to flow structure and cavitation-regime quality, not only to radical availability in the bulk liquid [45].

4.3. PFAS: Defluorination, Interfacial Effects, and Evidence Limits

PFAS treatment is the most demanding case considered in this section. For this contaminant class, parent compound disappearance is an insufficient metric. A meaningful assessment requires at least defluorination, fluorine balance, transformation intermediates, and energy demand. The available literature remains limited, but it already suggests two distinct process logics.

For PFOA treated in persulfate-assisted systems, degradation and defluorination are greater than expected from cavitation alone [46]. Sulfate radicals appear to play an important role, and shorter-chain species may be formed. This suggests that, for such compounds, treatment effectiveness depends largely on the ability to activate a more aggressive radical chemistry than that available in the aqueous bulk alone. At the same time, the

partial character of defluorination shows that transformation of the parent compound does not correspond to complete fluorinated mineralization [47].

PFOS treated in an orifice-based system without catalysts or additives suggests a partly different interpretation. Degradation and defluorination may occur without auxiliary oxidants, but both remain partial. The proposed mechanism points to the relevance of the bubble–liquid interface, where PFOS may accumulate because of its amphiphilic character. From this perspective, hydrodynamic cavitation may act not only through radicals in the bulk liquid, but also through high-energy interfacial environments. These findings are important, but the evidence remains less mature than that available for pharmaceuticals and several antibiotics. PFAS-related claims therefore require particular caution, especially when defluorination, fluorine balance, toxicity, intermediates, and energy cost are incomplete.

4.4. Critical Interpretation and Process Significance

Across these contaminant classes, hydrodynamic cavitation reaches its most convincing performance when its role is matched to contaminant chemistry, reactor design, and process configuration. Combinations with hydrogen peroxide, persulfate, ozone, photocatalysis, acoustic cavitation, or cold plasma should not be interpreted as simply stronger versions of the same treatment. Their advantage arises because cavitation can modify micromixing, mass transfer, oxidant activation, interfacial exposure, and, in some cases, target accessibility [36].

The significance of the process therefore changes with the contaminant class. For moderately recalcitrant pharmaceuticals, hydrodynamic cavitation may contribute directly to molecular transformation [38]. For antibiotics and endocrine-disrupting compounds, its main value more often lies in reactor-dependent intensification and activation of auxiliary oxidants [44]. For PFAS, the current evidence is promising but still limited, and the main unresolved gap remains the distance between initial transformation, effective defluorination, environmental-risk reduction, and energy feasibility [44,46,47].

This section also shows why removal-based evaluation is insufficient. Micropollutant treatment should be interpreted through mineralization, residual toxicity, intermediates, matrix effects, energy demand, and downstream compatibility. In real waters, contaminant behaviour may also depend on partitioning, transport, and interaction with organic matter or suspended phases. A process that transforms the parent compound inside the reactor may therefore still require additional assessment of the treated matrix before discharge, reuse, or biological polishing. Hydrodynamic cavitation is most credible in this domain when it is evaluated as part of an integrated treatment train rather than as an isolated removal step.

5. Degradation of Pesticides, Phenols, Chlorinated Compounds, and Other Industrial Organic Pollutants

The degradation of pesticides, substituted phenols, chlorinated solvents, and other industrial organic pollutants is one of the application areas in which hydrodynamic cavitation shows both its potential and its limitations most clearly. This group includes compounds that differ widely in volatility, hydrophobicity, electronic structure, toxicity, and resistance to conventional treatment. For nitrated and chlorinated phenols, as well as for many pesticides, stand-alone cavitation may initiate or promote degradation, but it rarely provides sufficient treatment depth to justify complete matrix treatment on its own [48]. By contrast, for volatile chlorinated solvents and some simple aromatic compounds, interfacial effects, gas-phase behaviour, and local pyrolytic contributions may become more relevant [49].

This application domain therefore cannot be interpreted through a single dominant mechanism. Performance depends on the contaminant–reactor pair, the prevailing degradation pathway, and the extent to which the process is combined with oxidants, catalysts, gases, or other treatment steps [48,49]. The same reactor may be only moderately effective for stable pesticides and more favorable for compounds that are volatile, interfacially active, or more susceptible to radical attack [50]. A critical comparison of this literature therefore requires a distinction among compounds mainly requiring hybrid radical-based systems, compounds for which cavitation alone can already play a meaningful role, and industrial matrices in which cavitation is better interpreted as an intensification step within a broader treatment train [48–50].

5.1. Phenols, Nitrophenols, and Chlorophenols

Phenolic compounds are among the most informative systems for evaluating hydrodynamic cavitation in an advanced-oxidation framework. For p-nitrophenol, the available evidence clearly shows the existence of an optimal operating window associated with pressure and cavitation-number conditions [51,52]. Beyond this window, increasing operating severity does not produce a proportional increase in useful degradation. This confirms that the nominally most intense cavitation regime is not necessarily the most efficient one, and that performance depends on the balance among collapse quality, active-zone distribution, reaction pathway, and energy cost.

The case of 2,4-dinitrophenol clarifies the role of hybrid configurations. Stand-alone cavitation can promote degradation, but the highest removal levels are obtained in the presence of hydrogen peroxide, activated persulfate, and especially Fenton or Fenton-like systems [53]. In these cases, the relevant gain concerns not only disappearance of the parent compound, but also deeper matrix transformation, including TOC reduction. For more recalcitrant phenols, hydrodynamic cavitation is therefore more convincing as an intensifier of established radical chemistries than as a self-sufficient treatment.

A similar interpretation applies to chlorophenols [54,55]. For 2,4,6-trichlorophenol, the strongest performance is obtained when cavitation is combined with ozone and hydrogen peroxide, leading to reductions in both contaminant concentration and TOC. For 4-chloro-2-aminophenol, coupling with UV and ozone produces stronger results than cavitation alone. In these systems, the decisive factor is not the mere occurrence of cavitation, but the ability of the reactor and the process partner to create a sufficiently effective and well-distributed oxidative environment.

5.2. Pesticides and Herbicides

Pesticides are a demanding test case because persistence, toxicity, and chemical stability often coincide. Within this class, stand-alone cavitation is generally able to initiate degradation, but the most substantial gains usually arise in hybrid systems. This pattern is evident for organophosphorus compounds. For methyl parathion and dichlorvos, treatment efficiency depends strongly on pressure, temperature, and pH, but the most effective configurations are those combined with hydrogen peroxide and, especially, Fenton-based systems [56,57]. The useful contribution of cavitation lies not only in radical generation, but also in improving contact among the liquid phase, oxidant, and contaminant.

Imidacloprid confirms the same trend and further highlights the role of reactor geometry. Stand-alone treatment produces only moderate degradation, whereas combinations with hydrogen peroxide, Fenton, advanced Fenton, and activated persulfate lead to much higher removal levels [58]. The available data also show that performance changes with the type of cavitator used, confirming that system chemistry cannot be separated from the quality with which the reactor converts hydraulic energy into useful events [59,60].

Atrazine and alachlor further illustrate the contaminant-specific character of the response. Some cavitation-based configurations can provide appreciable degradation of alachlor, whereas atrazine shows clearer improvement when coupled with hydrogen peroxide, persulfate, UV, or catalysts, with stronger reductions in both contaminant concentration and COD. In this class, hydrodynamic cavitation is therefore most credible when its role is defined as intensification of broader radical-based treatment schemes rather than as a universal stand-alone degradation process.

5.3. Volatile, Chlorinated, and Non-Conventional Industrial Pollutants

Chlorinated solvents and simple aromatic compounds follow a partly different logic from phenols and pesticides. For more volatile compounds, local pyrolytic contributions, gas-phase effects, and interfacial accumulation may become more important than radical oxidation in the bulk liquid. Chloroform is particularly informative in this respect [61,62]. The combination of hydrodynamic and acoustic cavitation produces a synergistic effect, suggesting a role for cavitation-nuclei density, interfacial collapse, and localized high-energy environments, in addition to radical formation [63].

Benzene provides a complementary indication [64]. Stand-alone cavitation can already lead to high degradation, while coupling with air may further increase removal and improve energy efficiency. In such systems, gas-phase management and thermal conditions become part of process design. For volatile compounds, performance therefore depends more strongly on cavity structure, collapse location, and gas–liquid interactions than it does for pollutants that are more polar and less prone to interfacial accumulation.

The available literature also includes highly toxic industrial streams, such as cyanide-containing effluents. In these systems, stand-alone cavitation can promote significant degradation, while hydrogen peroxide further improves performance [65]. The comparison with acoustic cavitation is relevant because hydrodynamic cavitation appears more favorable at comparable dissipated energy in the available studies. These results extend the application field beyond conventional organic micropollutants, but they also reinforce the need to match reactor configuration, contaminant chemistry, matrix composition, and treatment objective.

5.4. Reactor-Dependent Interpretation and Optimization Criteria

A cross-cutting conclusion across this application domain is that reactor geometry and operating parameters directly condition treatment significance. Pressure, cavitation number, temperature, pH, orifice diameter, nozzle shape, hole arrangement, gas addition, and auxiliary oxidants affect cavitation quality and process performance. This pattern is consistent across nitrophenols, pesticides, volatile aromatics, and advanced hybrid systems [66,67]. In most cases, the relationship between operating intensity and useful degradation is non-linear, with an optimal window beyond which energy input increases faster than treatment benefit.

This point is central for process design. Hydrodynamic cavitation should not be optimized by indiscriminately increasing pressure or operating severity. The optimal configuration depends on the reactor–contaminant pair, the dominant removal mechanism, and the required treatment endpoint [68,69]. Volatile or interfacially active compounds may require different configurations from those suitable for stable pesticides or highly substituted phenols. Reactor design is therefore not a secondary constructional variable, but an integral part of treatment selectivity [70,71].

Within this application domain, a unitary interpretation is not defensible. Performance depends on contaminant chemistry, matrix composition, reactor quality, operating window, and process integration. For many recalcitrant pesticides and phenols, the main limitation remains the difficulty of achieving deep removal without hybrid configurations

[48,49]. For volatile and interfacially active compounds, by contrast, the relevance of hydrodynamic cavitation may depend more strongly on gas–liquid effects, interfacial accumulation, and localized high-energy collapse. The most robust evaluation should therefore consider parent compound removal together with TOC or COD reduction, intermediates, toxicity, energy demand, and compatibility with downstream treatment.

6. Real Wastewaters and Complex Matrices

The application of hydrodynamic cavitation to real wastewaters represents the critical transition from proof-of-concept studies to technological relevance. In model solutions, treatment response is mainly governed by the selected contaminant and reactor geometry. In real matrices, by contrast, cavitation operates in the presence of suspended solids, colloids, surfactants, salts, radical scavengers, pH fluctuations, variable organic load, and changing hydraulic or compositional conditions [72]. Under these circumstances, performance cannot be evaluated only through target-compound removal. Broader indicators are required, including COD, TOC, colour, turbidity, biodegradability, residual toxicity, reagent consumption, specific energy, and reuse suitability [73].

The available evidence indicates that, in real wastewaters, stand-alone hydrodynamic cavitation is rarely the most effective option [8–10,72,73]. Its most convincing role emerges in three process functions: pretreatment to improve biodegradability, intensification of established oxidative processes, and reconditioning of process waters or partially treated effluents before polishing, recycling, or reuse. In this domain, hydrodynamic cavitation is therefore better interpreted as a process element within a treatment train than as an isolated advanced oxidation process applied independently of matrix composition and downstream requirements.

6.1. Pretreatment and Biodegradability Enhancement

One of the strongest application areas concerns the pretreatment of wastewaters with high organic load and limited biodegradability. In distillery wastewaters, reported results show an increase in the BOD/COD ratio together with reductions in colour, COD, and TOC [74]. In such cases, the main benefit is not immediate mineralization, but a qualitative shift in the matrix toward higher biological treatability [75]. A similar pattern has been observed in lignocellulosic matrices suspended in pretreated municipal wastewaters, where cavitation increases the soluble fraction, promotes monosaccharide release, and improves the biodegradability index without evidence of by-products likely to hinder subsequent biological treatment.

These results clarify the process role of hydrodynamic cavitation in complex matrices [76]. The most useful outcome does not necessarily coincide with maximum destruction of organic load inside the cavitation unit, but with improved behaviour of the matrix in downstream treatment. The pretreatment function is therefore especially relevant when the bottleneck of the treatment train is substrate accessibility, biological compatibility, or mass transfer rather than direct oxidation [8–10,74–76]. This interpretation also reduces the risk of overvaluing COD removal alone when the actual advantage lies in enhanced downstream treatability.

6.2. Oxidative Intensification, Reconditioning, and Reuse

The most robust contribution in real industrial wastewaters is often observed when hydrodynamic cavitation is integrated with advanced oxidation processes. In complex effluents, cavitation alone generally produces only modest COD or TOC reductions, whereas coupling with Fenton, ozone, H_2O_2 , or ternary configurations leads to stronger performance. This behaviour is consistent with the presence of radical scavengers and strong competition for reactive species in real matrices [77,78]. These factors limit stand-alone treatment, but they can be partly overcome when the reactor intensifies an already active oxidative environment.

The same pattern appears in sector-specific matrices, including textile, tannery, coking, and cellulosic-fibre wastewaters [79]. Combined configurations generally produce stronger reductions in COD, colour, and turbidity than cavitation alone. In tannery and coking wastewaters, improved performance is mainly associated with coupling to Fenton or other oxidative partners, whereas in cellulosic-fibre industry effluents the advantage of the hybrid system is more evident than that of hydraulic intensification alone. Real pharmaceutical wastewaters treated at the tertiary stage show a similar trend: the highest effectiveness is obtained when the reactor improves contact between reagents and matrix components rather than when it operates as a stand-alone stage [80,81].

A further application area concerns the reconditioning of process waters or partially treated effluents before polishing, recycling, or reuse [82,83]. In these cases, the objective is not necessarily removal of a very high organic load, but improvement of residual water quality, reduction in persistent contaminants or toxicity, and production of water more compatible with reuse. Examples include car-wash wastewaters, process waters containing surfactants or polycyclic aromatic hydrocarbons, and ozone-assisted configurations designed to enhance gas–liquid mass transfer and oxidation efficiency [84]. The position of the cavitation unit is decisive: if introduced too early, treatment may be excessively penalized by matrix competition; if introduced too late, its specific energy and chemical cost may not be justified [85,86].

6.3. Matrix Effects and System-Level Interpretation

Matrix composition is one of the main factors limiting transferability from model systems to real wastewaters. Radical scavengers reduce the fraction of reactive species available for the target, while solids and colloids may shield contaminants, alter nucleation, or modify the cavitation field [87,88]. Surfactants and dissolved organic compounds may also affect interfacial behaviour, gas–liquid transfer, and contaminant partitioning. As a result, two wastewaters with similar COD may respond very differently to the same reactor configuration, making assessments based only on COD reduction or target-contaminant disappearance insufficient [89,90].

A multiparametric evaluation is therefore essential. Alongside COD and TOC, colour, turbidity, biodegradability, residual toxicity, reuse potential, reagent consumption, specific energy, and downstream compatibility often become equally relevant [91,92]. This plurality of criteria complicates comparison across studies, but it provides a more realistic description of treatment value under non-ideal conditions. It also helps connect reactor-scale performance with system-level behaviour, including the fate of dissolved and particulate fractions after treatment, compatibility with biological stages, and suitability for discharge, reuse, or polishing.

In real wastewaters, hydrodynamic cavitation is most convincing when it improves the performance of the overall treatment train rather than when it is presented as a universal stand-alone treatment [8–10,72,73,87–92]. Its value depends on matrix composition, reactor design, operating window, treatment position, and the function assigned to the cavitation unit. Less consolidated aspects remain cross-device comparability,

standardized energy metrics, residual toxicity assessment, long-term operation, and industrial transferability.

7. Sludge, Energy Recovery, and Nutrients

The sludge line concentrates several demanding challenges in wastewater treatment. High water content, compact floccular structure, limited bioavailability of organic matter, and poor dewaterability reduce anaerobic digestion efficiency and increase management costs. In this context, hydrodynamic cavitation has been studied as a pretreatment able to modify sludge structure, increase the soluble organic fraction, and improve downstream steps, especially anaerobic digestion, dewatering, and, in some streams, ammoniacal nitrogen management [93]. The available literature includes waste activated sludge, aerobic granular sludge, dairy-derived DAF sludge, previously digested sludge, and concentrated streams with high ammoniacal nitrogen content [94].

Treatment performance in this area cannot be interpreted through a single indicator [9,10,95]. Increased SCOD, shorter lag phase, higher methane yield, improved dewaterability, and ammoniacal nitrogen removal describe different process functions and are not equivalent. The same operating severity that promotes solubilization may not provide the best energy balance, dewatering response, or nutrient-removal performance. The value of hydrodynamic cavitation therefore depends on the function assigned to the pretreatment and on its position within the sludge-treatment line.

7.1. Matrix Disintegration, EPS Modification, and Solubilization

The immediate effect of hydrodynamic cavitation on sludge is modification of the particulate matrix. Cavity collapse, microjets, and high local velocity gradients reduce particle size, increase accessible surface area, and promote the transfer of organic matter from the solid phase to the liquid phase [96]. In waste activated sludge, this typically leads to increased SCOD, release of soluble nitrogen compounds, and changes in particle-size distribution. Similar effects have also been reported in more structured matrices, including aerobic granular sludge.

This response is strongly linked to EPS and floc structure. Floc breakup may increase substrate accessibility and organic-carbon solubilization, but it can also increase the colloidal fraction and adversely affect mechanical separation [93,94]. Mild treatment may reorganize the matrix and increase soluble fractions without causing extensive cell destruction, whereas higher severity may intensify intracellular release, viscosity changes, and downstream instability [95]. For this reason, disintegration is not a sufficient performance metric. Maximum solubilization does not necessarily correspond to the most favourable overall process outcome [96].

7.2. Anaerobic Digestion and Methane-Yield Enhancement

The most consolidated evidence concerns anaerobic digestion. Hydrodynamic cavitation can increase organic-matter availability, accelerate hydrolysis, and make particulate or poorly accessible fractions more available to anaerobic consortia. As the literature has matured, however, it has become clear that SCOD increase alone cannot be treated as proof of pretreatment effectiveness [97,98]. A robust assessment must include methane yield, digestion kinetics, and net energy balance.

In waste activated sludge, reported results show significant increases in methane production, but also indicate that the maximum degree of disintegration does not necessarily coincide with the best energy benefit [99]. More severe regimes may increase SCOD and soluble fractions, while failing to provide the most favourable ratio between additional methane recovered and pretreatment energy input. The same logic applies to aerobic

granular sludge, where longer exposure can continue to intensify disintegration without generating a proportional gain in recovered energy [100].

Other sludge matrices confirm the need for function-specific evaluation. In dairy-derived DAF sludge, characterized by high fat content and initially limited digestibility, cavitation can increase SCOD, shorten the lag phase, and support high methane yields with a favourable energy balance. In previously digested sludge, the process does not increase primary methane potential, but may recover a residual energetic fraction still present in the matrix and improve residual biodegradability. These examples show that the relevant criterion is not solubilization alone, but the relationship between pretreatment severity, additional energy recovery, and downstream process response.

7.3. Dewaterability, Conditioning, and Nutrient Management

The value of hydrodynamic cavitation in the sludge line is not limited to methane recovery. Dewaterability is a separate process objective and requires different evaluation criteria [101]. Disintegration can have contradictory effects: floc breakup may increase matrix accessibility and release water, but excessive colloidal release may worsen filterability. For this reason, the most convincing evidence on dewaterability generally concerns hybrid conditioning strategies rather than cavitation alone.

In Fenton-based combined treatment, cavitation fragments the matrix and disrupts EPS layers, while the oxidative reaction promotes a reorganization more favourable to solid–liquid separation. Improvements in water content, capillary suction time, and specific resistance to filtration indicate that the advantage does not arise from structural breakup alone. It results from coupling disintegration with a chemical pathway able to limit the adverse effects of colloidal release. The optimal severity for methane enhancement therefore does not necessarily coincide with the severity required to improve dewaterability.

A further application concerns concentrated streams with high ammoniacal nitrogen content. In these systems, hydrodynamic cavitation is not primarily used to improve digestibility of a particulate matrix, but to intensify removal of a dissolved species that is difficult to manage [102]. Reported performance depends strongly on reactor configuration and on integration with aeration or oxygen sparging. Vortex-based devices generally appear more efficient than conventional orifice-based systems, confirming that gas–liquid mass transfer and flow-field quality may be at least as important as cavitation intensity alone. This extends the significance of hydrodynamic cavitation beyond organic-carbon valorization, provided that the treatment is designed around the target species and the appropriate reactor configuration.

7.4. Operating Severity and Design Criteria

Across sludge-line applications, effective treatment severity cannot be reduced to a single operating parameter. Pressure, exposure time, number of passes, solids content, viscosity, fat content, temperature, and flow pattern interact in determining the cavitation regime actually developed in the reactor [97]. This applies to swirling-jet systems, rotational devices, vortex-based systems, and milli-scale reactors. The key issue is not nominal intensity alone, but the ability of the reactor to maintain useful and reproducible cavitation under matrix-specific conditions.

Increased solubilization or a higher degree of disintegration is therefore insufficient as a universal indicator of success. If the objective is anaerobic digestion, the decisive criterion is the relationship between methane-yield increase and pretreatment energy input [98]. If the objective is dewaterability, the relevant issue is the behaviour of the matrix after floc disruption and colloidal reorganization. If the target is ammoniacal nitrogen, reactor configuration and mass transfer become central [102]. This plurality of criteria

makes comparison across studies more difficult, but it also provides a more accurate interpretation of the actual role of hydrodynamic cavitation in the sludge line.

In this domain, performance depends above all on the function assigned to the pre-treatment [9,10,93–100,102]. Reactor design, operating severity, solubilization, energy balance, dewaterability, and mass transfer lead to outcomes that are not interchangeable. The main limitation remains the lack of unified evaluation criteria able to compare different sludge-line functions without reducing them to a single disintegration-based metric.

8. Hybrid Configurations

A substantial part of the water-treatment literature shows that the potential of hydrodynamic cavitation becomes most evident in hybrid configurations [8–10,36,44,49]. Stand-alone treatment can be useful when the target is sensitive to mechanical stress, moderate radical oxidation, or mass-transfer intensification. When the objective is deeper matrix transformation, greater mineralization, faster microbial inactivation, or treatment of particularly persistent contaminants, integration with other processes is often more effective [13,26,49,103]. In these configurations, the contribution of hydrodynamic cavitation extends beyond cavity collapse alone. It may involve reagent distribution, interfacial renewal, oxidant activation, improved mass transfer, and greater target accessibility [8,32,36,44,104].

Hybrid configurations, however, should not be interpreted as a single category [105]. In some systems, the main advantage is the activation or more efficient use of H_2O_2 , persulfate, ozone, or Fenton-type reagents. In others, the cavitation reactor mainly prepares the matrix for UV treatment, photocatalysis, cold plasma, acoustic cavitation, or downstream biological processes. What changes is therefore not only the process partner, but also the function assigned to cavitation: radical activation, mass-transfer intensification, pre-oxidation, matrix pretreatment, biological support, or integration within multistage treatment trains.

8.1. Coupling with H_2O_2 , Persulfate, Ozone, and Fenton Systems

The most established combinations involve H_2O_2 , persulfate, ozone, and Fenton or Fenton-like systems. Their relevance lies in the ability of the reactor to intensify several processes simultaneously, including radical generation, reagent dispersion, interfacial renewal, and contact between the target and the most reactive zones [44,49,106,107]. In H_2O_2 -based systems, the available data often show stronger degradation than stand-alone cavitation, especially for pesticides, phenols, and complex industrial wastewaters [77,81,108,109]. In persulfate-based systems, the main interest lies in the formation of a more aggressive radical environment, which is particularly relevant for stable compounds such as atrazine, tetracyclines, BPA, and some PFAS [60,110,111]. In Fenton-based systems, the benefit is often reflected not only in apparent treatment rate, but also in TOC or COD reduction in real matrices.

Ozone-assisted configurations occupy a specific position because their performance depends not only on oxidation, but also on intensified gas–liquid mass transfer [112]. More broadly, cavitation-assisted oxidation may benefit from reactor conditions that improve oxidant utilization and treatment effectiveness beyond collapse intensity alone [113]. The reactor can increase interfacial area, gas dispersion, dissolution, and hydrolysis, which is particularly important when the limiting factor is the availability of reactive species in the liquid phase. This behaviour has been reported in textile-wastewater decolourization and biodegradability enhancement [114], as well as in other complex real matrices, including tannery wastewater [115]. In these cases, hybrid performance depends on mass-transfer quality at least as much as on radical generation.

8.2. Coupling with Photocatalysis, Auxiliary Oxidants, Plasma, and Acoustic Cavitation

A second group of hybrid configurations includes UV irradiation, heterogeneous photocatalysis, auxiliary oxidants, cold plasma, and acoustic cavitation [63,116–122]. In these systems, hydrodynamic cavitation does not replace the partner process. Its main role is to enhance process effectiveness by improving catalyst dispersion, renewing active surfaces, intensifying micromixing, and generating local conditions that favour reactivity. Evidence from dye systems such as Reactive Red 2, Rhodamine B, and Rhodamine 6G shows that coupling with photocatalysis or additional oxidants can intensify decolourization and, in some cases, support deeper reduction in organic load rather than simple parent compound disappearance [116–118].

Comparison with stand-alone hydrodynamic cavitation remains essential, because hybridization is justified only when it provides a measurable advantage rather than merely increasing process complexity [119]. Studies on textile dye wastewater and combined hydrodynamic cavitation–cold plasma systems indicate that the observed benefit may arise from improved micromixing, more effective oxidant utilization, and interaction among multiple activation fields, with applications extending from dyes to pharmaceutical contaminants [120–122]. Even in these cases, energy assessment remains necessary, because greater chemical effectiveness does not automatically correspond to the best overall process compromise.

8.3. Coupling with Biological Treatments

Integration with biological processes follows a different logic from hybrid AOPs and is more appropriately interpreted as process integration rather than purely oxidative hybridization [97–100,123]. In this case, the cavitation reactor is often used as a pretreatment step to increase biodegradability, solubilize poorly accessible fractions, or reduce inhibition caused by specific substrates. This function is particularly relevant in high-strength industrial wastewaters and sludge-treatment lines, where the useful effect does not consist in direct mineralization, but in modifying the matrix so that the downstream biological stage becomes more effective. The increase in the BOD/COD ratio observed in distillery wastewaters and the improvement in anaerobic sludge digestibility follow this pattern of indirect intensification [93,97–100].

The position of the cavitation unit relative to the biological stage is therefore decisive. If pretreatment is too mild, matrix modification may be insufficient. If it is too severe, colloidal release or formation of unfavourable intermediates may reduce the benefit for the downstream system. In these applications, the contribution of hydrodynamic cavitation should be defined in relation to a precise process function: increasing substrate bioavailability, improving anaerobic digestibility, facilitating biological polishing, or reducing inhibition in complex wastewaters.

Biological responses should therefore be interpreted not only as performance endpoints, such as biodegradability increase, toxicity reduction, or methane-yield enhancement, but also as coupled system responses that reflect how physical and chemical perturbations induced by cavitation modify downstream microbial activity and overall treatment behaviour.

8.4. Stand-Alone Treatment Versus Hybrid Configuration

The distinction between stand-alone treatment and hybrid configuration is not merely classificatory [124]. Hydrodynamic cavitation may be sufficient when the target is sensitive to mechanical effects, the matrix is relatively simple, or the required outcome is preliminary transformation rather than complete mineralization. This may apply to some disinfection uses, cyanobacterial bloom destabilization, and initial degradation of selected organic contaminants under controlled conditions [35–37,48,61]. When the matrix is more

complex, the contaminant is highly recalcitrant, or the treatment objective requires deeper reduction in TOC, COD, toxicity, or microbial load, hybrid configurations are generally more convincing [103–105].

The choice between stand-alone and hybrid treatment should therefore be based on process function rather than on an assumed hierarchy between simple and complex systems. Hybridization is justified when the partner process produces a real and measurable advantage in treatment depth, reagent use, energy performance, downstream compatibility, or final matrix quality. If this advantage is not demonstrated, stand-alone treatment may remain preferable because of simpler operation, lower chemical demand, and easier process control.

8.5. Comparative Limitations and Design Implications

The literature on hybrid systems still shows several recurring limitations [1–4,10,33,48]. Reactor type, oxidant type and dose, loop configuration, matrix composition, performance criterion, and energy metric often change simultaneously [125]. Under these conditions, cross-study comparison remains incomplete. A second limitation is the frequent reliance on parent compound disappearance without equally strong evidence on mineralization, residual toxicity, biodegradability, transformation intermediates, or specific energy cost. A third issue concerns attribution of the observed benefit: the contribution of the cavitation reactor is not always clearly separated from that of the partner process.

From a design perspective, the most robust conclusion is that hybrid configurations become valuable only when they are built around the function assigned to the cavitation module. If the objective is mass-transfer enhancement, both reactor and partner process should be selected accordingly. If the objective is more effective radical chemistry, persulfate, Fenton, UV, ozone, or photocatalysis may become more relevant. If the target is a biologically treatable but poorly accessible matrix, a pretreatment role is more appropriate. Hybrid configurations therefore represent a set of process architectures requiring different selection criteria, not a single treatment class.

Overall, hybrid configurations are among the most mature expressions of hydrodynamic cavitation in water treatment [8–10,36,44,49]. Their performance depends on the coherence among reactor, process partner, matrix, operating window, and final objective, rather than on the simple addition of coupled treatments. Less consolidated aspects remain the quantitative demonstration of synergy, the actual depth of treatment, the attribution of the cavitation-specific contribution, and the energy comparability of different configurations.

9. Reactors, Modelling, and Scale-Up

The maturation of hydrodynamic cavitation as a process technology depends increasingly on reactor quality, modelling reliability, controllability, and scale-up criteria. Treatment effectiveness is not determined by the mere occurrence of cavitation, but by the way the device generates the pressure field, controls cavity formation, governs collapse, and distributes mechanical, interfacial, and chemical effects throughout the treated volume. Recent literature shows a shift from a predominantly empirical phase toward a more engineering-oriented one, in which bubble dynamics, reactor modelling, geometric optimization, cavitation-regime control, energy demand, and scale-up are treated as connected aspects of the same problem [5,8–11,126].

This shift involves both established and emerging reactor families. Orifice plates, conventional Venturi devices, vortex diodes, cavitating jets, and rotational reactors remain central because they provide the main experimental basis for comparison across applications. Advanced rotational reactors aim to enlarge the active zone, increase the frequency

of useful events, and improve the balance between intensification and energy consumption [21–24,39–42,126,127]. More recent non-conventional or dynamic Venturi concepts are relevant mainly as design-oriented approaches to hydraulic controllability. Their practical advantage over established configurations should still be interpreted cautiously, because application-level validation and comparative benchmarking remain limited.

Table 2 summarizes the main reactor families used in hydrodynamic cavitation, comparing their cavitation-generation mechanism, principal process relevance, and main limitations.

Table 2. Main hydrodynamic cavitation reactor families: generation mechanism, process relevance, and main limitations.

Reactor Family	Cavitation-Generation Mechanism	Principal Process Relevance	Main Limitation
Orifice plates ¹	Fixed hydraulic restriction	Simplicity and benchmark value	Dissipation, limited active volume, clogging risk
Conventional Venturi Devices ²	Converging–throat–diverging acceleration	Regime stability	Strong geometric sensitivity
Vortex diodes ³	Swirling-flow-induced pressure depression	Efficient event generation	Flow-structure sensitivity
Cavitating jet reactors ⁴	High-velocity jet collapse	Strong local intensity	Localized treatment
Rotor–stator/rotor–rotor reactors ⁵	Rotation-induced pressure fluctuation and shear	Continuous-flow intensification	Mechanical and operational complexity
Advanced rotational Reactors ⁶	Geometry-optimized internal cavitation units	Potentially improved active-zone utilization	Incomplete comparative validation
Advanced/dynamic Venturi devices ⁷	Non-conventional and/or adjustable throat-controlled cavitation	Design-oriented controllability	Limited application-level validation

Note: This comparison is qualitative and highlights engineering differences in cavitation-generation mode, process relevance, and main limitations. It does not imply an absolute performance ranking independent of matrix, target, or operating conditions. ¹ Orifice plates are simple and useful as benchmark devices, but useful cavitation is often highly localized, with significant hydraulic dissipation and possible clogging in solids-containing matrices. ² Conventional Venturi devices generally provide smoother pressure recovery and more stable cavitation than orifice plates, but performance remains highly sensitive to throat diameter and diffuser geometry. ³ Vortex diodes may convert hydraulic energy into useful cavitation events efficiently, provided that the internal swirling-flow structure is maintained. ⁴ Cavitating jet reactors generate highly aggressive but localized cavitation, which may limit uniform exposure and scale extension. ⁵ Rotor–stator and rotor–rotor reactors can generate repeated cavitation events under continuous-flow operation, but require careful control of rotational speed, clearance, maintenance, and mechanical complexity. ⁶ Advanced rotational reactors may enlarge the useful cavitation zone and improve controllability through geometric optimization, but broader comparative validation is still required. ⁷ Advanced or dynamic Venturi devices are mainly design-oriented and control-oriented concepts; their practical advantage over conventional Venturi devices still requires application-level validation.

As this comparison indicates, reactor design matters not simply because it generates cavitation, but because it determines how cavitation is spatially distributed, hydraulically sustained, and matched to the process function required.

9.1. Reactor Quality and Useful Cavitation

A portion of the cavitation generated in a device may develop in unfavourable regions or collapse with insufficient intensity for the intended treatment function. A reactor should therefore not maximize cavitation in a generic sense, but maximize the fraction of cavitation that produces useful, well-distributed, and reproducible events [21–24,45,128]. Two devices may generate apparently similar vapour volumes while differing substantially in their ability to convert hydraulic energy into process-relevant effects.

Comparison among static devices, vortex-based systems, and rotational reactors should therefore not be based on cavitation volume alone [129]. More informative criteria include active-zone distribution, effective event frequency, pressure-loss management, operational stability, erosion or clogging risk, and coupling between the cavitation field and the treated volume. These criteria are also more useful for linking reactor-scale behaviour with downstream treatment performance. Nominal pressure, pressure drop, or cavitation number alone cannot provide a complete description of reactor performance.

9.2. Reactor Modelling, Performance Metrics, and Control

Reactor modelling remains a central challenge because hydrodynamic cavitation involves multiple spatial and temporal scales, from single-bubble dynamics to the overall response of the treatment loop. Available approaches include semi-empirical, data-driven, and physics-based models [34,45,129,130]. Semi-empirical models can describe selected trends, but their transferability is often limited. Data-driven approaches can capture complex operating patterns, but require sufficiently large and well-described datasets. Physics-based and CFD models are more directly connected to reactor design, but still face the difficulty of representing turbulence, cavitation, collapse, mass transfer, and chemical or biological response within a single framework.

A remaining methodological weakness is the use of global pseudo-kinetics in recirculating systems. When performance is referred only to total treatment time, reactor behaviour becomes entangled with tank volume, pass number, and loop dynamics [129]. More robust approaches separate the yield of the cavitating device from that of the entire loop, using per-pass quantities or metrics linked more directly to actual exposure of the matrix to useful cavitation events.

AI-assisted and machine-learning approaches are relevant within this modelling context, but they should be treated as support tools rather than as substitutes for mechanistic interpretation. ANN-based modelling has already been applied to hydrodynamic cavitation processes involving biomass pretreatment, wastewater treatment, and dye degradation, while recent deep-learning approaches have also been used for cavitation-intensity prediction and optimization in Venturi-type reactors [131–133]. These studies indicate that data-driven tools may help identify operating windows, relate reactor and process variables to treatment outcomes, and support multi-objective optimization. Their usefulness for water and wastewater treatment will depend on dataset quality, domain transferability, and experimental validation, especially in biological-treatment integration and advanced oxidation configurations where several variables interact non-linearly.

9.3. Established and Advanced Reactor Development

Conventional static reactors, especially orifice plates and Venturi devices, have played a fundamental role because of their simplicity, low cost, and ease of integration into recirculation loops. Their main limitations are high pressure losses, clogging risk, relatively small active volume, and limited fine control of the cavitation field when flow rate, temperature, gas content, or fluid properties change. Vortex-based systems address some of these limitations by using swirling-flow structures to generate cavitation with

potentially favourable event distribution, although their performance remains sensitive to chamber geometry and hydraulic stability.

Rotational architectures respond to the need for larger active zones, repeated cavitation events, and closer proximity to continuous operation [134]. In rotor–stator and rotor–rotor devices, cavitation is generated by periodic pressure fluctuations and strong shear effects [135]. These configurations are promising for water treatment, disinfection, sludge disintegration, and other process-intensification applications because they can increase exposure frequency per fluid element. Their engineering relevance must nevertheless be assessed together with mechanical complexity, maintenance requirements, clearance control, energy demand, and robustness under real-matrix conditions.

In optimized rotational reactors, rotor and stator geometry directly affect low-pressure zones, vortices, and cavitation-cloud distribution. Studies on tapered rotors with internal passages, radial-cavity configurations, and rotor–radial groove systems show that active-unit number and shape, rotor–stator clearance, inclination of cavitation-generating elements, and internal-passage diameter can simultaneously affect degradation rate, energy use, and operating cost [136]. A recurring result is that the best performance does not coincide with the most extreme geometry, but with configurations able to enlarge useful cavitation without producing excessive dissipation [137]. Studies on stacked cavitation support the same principle by linking inertial forces, shear, pressure gradients, and gas-phase contribution to mass-transfer intensification and final process function [138].

Advanced Venturi concepts should be placed at a lower maturity level. Design-oriented proposals have considered non-conventional cross-sections, including a Reuleaux-triangle geometry, with the rationale that, at equal effective flow area, a larger perimeter may alter pressure-gradient distribution and nucleation-site availability [139]. A further control-oriented proposal combines an actuatable throat with boundary-imposed swirl in a dynamic Venturi configuration, formulating cavitation regulation in terms of admissible and achievable configurations rather than fixed nominal geometry [140]. These concepts are useful for illustrating possible future directions in controllability, but they should be regarded as emerging design frameworks rather than mature treatment technologies until application-level validation, durability assessment, benchmarking, and techno-economic evaluation become available.

9.4. Scale-Up, Benchmarking, and Techno-Economic Viability

Reactor scale-up cannot be treated as simple geometric enlargement of a device that performs well at laboratory scale. When size, flow rate, loop configuration, gas content, solids concentration, and fluid properties change, pressure distribution, residence time, pass frequency, collapse quality, and exposure pattern also change [141]. A reactor that is effective at small scale is therefore not automatically effective at larger scale unless the conditions generating useful cavitation are maintained, reconstructed, or deliberately controlled.

Benchmarking requires more robust metrics than those traditionally used. Energy per treated volume, energy per order, per-pass performance, active-zone exposure, effective event frequency, and quantities linked to actual matrix passage through cavitational active regions are more informative than global pseudo-kinetics alone. For this reason, energy-related comparison should be based on a set of reactor- and function-specific metrics rather than on a single energy value applied uniformly across all configurations. Comparison should also include operational stability, matrix sensitivity, erosion risk, clogging tendency, maintenance requirements, continuity of operation, and compatibility with existing treatment trains. These criteria help connect reactor-scale performance with system-level behaviour, including downstream biological treatment, polishing, reuse, or discharge.

Techno-economic viability is equally important. The practical question is not only whether a target can be removed or transformed, but whether the observed benefit justifies hydraulic energy input, equipment complexity, maintenance requirements, reagent addition, and downstream integration. For stand-alone applications, the main cost driver is usually energy demand relative to treatment outcome. For hybrid systems, assessment must also include oxidant dose, reagent utilization efficiency, catalyst or chemical cost, residual management, and the incremental benefit compared with the partner process alone. For sludge-line applications, the relevant balance is between pretreatment energy input and additional methane recovery, dewaterability improvement, or nutrient-management benefit.

Controllability becomes central at larger scale. A reactor suitable for industrial operation must not only generate intense cavitation, but maintain a stable and interpretable cavitation regime as operating conditions vary. This requires monitoring pressure drop, managing gas content, controlling flow and temperature, and, in more advanced systems, adapting geometry or operating mode to preserve useful treatment conditions. The maturity of the field will depend largely on the transition from devices that are effective in experiments to reactors that are controllable, maintainable, and economically credible in operation.

At this stage of development, reactor quality remains one of the main factors shaping treatment performance. The decisive issue is the ability of the device to convert input energy into useful, well-distributed, reproducible, and controllable cavitation under realistic matrix conditions. Less consolidated aspects remain modelling transferability, AI-ready dataset availability, reactor benchmarking, techno-economic assessment, and scale-up criteria sufficiently robust for practical implementation.

10. Cross-Cutting Critical Assessment

Taken together, the available studies indicate that hydrodynamic cavitation has moved beyond a purely exploratory stage [9–11,142]. The documented applications now include microbial disinfection, cyanobacterial bloom control, degradation of organic micropollutants, treatment of real wastewaters, and sludge pretreatment for energy recovery [12–47,72–102]. This breadth, however, does not correspond to a uniform level of maturity across the field. Some domains already provide a relatively coherent experimental basis, whereas others remain promising but less consolidated in terms of transferability, comparability, and process control. Recent general reviews converge on this point: the field is expanding rapidly, but methodological heterogeneity and reactor-dependent effects still limit robust comparison across applications and device types [9–11].

10.1. Uneven Maturity Across Application Domains

The first cross-cutting point is that maturity differs substantially across applications. Microbial disinfection, sludge pretreatment for anaerobic digestion, and several classes of organic contaminants already show a sufficiently broad experimental base to support relatively stable assessments [13,36,44,99]. In these domains, the central question is no longer simply whether hydrodynamic cavitation can produce a measurable effect, but whether the available evidence is sufficient to define reliable design, comparison, and selection criteria [126,127].

Other domains remain less uniform. In cyanobacterial bloom control, the potential of the process is well documented, but treatment significance depends strongly on the distinction between selective destabilization and extensive cellular damage [29–32]. In PFAS treatment, the interest is clear, but the evidence base is still narrower and requires stricter interpretation, especially regarding defluorination, fluorine balance, transformation

intermediates, and treatment energy cost [46,47]. The field should therefore not be described as immature in a general sense; rather, it is internally uneven.

10.2. Reactor Function and Process Intensification

The role of the reactor is the most stable interpretive axis across the literature. Observed performance does not depend on the mere occurrence of cavitation, but on how the device generates the pressure field, distributes active zones, and converts input energy into useful collapse events [126,128]. This principle appears consistently across disinfection, micropollutant degradation, real-wastewater treatment, sludge pretreatment, and hybrid systems. In each case, reactor design affects not only treatment intensity, but also the process function actually delivered by the cavitation module.

This also clarifies the relationship between stand-alone treatment and process intensification. The available evidence does not support an interpretation of hydrodynamic cavitation as a self-sufficient solution in all contexts. Its contribution is more coherent when read as a process-intensification function: increasing substrate availability, improving mass transfer, activating oxidants, destabilizing biological structures, or preparing the matrix for a downstream stage [8,26,104,125]. Stand-alone treatment may be convincing when the target is sensitive to mechanical effects or when preliminary transformation is sufficient. In many other cases, the value of the process emerges mainly in hybrid or multistage configurations [103–105].

10.3. Matrix Effects and System-Level Behaviour

Matrix composition strongly conditions treatment response. Results obtained in simple water or model systems cannot be transferred automatically to real wastewaters, natural blooms, or complex sludges [6,73,88,93–100]. Salinity, natural organic matter, suspended solids, colloids, surfactants, radical scavengers, biological composition, gas content, and pH variability can all modify both the cavitation field and the meaning of the observed performance. The transition from simplified matrices to real ones is therefore not a secondary experimental detail, but a different level of process evaluation.

A further issue concerns system-scale behaviour after treatment. Reactor-scale transformation does not necessarily define the final environmental or technological outcome of the treated matrix. Contaminants, organic matter, biomass residues, and transformation products may undergo redistribution among dissolved, colloidal, particulate, and biological phases, and their behaviour may change after discharge, reuse, polishing, or biological treatment. This point is especially relevant for micropollutants, cyanobacterial biomass, sludge-derived matrices, and real effluents, where transport, phase partitioning, transient inputs, hydraulic fluctuations, variable solids loads, and disturbance–recovery dynamics may influence exposure to active zones, downstream biological response, and the effective treatment outcome [143,144]. Hydrodynamic cavitation should therefore be assessed not only through immediate reactor performance, but also through the fate and compatibility of the treated matrix within downstream treatment units, receiving environmental continua, or wider environmental systems.

10.4. Performance Metrics and Comparative Limitations

The choice of performance indicators is central. Parent-contaminant removal, microbial inactivation, increased biodegradability, methane-yield enhancement, biomass destabilization, defluorination, and dewaterability describe different treatment functions and are not interchangeable. In micropollutant treatment, initial transformation does not necessarily imply mineralization or toxicity reduction [36,44–47]. In sludge treatment, maximum disintegration does not necessarily correspond to the best net methane recovery [97–100]. In cyanobacterial bloom control, maximum lysis may be less favourable than

selective destabilization when final water quality and toxin release are considered [29–32]. The function assigned to hydrodynamic cavitation must therefore guide both process design and the metrics used to evaluate it.

Future benchmarking should move toward harmonized, process-oriented metrics that connect reactor exposure, effective cavitation events, matrix response, downstream compatibility, and final system-level outcome, rather than relying only on removal-based indicators.

Because the numerical values reported in the literature are strongly dependent on reactor geometry, matrix composition, oxidant dose, scale, operating window, and metric definition, pooled quantitative comparison across all domains would not be methodologically robust. Accordingly, the comparison is organized around the parameters most appropriate for evaluating performance within each process objective.

In this sense, Table 3 is intended as an integrative framework for comparing treatment significance across application domains, rather than as a simple summary of individual studies. Table 3 links the main process objectives to the most informative evaluation parameters and highlights indicators that are not sufficient alone for a robust interpretation of treatment performance.

Table 3. Relationship between process objectives, preferred evaluation parameters, and parameters that are not sufficient alone across the main application domains of hydrodynamic cavitation.

Process Objective	What to Evaluate	Not Sufficient Alone
Bacterial disinfection ¹	Log reduction; energy per order; number of passes	Treatment time
Viral disinfection ²	Infectivity reduction; number of passes; effective exposure within the loop	Treatment time
Cyanobacterial bloom control ³	Buoyancy loss; sedimentation; regrowth; toxin release	Biomass reduction
Pharmaceuticals ⁴	Parent compound removal; TOC/COD; mineralization; residual toxicity	Parent compound disappearance
Antibiotics ⁵	Parent compound removal; TOC/COD; mineralization	Parent compound disappearance
Endocrine-disrupting Compounds ⁶	Parent compound removal; TOC/COD; reactor–cavitation response	Initial concentration decrease
PFAS ⁷	Defluorination; fluorine balance; transformation intermediates; energy demand	Initial PFAS decrease
Phenols and Chlorophenols ⁸	Pollutant removal; TOC/COD; useful operating window	Target pollutant reduction
Pesticides and Herbicides ⁹	Pollutant removal; TOC/COD; energy–performance trend	Target pollutant reduction

Chlorinated solvents and volatile aromatics ¹⁰	Pollutant removal; energy demand; gas-phase effects	Residual liquid-phase concentration
Real wastewaters: biodegradability enhancement ¹¹	BOD/COD; TOC/COD; downstream biological response	COD reduction
Real wastewaters: oxidative-process intensification ¹²	COD; TOC; colour; residual toxicity; reagent consumption; specific energy	Target pollutant abatement
Real wastewaters: polishing and reuse ¹³	Residual COD/TOC; colour; toxicity; reuse suitability	Improvement of a single parameter
Sludge pretreatment for anaerobic digestion ¹⁴	SCOD; methane yield; net energy balance	Degree of disintegration
Sludge dewaterability Improvement ¹⁵	CST; SRF; water content; cake solids	Matrix solubilization
NH ₄ ⁺ management/removal in concentrated streams ¹⁶	NH ₄ ⁺ removal; energy demand; reactor performance	Nominal treatment intensity

Note: This table is qualitative and compares evaluation parameters according to process objective rather than as universally equivalent indicators of performance. In all cases, performance depends on the role assigned to the cavitation step and on its position within the treatment train. ¹ In bacterial disinfection, log reduction remains central, but total treatment time alone is weak, especially in recirculating systems where exposure depends on reactor design and pass number. ² In viral disinfection, infectivity reduction should be related to cumulative exposure to effective cavitation events rather than to nominal treatment time alone. ³ In cyanobacterial bloom control, biomass reduction may be misleading because excessive treatment severity can promote lysis, toxin release, and deterioration of liquid-phase quality. ⁴ For pharmaceuticals, parent compound disappearance does not necessarily indicate treatment depth; TOC, mineralization, and residual toxicity are often required. ⁵ For antibiotics, parent compound reduction may overestimate performance when degradation does not correspond to lower persistence or organic burden. ⁶ For endocrine-disrupting compounds, treatment significance depends on both the activated radical system and the relationship between chemical response and reactor hydrodynamics. ⁷ For PFAS, initial transformation cannot be equated with class destruction; defluorination, fluorine balance, intermediates, and energy demand are essential. ⁸ For phenols and chlorophenols, target reduction alone is insufficient because treatment depth also depends on TOC reduction and on a useful operating window. ⁹ For pesticides and herbicides, response is strongly contaminant-specific, and stand-alone cavitation often initiates degradation rather than completing it. ¹⁰ For chlorinated solvents and volatile aromatics, interfacial phenomena and gas-phase effects make residual liquid-phase concentration alone insufficient. ¹¹ In biodegradability-oriented wastewater pretreatment, COD reduction may underestimate process value when the main benefit is improved downstream biological response. ¹² In hybrid oxidative treatment of real wastewaters, target abatement should be assessed together with organic-load reduction, reagent consumption, residual toxicity, and specific energy. ¹³ In polishing and reuse applications, treatment success depends on combined residual quality, toxicity, and compatibility with the intended reuse. ¹⁴ In sludge pretreatment for anaerobic digestion, disintegration or SCOD increase alone is insufficient; the key criterion is the balance between pretreatment energy and methane gain. ¹⁵ In sludge dewaterability improvement, matrix solubilization is ambiguous because colloidal release may worsen solid–liquid separation. ¹⁶ In NH₄⁺ management, nominal treatment

intensity is meaningful only when related to actual removal, energy demand, and reactor-dependent mass transfer.

As this comparison shows, treatment performance can only be interpreted in relation to the specific process objective. No single parameter is universally representative of hydrodynamic cavitation effectiveness, and no reactor configuration can be ranked independently of matrix, target, operating window, energy demand, and position within the treatment train.

A major source of fragmentation remains the limited comparability of the available literature [13,33,48,103–105]. Different reactors are often evaluated under non-equivalent conditions, with different matrices, process partners, operating windows, performance criteria, and energy metrics. This limitation is especially evident in hybrid systems, where oxidant type and dose, loop configuration, cavitation regime, and treatment criterion frequently change at the same time [10,103–105]. It also affects disinfection, sludge treatment, and reactor assessment from a scale-up perspective [13,99,126,129].

Overall, the available literature portrays hydrodynamic cavitation as a scientifically grounded and increasingly credible process-intensification platform, but one whose maturity remains uneven across application domains [9–11,142]. The central issue is no longer whether the process can produce measurable effects in individual cases, but when, with which reactor, under which matrix conditions, and at which point in the treatment train it represents a rational technological choice [126,127]. Its value therefore depends on the relationship among reactor design, matrix composition, process partner, treatment objective, energy demand, and system-level compatibility [8,125,143,144]. General claims of cavitation effectiveness should increasingly be replaced by application-specific evidence, reactor-specific metrics, and system-scale validation.

11. Research Priorities and Future Perspectives

The future development of hydrodynamic cavitation in water and wastewater treatment will depend less on expanding the number of reported applications than on consolidating the field through stronger methodological, design, and comparative foundations. The available evidence already shows that hydrodynamic cavitation can produce useful effects in microbial disinfection, cyanobacterial bloom control, organic-contaminant degradation, real-wastewater treatment, sludge pretreatment, and hybrid configurations. This breadth, however, should not be confused with technological maturity, because many application domains still lack comparable metrics, reactor-to-reactor benchmarking, real-matrix validation, and energy-based justification. The decisive step is therefore to clarify when hydrodynamic cavitation represents a rational process choice, which reactor configuration is appropriate for a given objective, and what measurable advantage it provides over competing or complementary technologies.

Future work should move from demonstration to discrimination. It is no longer sufficient to show that a contaminant can be degraded, a microbial target can be inactivated, or a sludge matrix can be disintegrated. More informative studies should define the operating window, reactor function, matrix constraints, energy demand, and downstream benefit associated with the cavitation step. This requires more comparable protocols, complete reporting of reactor geometry and operating conditions, and evaluation metrics consistent with the assigned process function. Parent compound disappearance, log reduction, increased SCOD, higher methane yield, improved biodegradability, defluorination, and dewaterability describe different outcomes and should not be treated as equivalent. More robust assessments should include energy per treated volume, energy per order, per-pass performance, active-zone exposure, effective event frequency, reagent consumption, residual toxicity, downstream biological response, and final matrix compatibility.

Reactor design and controllability remain central priorities. The available evidence indicates that hydrodynamic cavitation is not independent of the device that generates it [21,24,126,127]. Future development should therefore focus not on indiscriminately increasing cavitation intensity, but on producing reactors that are stable, controllable, energy-efficient, and suitable for real matrices. Rotational devices, vortex-based systems, and adjustable geometries remain promising development lines, but their practical value must be demonstrated through longer operation, real-matrix testing, durability assessment, and comparison with more established configurations [134,138,140]. Modelling should also be more tightly connected to experimental validation and process design, especially for rotational reactors, advanced Venturi devices, and adjustable systems, where CFD and geometric optimization are increasingly used to guide reactor development [129,130,136–140]. AI-assisted and machine-learning approaches may support this direction by helping identify operating windows, optimize energy–performance trade-offs, and assist control strategies under variable matrix conditions [131–133]. Their role should remain complementary to mechanistic interpretation, CFD, and experimental validation, rather than replacing them with purely empirical prediction.

Validation under application-relevant conditions is equally important. A substantial part of the literature is still based on model contaminants, simple aqueous matrices, or small recirculating systems. These studies remain useful for mechanistic clarification, but they are insufficient to define technological readiness. Future work should place greater emphasis on real wastewaters, natural blooms, sludge lines, industrial effluents, and variable process streams, with attention to operational stability, fouling, erosion, performance drift, gas content, solids concentration, and sensitivity to fluid properties. Continuous operation and pilot-scale validation should therefore become more central than short-term batch or recirculating tests under tightly controlled conditions.

A broader system-level perspective is also required. Reactor-scale removal does not necessarily determine the final behaviour of the treated matrix. After treatment, contaminants, organic matter, biomass residues, and transformation products may redistribute among dissolved, colloidal, particulate, and biological phases. Transport, phase partitioning, transient inputs, and disturbance–recovery dynamics should therefore be considered when treated waters, sludges, or bloom-affected matrices are returned to downstream treatment, reuse, discharge, or environmental systems [143,144]. This issue is particularly relevant for micropollutants, cyanobacterial biomass, real effluents, and sludge-derived matrices, where immediate treatment performance may not fully describe environmental fate or final process compatibility.

Energy and techno-economic assessment remain essential for technological consolidation. In several domains, hydrodynamic cavitation shows real advantages when it reduces reagent consumption, improves gas–liquid mass transfer, increases biodegradability, enhances methane recovery, or improves the efficiency of the overall treatment train [48,88]. Nevertheless, maximum removal does not necessarily coincide with the most favourable process compromise, and maximum disintegration does not necessarily correspond to the best net energy recovery. In sludge lines, the relevant balance is between pretreatment energy input and the increase in methane production, dewaterability improvement, or nutrient-management benefit [97–100]. In hybrid systems, the key question is whether the additional process partner produces a measurable gain that justifies oxidant dose, reagent cost, operational complexity, and residual management [104,105,112]. In real wastewaters, practical viability depends not only on local treatment performance, but also on whether cavitation reduces the burden on downstream units or improves reuse and polishing potential.

Several application domains require targeted consolidation. In PFAS treatment, future studies should focus on defluorination, fluorine balance, transformation

intermediates, residual toxicity, and energy demand, rather than on initial PFAS decrease alone [46,47]. In cyanobacterial bloom control, the relationship among treatment severity, buoyancy loss, toxin release, regrowth, and final water quality remains central [29–32]. In microbial disinfection, more robust reactor-to-reactor comparisons and stronger evidence from real matrices, continuous systems, and resistant microbial targets are needed [13,20–25]. In sludge applications, the relationship among disintegration, colloidal release, digestibility, methane recovery, dewaterability, and net energy balance must be clarified more rigorously [96–101]. Across all domains, the priority is not simply to produce more data, but to generate data through comparable protocols and explicitly defined process objectives.

Overall, the most promising future direction is not generically more intense cavitation, but cavitation that is more controlled, more selective, more measurable, and more clearly justified from a process perspective. Hydrodynamic cavitation will become more credible as a treatment platform only if future studies connect reactor design, matrix behaviour, performance metrics, energy demand, treatment-train positioning, and system-level compatibility within a coherent evaluation framework.

12. Conclusions

The available literature shows that hydrodynamic cavitation has moved beyond a stage in which its relevance can be judged only by proof-of-concept feasibility. Documented applications now include microbial disinfection, cyanobacterial bloom control, degradation of organic micropollutants, treatment of real wastewaters, sludge pretreatment, energy recovery, nutrient management, and hybrid process configurations. This breadth confirms that hydrodynamic cavitation is a scientifically grounded and increasingly relevant process-intensification approach in water and wastewater treatment.

The evidence, however, does not support a uniform interpretation of the technology. Maturity differs substantially across application domains. Microbial disinfection, sludge pretreatment for anaerobic digestion, and several classes of organic contaminants are supported by a broader experimental base, whereas PFAS treatment, cyanobacterial bloom control under field-relevant conditions, continuous operation, and system-level validation remain less consolidated. The main limitation of the field is therefore not the absence of promising results, but the uneven quality, comparability, and transferability of the available evidence.

The most robust conclusion is that treatment performance depends on the interaction among reactor design, matrix composition, target species, operating window, and assigned process function. Hydrodynamic cavitation should not be interpreted as a single treatment mode or as a universally applicable substitute for existing processes. Its value may lie in direct treatment, pretreatment, biodegradability enhancement, mass-transfer intensification, oxidant activation, sludge conditioning, or support to downstream biological and polishing steps, depending on its position within the treatment train.

Removal-based assessment is therefore insufficient. Parent compound disappearance, microbial reduction, SCOD increase, biomass destabilization, or sludge disintegration cannot alone define treatment success. More reliable evaluation requires application-specific metrics, including mineralization, TOC or COD reduction, residual toxicity, defluorination, fluorine balance, biodegradability, methane yield, dewaterability, reagent consumption, energy demand, and final matrix compatibility. In complex systems, performance must also be interpreted in relation to matrix composition, transport, phase partitioning, downstream behaviour, and system-level consequences.

Future progress will depend on more controllable reactors, better reactor-to-reactor benchmarking, validated modelling tools, careful use of data-driven and AI-assisted optimization, stronger real-matrix testing, continuous and pilot-scale studies, and more

rigorous techno-economic assessment. Hydrodynamic cavitation is most credible when it provides a measurable advantage in the overall treatment train. Its practical value should therefore be judged by the coherence among reactor design, matrix characteristics, treatment objective, energy cost, operational stability, and downstream integration.

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