



Integrative Platform of Microbubble Ozonation: A Systematic Review of the Upstream-Midstream-Downstream Efficiency Chain

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Abstract: Microbubble ozonation has long been treated as a means of raising the mass transfer coefficient (kLa) alone. Yet operational efficiency depends on mechanistic synchronization between gas stability, reactor design, and water-matrix complexity. This review proposes a new paradigm, the “Integrated Platform of Microbubble Ozonation,” linking the upstream, midstream, and downstream domains in a single efficiency chain to overcome the thermodynamic bottleneck of conventional ozonation. Following the PRISMA protocol, we screened 129 Scopus records (2000–2026) and retained 97 primary studies under strict inclusion criteria. Bibliometric mapping in VOSviewer validated the three-pillar clustering before we synthesized technical and economic data in depth. The upstream pillar showed that DBD packed-bed technology delivers a good-standard ozone yield of 150 g/kWh and, when coupled with a dispersion system, raises ozone dissolution to 13.8-fold. The midstream pillar identified an optimal Sauter diameter of 37–40.6 μm as the driver of a peak kLa of 1.0258 min^{-1} in hybrid reactors. The downstream pillar confirmed adaptability to real water matrices, achieving 98.4% ibuprofen removal and operational savings of CNY 2,360.48 per ton of TOC in extreme alkaline industrial wastewater. Synthesis of “The Nexus” revealed that microbubble collapse yields a hydroxyl radical (OH) exposure of 0.97×10^{-9} Ms, shifting oxidation from a selective molecular to a non-selective radical pathway and enabling complete mineralization of toxic pollutants into ecosystem-safe residues, evidenced by a 93.3% mustard seed germination rate. Integration is therefore key to sustainable advanced oxidation, with standardized characterization metrics and AI-based intelligent control as future directions.

Keywords: Microbubble ozonation; integrated platform; ozone yield; hydrodynamics; hydroxyl radicals

1. Introduction

Amid the rapid pace of global industrialization, persistent organic pollutants such as pharmaceutical compounds (PhACs), personal care products (PCPs), and endocrine-disrupting chemicals (EDCs) have exceeded the capabilities of standard biological treatment units [1]. Ozonation has long been used in Advanced Oxidation Processes (AOPs) because of its high oxidation potential (2.07 V) and its ability to leave no hazardous chemical residues [2, 3].

However, industrial-scale implementation faces fundamental hydrodynamic challenges: low ozone solubility in water, the very short lifetime of reactive species, and mass-transfer inefficiency [4]. Historically, industry has attempted to overcome these barriers by increasing the gas input dose or building giant contactor tanks, which in turn leads to increased operational costs [5]. Ozone generation costs often dominate the total cost of an oxidation system, creating a paradox between treatment effectiveness and economic sustainability. One solution to this inefficiency has led to the emergence of the Process Intensification (PI) approach, which aims to increase process efficiency at a local scale without enlarging the physical dimensions of the system [6,7]. One of the most significant PI breakthroughs is using microbubbles and nanobubbles as gas-liquid contact media. Compared with conventional millimeter-sized bubbles, microbubbles with diameters below 100 μm offer a very large interfacial surface area, low rise velocities that extend residence time, and high internal pressure based on the Young-Laplace law [8,9].

Current global research shows that system efficiency depends not only on how fast ozone changes phase, but also on controlling the optimal bubble diameter (~37–42.66 μm) that maximizes the interfacial area between the phases [8,9,10]. Microbubbles trigger a self-pressurization phenomenon based on the Young-Laplace equation: a drastic reduction in bubble size increases internal pressure, leading to bubble collapse and in situ formation of hydroxyl radicals ($\cdot\text{OH}$) with a higher oxidation potential (2.80 V) [10, 11]. Despite a surge in publications on microbubble ozonation since 2000, the current literature synthesis tends to be fragmented; research on upstream plasma yield is rarely systematically coupled with reactor hydrodynamic design in the midstream or water matrix adaptability in the downstream [12, 13]. Consequently, a significant gap remains in understanding how cross-domain synchronization determines the successful transition of the technology from laboratory scale to industrial implementation. This Systematic Literature Review (SLR) aims to fill this conceptual gap by proposing a paradigm: "Integrated Platform Microbubble Ozonation." We position ozone microbubbles as a nexus connecting three core domains:

1. Upstream Pillar: Focusing on reactive species engineering through packed-bed DBD technology capable of producing a gold-standard ozone yield of 150 g/kWh [14].
2. Midstream Pillar: Analyzing reactor hydrodynamic manipulations, such as an inner-cylinder jet design that is 8.6 times more compact [10] and capable of optimizing monodisperse bubble diameters in the 37 μm range [8].
3. Downstream Pillar: Validating the effectiveness of the system on a real water matrix, which is capable of generating operational cost savings of up to 2360 CNY per ton TOC [12] and ensuring ecosystem security with a seed germination rate of 93.3% [13].

Using the PRISMA protocol and 97 primary research papers from 2000–2026, this review quantitatively shows that microbubble ozonation performance results from a closed efficiency chain. This SLR is expected to provide a strategic perspective on bubble characterization and the future development of artificial intelligence (AI)-based advanced oxidation technologies.

2. Materials and Methods

A literature search was conducted through the Scopus database using search terms including "dielectric barrier discharge," "DBD," "corona plasma," ozone, microbubble, venturi, "venturi tube," "dissolved ozone," dissolution, "ozone solubility," "mass transfer," k_La , and "ozone utilization." To ensure transparency and replicability in selecting primary data, we conducted the literature screening process in four systematic stages, as illustrated in Figure 1. Following the PRISMA protocol, 97 primary research articles were selected from 153 initial records in the Scopus database after meeting strict inclusion criteria, ensuring the review is based on valid empirical data. The selected articles were in English and published between 2000 and 2026. Included categories are primary research articles (experimental and modeling) on microbubble or nanobubble ozonation technology, applications in water treatment (including wastewater and environmental remediation), and technical data (e.g., k_La , ozone yield, pollutant degradation). Excluded articles include review articles (narrative/critical reviews), non-water applications (medical/blood therapy, vegetable oil, or solid food), trade journals, retracted articles, and brief technical notes. The initial results show 153 documents, limited to the year range 2000–2026 and English; 3 articles published in 1996, 1997, and 1998 were excluded, as

well as 2 Japanese articles and 19 Chinese articles. For document type, we included only articles (107) and conference papers (10), while excluding books (1), book chapters (1), technical notes (1), and reviews (9). Of the 117 selected articles, then reviewed one by one, the following articles were obtained as excluded: 2 review articles were still found, 4 articles discussing medical/food therapy, 4 trade journal/note/short communication articles, 3 articles on hydroponics/food oxidation/construction, and 7 articles presenting less in-depth data (no kLa, ozone yield, degradation), so that 97 articles met the inclusion criteria.

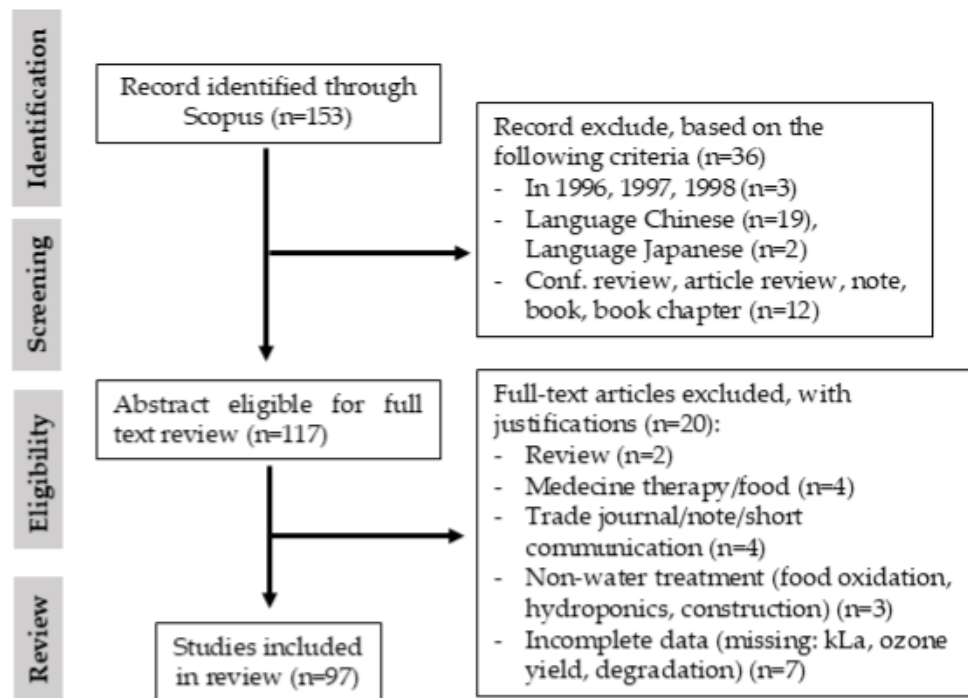


Figure 1. PRISMA flow diagram of the literature selection process.

We processed metadata from 97 documents using OpenRefine (v3.9.5). This step cleaned the data for typos and duplicates. Biblioshiny (R package) extracted publication growth statistics, average publication citations, influential authors, and affiliations, and captured research topic trends and theme evolution from 2000 to 2026. We used VOSviewer to map technology clusters. The "Dielectric Barrier Discharge" and "Microfluidics" clusters confirmed the integrity of the upstream pillar [14, 15], while the "Mass Transfer" and "Process Intensification" clusters supported the midstream pillar argument [7, 10].

3. Bibliometric Landscape

3.1 Research Acceleration and Global Scientific Impact

Figure 2 reflects the growth in research interest in this domain through the annual scientific output trend. This visualization shows an annual growth rate of 4.49%, with a significant spike in 2020–2026, signaling the technology's transition from fundamental research to more complex practical applications. Ozone microbubble research has shifted from basic mechanistic studies to integrated technological solutions. The sharp increase in citations after 2018 (reaching an average of 12.93 citations per year) indicates a shift in scientific interest toward optimizing more complex systems. The peak productivity recorded in 2024–2025, with 13 articles per year, reflects the maturity of this technology for full-scale implementation.

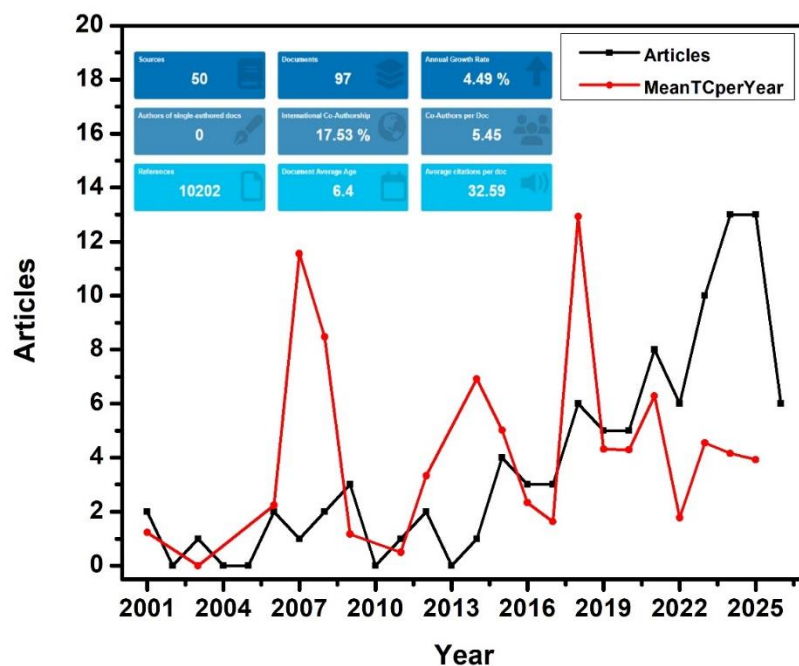


Figure 2. Global article production from 2000 to 2026

3.2 Dominance of Knowledge Authority: Xi'an Jiaotong University

Figure 3 shows the significant dominance of Chinese institutions, led by Xi'an Jiaotong University (26 articles). This lends legitimacy to the technical data used, as the ozone yield of 150 g/kWh comes from the institution's State Key Laboratory [14]. The concentration of publications in highly reputable journals such as Separation and Purification Technology (8 articles) demonstrates that this research meets the technical rigor of the chemical engineering field.

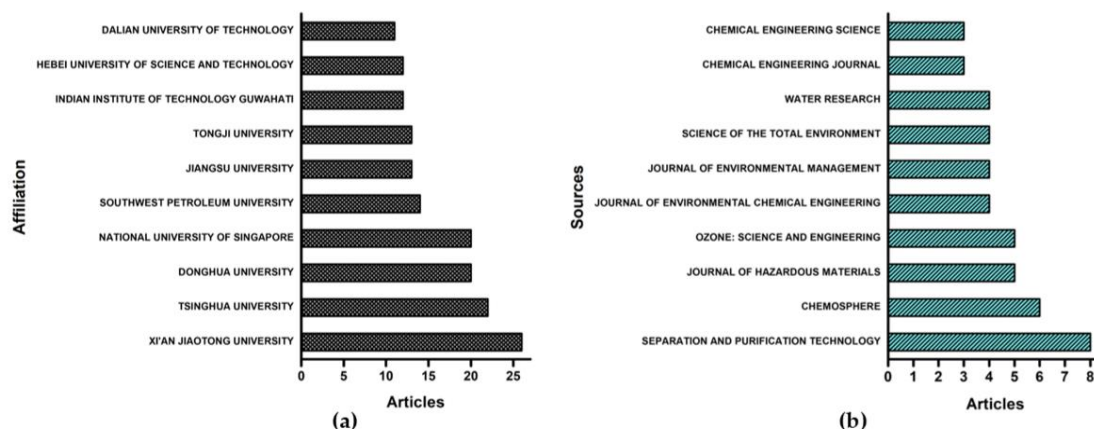


Figure 3. Most relevant: (a) affiliations, (b) sources

3.3 Thematic Evolution: The Rise of "Motor Themes."

The Thematic Evolution Analysis in Figure 4 reveals a shift in research paradigms over three decades: the 2000–2010 phase focused on the basic mechanisms of "mass transfer." The 2011–2020 phase expanded toward "advanced oxidation" and catalytic ozonation. The 2021–2026 phase culminated in the themes of "degradation" and "process intensification."

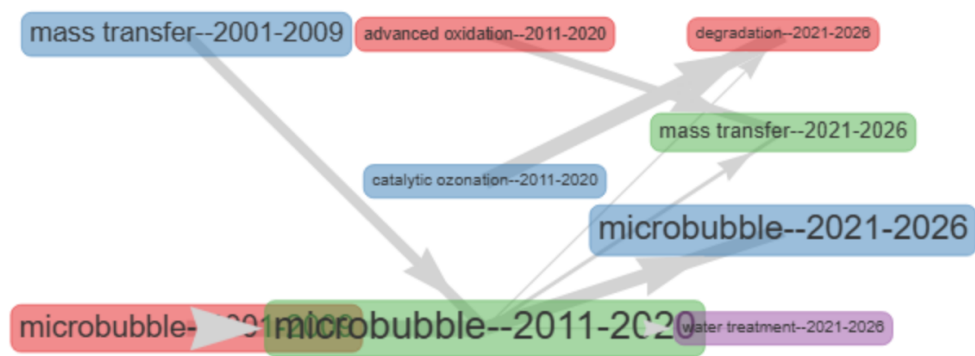


Figure 4. Theme Evolution Over Nearly Three Decades

The placement of "process intensification" as the Motor Theme in the upper-right quadrant of Figure 5 provides scientific confirmation that the future direction centers on technological efficiency and that the Integrated Platform idea is highly relevant. The cluster relationship between "Hydroxyl Radical" and "Water Treatment" reinforces the relevance of practical applications for specific pollutants [11, 16].

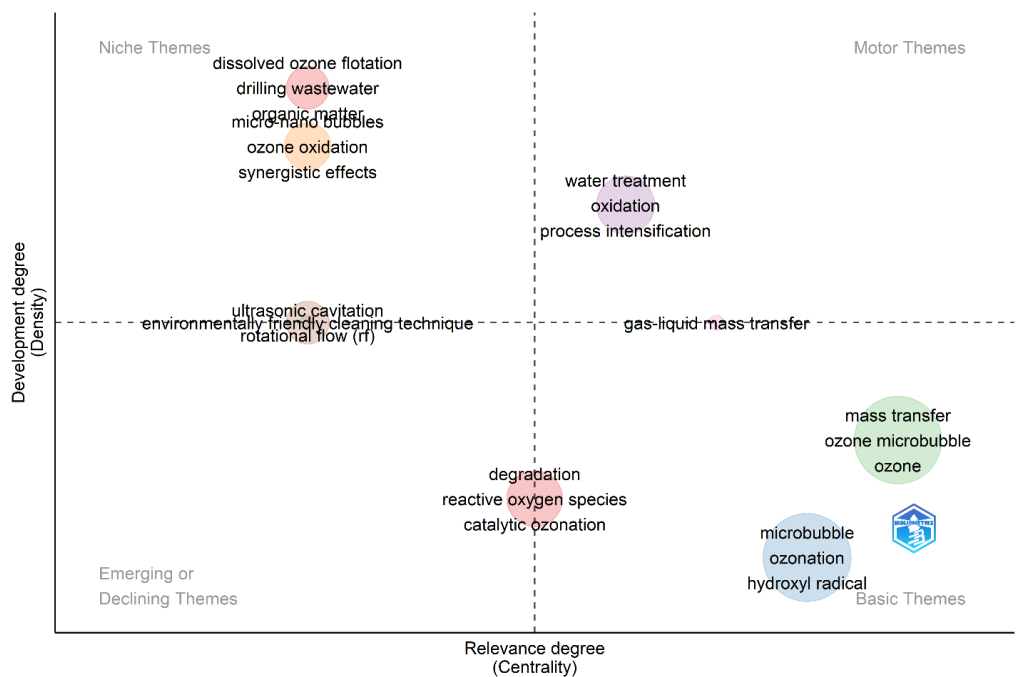


Figure 5. Thematic Map (Quadrant 2020-2026) (showing the position of "process intensification" as the Motor Theme)

3.4 VOSviewer Network Mapping: Mechanistic Synchronization of the Three Pillars

Keyword co-occurrence network analysis using VOSviewer provides evidence of the intellectual structure that shapes the integrated microbubble ozonation platform. Based on the network visualization in Figure 6, the terms "microbubble" and "ozonation" emerge as central nodes with the highest density, serving as the meeting point for the three main clusters representing the efficiency pillars in this paper.

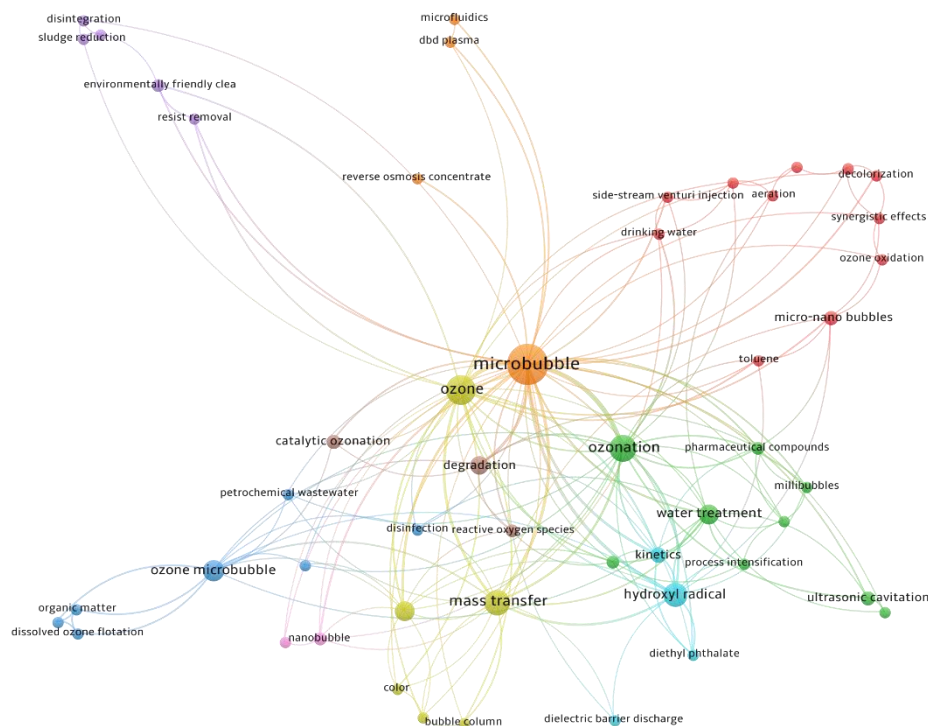


Figure 6. VOSviewer Network Visualization (cluster map connecting “microbubble”, “ozonation”, and “DBD plasma”).

3.4.1 Upstream Cluster: Plasma and Microfluidics Integration

Network visualization shows a very strong link strength between the terms "Dielectric Barrier Discharge" (DBD), "plasma," and "microfluidics." This scientifically validates the Upstream Cluster as the system's foundation. This cluster shows that the global scientific community recognizes that the generation technology determines the stability of reactive species early on. Technical data on local electric-field amplification in Wang et al. [14] and thermal expansion in microfluidic chips in Ogurnyinka et al. [15] provide physical evidence that strengthens the link between the keywords in this upstream cluster.

3.4.2 Midstream Cluster: Hydrodynamic Intensification and Mass Transfer

At the center of the network map, keywords cluster around "mass transfer," "ultrasonic cavitation," and "process intensification." Placing "process intensification" as one of the main Motor Themes in this cluster lends legitimacy to our proposed Midstream. This visual synchronization shows that research on monodisperse contactors (as in Ding et al. [10]) and dual-field UC-RF systems (as in Zhang et al. [7]) is the mechanistic core that enables ozone dissolution through precise hydrodynamic control.

3.4.3 Downstream Cluster: Radical Pathways and Real Matrix Applications

The third cluster explicitly links "hydroxyl radicals" with various aqueous matrices such as "pharmaceutical compounds," "petrochemical wastewater," and "water treatment." The VOSviewer map demonstrates that downstream system efficiency is measured by its ability to generate non-selective oxidation via free radicals ($\cdot\text{OH}$) to treat specific contaminants. This aligns with data on pharmaceutical compound removal in Rojas et al. [16] and radical augmentation via nanobubbles in Temesgen et al. [11].

3.4.4 Visual Synthesis: Integrated Efficiency Chain

Overall, the VOSviewer mapping shows that the three clusters are not isolated silos but are connected through "degradation" and "kinetics" pathways. This synchronization scientifically reinforces the concept of an "Integrated Platform," which includes: an upstream pillar providing gas stability, a midstream pillar optimizing physical dissolution, and a downstream pillar executing radical oxidation of target pollutants. Thus, this platform constitutes a unified efficiency chain that cannot be separated mechanistically.

4. Results and Discussion

4.1 Upstream Pillar: Ozone Generation Stability and Yield

The upstream pillar plays a fundamental role in an integrated microbubble ozonation platform because overall system efficiency depends on the density and stability of the reactive species generated in the initial stage. Based on a synthesis of 12 primary research papers (Table 1), this domain shows the technological transition from conventional corona generators to Dielectric Barrier Discharge (DBD) and Radio Frequency (RF) plasma systems that manipulate electrical discharges at the microscale.

Table 1. Synthesis of Upstream Integration Technical Parameters

Journal	Generation Technology	Main Operational Parameters	Key Findings and Results (Yield/Efficiency)
[14]	Packed-bed DBD (PB-DBD)	Local electric field: 4.06×10^7 V/m; Manufacturing: 3 mm glass beads.	Gold standard ozone yield: 150 g/kWh; electric field amplification >10-fold compared to empty-bed.
[17]	Coaxial DBD + Venturi	Negative pressure injection system integration.	13.8-fold increase in ozone dissolution compared to conventional bubble diffusion.
[15]	Integrated Microfluidic Chip	Gas flow rate: 0.2–2 sccm; Voltage: 5 kVrms; Frequency: 24 kHz.	Thermal expansion of the gas by 17–25% increases the diameter of the MB by 5–8% (~200 μ m).
[2]	RF Ozonizer (Mesh Electrode)	Operating frequency: 139.5 kHz; Voltage: 6 kVpp.	Efficiency: 2.7 g/W; Ozonated water production > 0.2 ppm effectively inhibits enzymatic browning.
[18]	DBD in a Microbubble	Energy density (ED): 4.58×10^5 J/L; Input power: 38.2 W.	Stable plasma generation in bubbles with a diameter of $\geq 30 \mu$ m (Debye scale).
[3]	Corona Discharge + Microbubble	Controlled bubble size: 34.5 μ m; Power: 22.9 W.	Synergistic Factor (SF) 1.43 in pollutant dehalogenation; Maximum $\bullet$ OH intensity in Argon gas.
[19]	HC-UC/RF System	Synergy of Hydrodynamic-Ultrasonic Cavitation + Swirling Flow.	kLa reached 0.1166 min ⁻¹ ; Significant increase in hydroxyl radical ($\bullet$ OH) generation.
[20]	Plasma-Microbubble Coupling	Persulfate (PS) Activation; Discharge power: 65–105 W.	Microbubbles contribute 13% to increased gas-liquid mass transfer.
[21]	DBD-Microbubble Pilot Scale	Field integration system configuration.	The specific energy yield (EEO) reaches 7.62 kWh/m ³ under optimal conditions.
[22]	Micro-Nano Bubble Electro-peroxone (EP)	Micro-Nano bubble aeration on graphite felt cathode.	Increasing O ₂ /O ₃ dissolution increases pharmaceutical removal efficiency to below 30 mg/L.
[23]	VUV/TiO ₂ + Ozone	Photocatalytic reactor with simultaneous ozone utilization.	Intensification of degradation through dual use of UV radiation and gaseous oxidation species.
[24]	Gas-Liquid Interface DBD	Focus on the transfer of short-lived species.	Allows direct delivery of $\bullet$ OH and O atoms to the liquid phase in the zone nearest the plasma.

4.1.1 Electric Field Modulation and Ozone Production Intensification

Ozone generator efficiency is often a weak point in conventional AOP systems. According to a study in Wang et al. [14], a Packed-bed DBD (PB-DBD) reactor filled with 3 mm glass beads has been shown to alter

the distribution of electric charge. This dielectric material concentrates the field lines, increasing the local electric field intensity up to 10-fold, to 4.06×10^7 V/m. This field enhancement is crucial for accelerating electrons that dissociate oxygen molecules (O_2) into reactive oxygen atoms, which then form ozone with a gold-standard yield of 150 g/kWh. As shown in the reactor schematic in Figure 7.

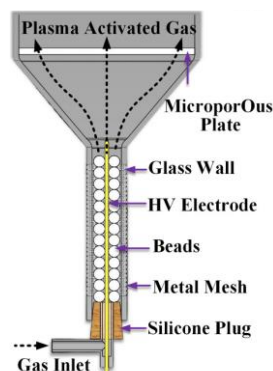


Figure 7. Schematic of a packed-bed DBD (PB-DBD) reactor with glass beads [14].

This advantage is synchronized with the coaxial DBD design coupled to a Venturi injector in Wang et al. [17]. This system utilizes negative pressure to increase ozone dissolution by 13.8 times compared to conventional diffusion methods. Innovations at the gas-liquid interface [24] further enable the direct delivery of short-lived reactive species to the liquid phase right at the plasma discharge zone, preventing premature ozone decomposition before it reaches the pollutant.

4.1.2 Microscale Thermodynamic Phenomena: Thermal Expansion and Laplace Pressure

This pillar also reveals unique physical behavior at the gas-plasma interface. We observed thermodynamic phenomena during the generation phase in real time using microfluidic technology. Figure 8 shows the bubble formation process, where DBD plasma release triggers a 17–25% thermal expansion of the gas. This visualization is crucial for understanding why the microfoam diameter increases by approximately 5–8% (at a scale of ~ 200 μm) when first released into the liquid, which underlies the regulation of plasma stability in the initial stage [15].

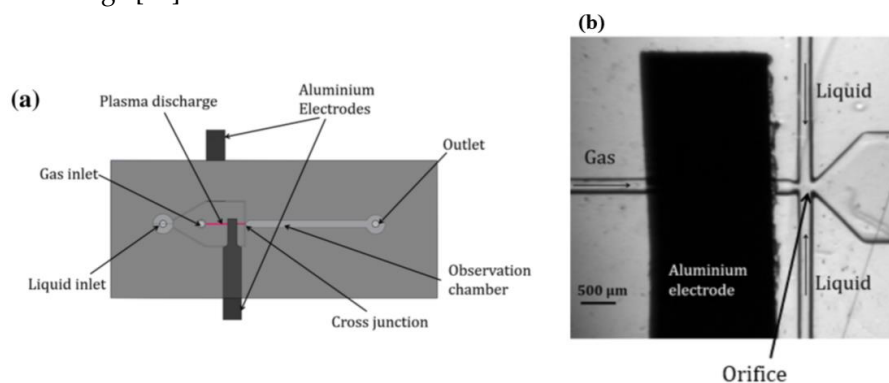


Figure 8. Microchip design: (a) plan view of the microchip, (b) microscopic image of the bubble formation [15].

In addition to thermal factors, plasma stability within the bubble depends strongly on its physical dimensions. Journal 18 explains that to maintain stable plasma release, the bubble diameter must be above the Debye length scale (λ_D), which is at least 30 μm [18]. Mechanical modeling shows that reducing bubble size to the microscale drastically increases internal pressure (Laplace pressure), the main driver of accelerated dissolution of ozone gas into water before the bubble reaches the surface [18].

4.1.3 Chemical Pathways of Reactive Species and Hybrid Synergy

The upstream pillar demonstrates that microbubbles function as active chemical reactors. In the degradation of complex compounds such as Dichloroacetic Acid (DCAA) in Liu et al. [3], the use of a corona discharge reactor integrated with microbubbles (34.5 μm in size) resulted in a synergy factor of 1.43. The

degradation mechanism involves hydrogen abstraction and dehalogenation, as indicated by the detection of intermediate products such as acetic acid and formic acid [3].

Another integrated hybrid system, such as HC-UC/RF, achieved a mass transfer coefficient (kLa) of 0.1166 min^{-1} through hydrodynamic-ultrasonic cavitation synergy [19]. Meanwhile, Wang et al. [20] reported that microbubbles contributed 13% to mass-transfer enhancement in a persulfate activation system, where reactive species such as singlet oxygen ($^1\text{O}_2$) and nitrogen radicals participated in the oxidation process. This augmentation was reinforced in the electro-peroxone process, where microbubble aeration significantly increased midstream radical yield through more efficient $\text{O}_3/\text{H}_2\text{O}_2$ activation [22].

4.1.4 Application Flexibility and Field Performance

Upstream applications span a wide range of domains, from the food industry to environmental remediation. Chankuson et al. [2] developed an RF-powered ozonizer (139.5 kHz) that produces ozonated water $>0.2 \text{ ppm}$ to inhibit enzymatic browning in cut mangosteen fruit. Furthermore, a pilot-scale application in Yingprayoon et al. [21] recorded an Oxidation-Reduction Potential (ORP) value of 821 mV when using pure oxygen as feed gas, demonstrating the system's oxidative strength and suitability for full-scale industrial implementation. Meanwhile, the photocatalytic reactor in Szeto et al. [23] uses lamp-generated ozone to intensify pollutant mineralization through VUV radiation.

4.2 Midstream Pillar: Contactor Hydrodynamics and Reactor Design

The midstream pillar is the mechanistic heart of this integrated platform, where flow-field manipulation and control of bubble physical parameters determine ozone dissolution efficiency. A synthesis of 20 primary research articles reveals that process intensification at this stage focuses on three key domains (Table 2): contactor geometry innovation, bubble size distribution optimization, and advanced fluid dynamics modeling.

Table 2. Complete Synthesis of Midstream Integration Hydrodynamic Parameters

Journal	Reactor Design Innovation	Main Hydrodynamic Parameters	Key Findings and Results (Efficiency & Mechanism)
[25]	Swirling Microbubble	Venturi Coupling & Rotary Flow Field.	Optimization of spiral flow pattern to extend gas residence time.
[26]	Impinging-Jet Column	125° Dual Venturi Injector.	Elimination of dead zones; increased turbulence at the jet impact point.
[27]	Venturi Optimization	Venturi throat diameter variations.	Determination of the optimal diameter ratio to maximize the passive air injection rate.
[28]	Correlation Modeling	Mixing and mass transfer coefficients.	Development of new empirical correlations for predicting large-scale contactor performance.
[6]	Venturi-Swirling	O_3 dose: 35 mg/min; pH 10.	Lowest SEC: 0.017 kWh/g; energy efficiency jumps dramatically from the old standard.
[29]	CFD-PBM Simulation	Venturi aerator structure.	Accurate prediction of bubble breakup rate through turbulent dissipation energy.
[8]	Regenerative Turbine	d_{32} 37 μm vs conventional 5.4 mm.	Interfacial area increase >510 -fold; kLa enhancement factor up to 2.0x.
[5]	Sidestream Addition	Pilot-scale SSA vs FBD.	Transfer efficiency (TE) $>95\%$; SSA is more cost-effective for pilot-scale installations.
[30]	Wire Mesh Contactor	Stainless steel mesh.	kLa increased by 51% due to mechanical cleavage of bubbles as they passed through the mesh.
[7]	UC-RF Coupled-Field	Ultrasonic Fields and Rotational Flow.	Maximum kLa 1.0258 min^{-1} ; dissolved O_3 concentration increased by 83.48%.

Table 2. Complete Synthesis of Midstream Integration Hydrodynamic Parameters (continue)

Journal	Reactor Design Innovation	Main Hydrodynamic Parameters	Key Findings and Results (Efficiency & Mechanism)
[31]	Diameter Regulation	Bubble size control mechanism.	Discovery of the correlation between fluid shear stress and the stability limit of microbubble diameter.
[4]	Gas Induction Contactor	New microbubble gas induction design.	Increased ozone dissolution efficiency without the need for high-pressure compressors.
[10]	Inner-Cylinder Jet	HRT 3.5 s; d_{32} 40.6 μm .	29.2% more efficient and 8.6 times more compact than commercial tank designs.
[32]	Ozone Flotation Column	Hydrodynamics of deinking flotation.	Synergy of ink particle separation and contaminant oxidation in one hydrodynamic column.
[9]	Hybrid Distribution	Nanobubble (217 nm) & Microbubble (37 μm).	Microbubbles dominate ozone mass transfer, while nanobubbles ensure long-term residual stability.
[33]	Packed Column Microbubble	Addition of packing material.	The decolorization rate increased by 62.02%; the packing physically prevented bubble coalescence.
[34]	In-line Multi-Jet	Algebraic Slip Mixture (CFD) Model.	Highly uniform distribution of ozone residue through multi-nozzle position optimization.
[35]	Multi-Orifice	High-density micro-nano bubble generator design.	Massive bubble production with minimal driving water consumption.
[36]	Ceramic Membrane	CA/O ₃ microbubble aeration.	Produces monodisperse microbubbles with minimal pressure drop.
[11]	Radical Augmentation	Transition from microbubble to nanobubble.	Reducing the bubble size increases the surface charge density and $\bullet\text{OH}$ yield.

4.2.1 Contactor Configuration Innovation and System Compaction

The transition from conventional bubble column contactors to high-performance hybrid reactors is a central theme in this pillar. One of the most significant breakthroughs is the inner-cylinder jet reactor design (Figure 9) developed in Ding et al. [10]. By utilizing axial circulation through the inner cylinder combined with the initial e number of a Venturi jet, this reactor achieves a gas dissolution efficiency 29.2% higher than that of commercial horizontal designs. Most impressive is the system compaction aspect, where the reactor volume can be reduced by up to 8.6 times while still producing peak dissolved gas concentrations of 22 mg/L in just 3.5 seconds of hydraulic residence time (HRT) [10].

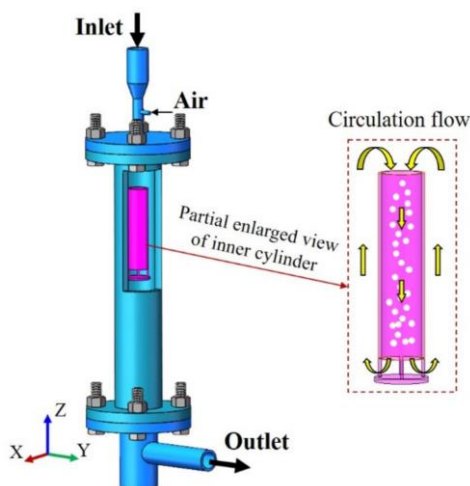


Figure 9. The inner cylinder-type jet dissolved gas tube [10].

Other innovations in this pillar include an impinging-jet column reactor [26], in which two Venturi injectors are strategically placed at a 125° intersection angle. This configuration physically eliminates the “dead pockets” often found in conventional columns, creating very high local turbulence at the base of the column to maximize gas-liquid contact. Additionally, Pathapati et al. [34] introduce an in-line multi-jet design optimized using an algebraic slip mixture model, ensuring stable ozone residuals along the mixing pipe through precise multi-nozzle placement [26, 34].

4.2.2 Interface Dynamics: Sauter Diameter (d_{32}) and Surface Renewal Metrics

This pillar shows that interfacial surface area (a) is far more crucial than the mass transfer constant (kLa). The Sauter mean diameter (d_{32}) metric is identified as a key efficiency parameter. According to Journal 10, reducing the bubble diameter from 5.4 mm (conventional) to $37\ \mu\text{m}$ (microbubbles) significantly increases the interfacial area between the phases, contributing to a 2.0-fold increase in kLa [8]. The accelerated surface renewal rate also explains this advantage. CFD-PBM modeling Li et al. [29] found that the high turbulence dissipation intensity around the Venturi aerator structure actively thins the boundary layer around the bubbles. This phenomenon facilitates ozone mass transfer faster than its natural decomposition rate. Meanwhile, John et al. [9] and Temesgen et al. [11] highlighted the strategic role of nanobubbles (217 nm) that ensure long-term residue stability, where reducing the bubble size to the nanoscale was shown to increase the surface charge density and midstream radical yield up to 3.5 times due to the release of cavitation energy when the bubbles collapse.

4.2.3 Dual Field Synergy and Energy Intensification (SEC)

The midstream pillar also supports integrating additional physical fields to maximize mass transfer. The UC-RF Coupled-Field dual-field system [7], which combines ultrasonic cavitation (UC) with rotary flow (RF), recorded a maximum kLa value of $1.0258\ \text{min}^{-1}$. This synergy increased dissolved ozone concentration by 83.48% compared to standard micropore aeration methods, as ultrasonic cavitation continuously breaks up bubbles that tend to coalesce within the rotary spiral flow [7]. From an operational economic perspective, the Venturi-swirling reactor [6] reduced specific energy consumption (SEC) to an optimal $0.017\ \text{kWh/g}$. This figure is significantly more efficient than the old literature standard of $0.459\ \text{kWh/g}$. Analysis in Rakness et al. [5] adds that the sidestream addition (SSA) system offers transfer efficiency (TE) $>95\%$ and is more cost-effective for pilot-scale installations than the fine bubble diffusion (FBD) system, although it requires higher initial pump costs [5, 6].

4.2.4 Contactor Mechanical and Material Optimization

This pillar encompasses innovations in contactor materials and internal structures to prevent coalescence. Huang et al. [30] showed that using stainless steel wire mesh in the circulation circuit increased kLa by 51% by mechanically severing bubbles as they passed through the mesh. Similarly, adding packing

material in a microbubble column reactor in Dong et al. [33] increased the decolorization rate constant by 62.02% because the packing acts as a physical barrier that keeps the bubbles dispersed. Monodisperse ceramic membrane aeration technology and high-density multi-orifice generator designs complete the midstream pillar innovation chain by providing a stable method for producing microbubbles with minimal pressure drop [35, 36].

4.3 Downstream Pillar: Water Matrix Adaptation and Specific Applications

The downstream pillar is the operational validation phase where the efficiency of the microbubble ozonation system is tested against the complexity of real water matrices. Based on a synthesis of 65 primary research articles, this pillar is categorized into five thematic groups to examine oxidation mechanisms under various pollutant types and environmental conditions.

4.3.1 Emerging Contaminant Degradation: Pharmaceuticals and PPCPs

This group explores the effectiveness of microbubbles in degrading persistent organic compounds that conventional ozonation struggles to treat. Table 3 summarizes a synthesis of technical data from key papers in this domain.

Table 3. Microbubble Ozonation Synthesis of Pharmaceutical Compounds and PPCPs

Journal	Target Pollutant	Matrix Parameters/Conditions	Key Findings and Results (Efficiency/Kinetics)
[22]	Ibuprofen (IBU), Sulfamethoxazole, Tetracycline	Aeration of MNBs; Electro- peroxone (EP) Process	IBU removal: $98.4 \pm 1.5\%$ vs $47.3 \pm 4.7\%$ (conventional); Yield $\bullet\text{OH}$: 0.97×10^{-9} M s.
[16]	Ibuprofen, Diclofenac, Sulfamethoxazole	Continuous flow system; Wastewater matrix effect	Increased efficiency through more massive radical generation at the Microbubble interface.
[37]	Various PPCPs	Secondary wastewater	Effectiveness of micro pollutant removal at low concentrations (ng/L).
[38]	Pharmaceutical Hormones	Effects of temperature and humic acid	Identification of the role of humic acid as a promoter or radical scavenger.
[39]	Naproxen	Addition of H_2O_2 (Microbubble-peroxone ozonation)	Increased mineralization rates and reduced toxicity.
[40]	Ciprofloxacin (CIP)	Combination of microbubble- O_3 and electro- H_2O_2	Synergy of hybrid technology in breaking down stable antibiotic structures.
[41]	Antioxidant BHT	Metabolite detection and toxicity testing of <i>D. magna</i>	$\bullet\text{OH}$ contributed 82% to the degradation; significant reduction in biological oxidative stress.

Based on a review of Table 3, microbubbles remove pharmaceutical compounds by significantly increasing the concentration of hydroxyl radicals ($\bullet\text{OH}$). For example, a study in Zhang et al. [22] showed that using micro-nanobubbles in an electro-peroxone system increased the ozone mass transfer coefficient from $0.090\text{--}0.220 \text{ min}^{-1}$ (conventional aeration) to $0.265\text{--}0.536 \text{ min}^{-1}$. This increase in mass transfer was directly proportional to the $\bullet\text{OH}$ yield, which reached $0.97 \times 10^{-9} \text{ M s}$, enabling Ibuprofen (IBU) degradation to reach 98.4% in a short time [22]. This phenomenon is further supported by findings in Achar et al. [41], which conducted a detailed analysis of BHT degradation. Kinetic analysis shows that $\bullet\text{OH}$ radicals formed from the collapse of microbubbles account for 82% of the total degradation pathway. This is crucial because compounds such as BHT and antibiotics (e.g., ciprofloxacin in Zhang et al. [40]) are highly resistant to direct, selective ozone (O_3) attack. Ozone microbubbles convert the process to non-selective oxidation via free radicals, which not only removes the parent pollutant but also effectively reduces the toxicity of intermediate products, as demonstrated by enzyme assays in *Daphnia magna* [40, 41]. Furthermore, integrating microbubble technology

with hybrid processes, such as adding H_2O_2 or using photo-electrochemical processes, has been shown to address the scavenging effects of natural organic matter (NOM). Lee et al. [38] note that although humic acid is often considered an inhibitor in conventional ozonation, in controlled microbubble systems, interfacial interactions can actually trigger a radical chain reaction that accelerates pollutant mineralization [39].

4.3.2 Heavy Industrial Wastewater Treatment

The petrochemical, textile, and pulp and paper industries generate wastewater with complex organic characteristics that resist standard biological treatment. Based on a synthesis of key studies in this domain (Table 4), integrated ozone microbubbles have been shown to break down these pollutants significantly.

Table 4. Synthesis of Microbubble Ozonation in Heavy Industrial Wastewater

Journal	Type of Industry	System Innovation	Key Findings and Results (COD/Color/Cost)
[42]	Petrochemicals	Microbubble-Catalytic (Fe/GAC)	COD removal: 88%; operating cost \$0.18/kg COD (64% lower than pure Microbubble).
[43]	Coal (BCCW)	Microbubble-Catalytic + Biological Process	Ozone efficiency: 98%; Total COD removal of the hybrid system: 60.82%.
[44]	Textiles	Microbubble Generator vs Conventional	Decolorization is 2 times faster; ozone mass transfer rate is drastically increased.
[45]	Textiles (High Salt)	Pilot Scale (Pressure 0.2 MPa)	Effectiveness of dye degradation in high salinity matrices through increasing ozone solubility.
[46]	Pulp & Paper (Kraft)	Impinging-Jet Column	Maximization of oxidation through increasing the intensity of turbulent mixing.
[47]	Acrylic Fiber	Microbubble Ozonation Intensification	Increasing the BOD/COD ratio, converting toxic waste into biodegradable waste.

Analysis of this downstream pillar primary paper reveals that the success of heavy industrial wastewater treatment depends on synergy between mass-transfer intensity and catalytic stability. In treating high-load petrochemical wastewater, a study in Jothinathan et al. [42] showed that ozone microbubbles coupled with an Fe/GAC catalyst (sol-gel method) can achieve COD removal of up to 88%. The most important finding is the economic aspect: this system reduces operational costs to \$0.18 per kg of COD, which is 64% cheaper than microbubble ozonation without a catalyst. This addresses the challenge of operational cost efficiency, which is often a barrier at the industrial scale. In the domain of Biotreated Coal Chemical Wastewater (BCCW), hybrid system integration is key. Liu et al. [43] report that using microbubbles in an activated carbon catalytic reactor achieves ozone utilization efficiency of up to 98%. Microbubble ozonation helps break the chain of refractory pollutants that bacteria cannot decompose, allowing the high dissolved oxygen (DO) residue in the effluent (12.6–23.1 mg/L) to be used directly by the subsequent biological process unit without additional aeration. This synergy results in a total organic removal rate of 60.82% for the hybrid system. For the textile and pulp industry, the downstream pillar demonstrates the superiority of the hydrodynamics developed in the midstream pillar. Using an impinging-jet reactor on Kraft pulp wastewater showed that increased local turbulence at the microbubble interface maximized reductions in OX and color parameters [46]. Meanwhile, Chu et al. [44] quantitatively confirmed that decolorization of real textile wastewater occurred twice as fast with microbubble technology. This performance improvement is closely related to the "surface renewal" phenomenon, where shear stress at the bubble interface continuously renews the boundary layer, facilitating the penetration of $\cdot\text{OH}$ radicals into the complex dye structure.

4.3.3 Adaptation to Extreme Conditions: High Salinity and Alkaline pH

One of the main criticisms of conventional ozonation is its inefficiency in complex aqueous matrices. This group (Table 5) showed that ozone microbubbles perform better under conditions considered "toxic" to standard systems.

Table 5. Synthesis of Microbubble Performance under Extreme Conditions

Journal	Matrix Characteristics	Types of Pollutants	Key Findings and Results (Economics/Efficiency)
[12]	Bayer Liquor (Strong Alkali, High Salt)	TOC (10.89 g/L)	Savings of 2360.48 CNY per ton TOC; O ₃ consumption decreased by 33.62%; degradation efficiency of 39.58%.
[48]	Salinity 35 ‰ (Sea Water)	Bio-colloid Virus	Removal > 3.00-lg in 3 min; virions trapped at the bubble interface
[49]	Salt Solution (0-2 M)	BTEX	Bubble stability increases at high ionic strength
[50]	RO Concentrate	Organic Refractories	Effectiveness of HOC process in concentrated wastewater mineralization
[51]	High Salinity	Organic Pollutants	Nanobubbles ensure stable mass transfer in saline environments

The data in Ran et al. [12] provide the strongest economic evidence in our entire database. In the Bayer Liquor process, which has an extremely alkaline pH and high salt content, integrating ultrasonic cavitation with ozone microbubbles reduced operational costs by CNY 2,360.48 per ton of TOC degraded. This mechanism is possible because smaller bubbles increase internal pressure (Laplace Pressure) and accelerate surface renewal, allowing ozone to penetrate the highly viscous matrix. This performance is reinforced by the findings of Zhang et al. [48] where at a salinity equivalent to seawater (35‰), ozone microbubbles functioned as a highly effective virus biocolloid scavenger. In just 3 minutes, virus removal of >3.00 lg was achieved through a micron surface enrichment mechanism at the gas-liquid interface. In addition, Tsujimoto et al. [52] noted that alkaline conditions trigger the decomposition of ozone into midstream radicals more extensively, which benefits the degradation of refractory compounds that are not responsive to neutral pH.

4.3.4 Sludge Solubilization and Porous Media Remediation

The downstream pillar also extends to purely non-liquid applications, namely the destruction of activated sludge structures and the cleanup of contaminated soil (Table 6).

Table 6. Synthesis of Sludge Applications and Environmental Remediation

Journal	Application Objects	Target Parameter	Key Findings and Results
[53]	Oil Refinery Mud	"Water-oil-gel" structure	Enhanced solubilization through radical energy from microbubble collapse.
[54]	Activated Sludge	Sludge Solubilization	Increased efficiency through accelerated bacterial cell lysis
[55]	Sewage Sludge	Disintegration	The use of charcoal-based catalysts increases nutrient release
[56]	Groundwater (Field)	Trichloroethylene (TCE)	Successful remediation through injection of micro-nano bubbles of ozone at a real well site
[57]	Groundwater	Toluene	Increased oxidation under static well pressure

The use of microbubbles in activated sludge treatment ([53, 54]) demonstrated that intense mass transfer can trigger bacterial cell lysis and release organic material into the liquid phase for further processing. Sun et al. [53] noted that increasing the temperature of the microbubble system naturally accelerates radical production, which is highly effective at breaking down oil-water gel bonds in refinery sludge. At the field scale, Hu et al. [56] reported successfully remediating groundwater contaminated with TCE using ozone-based micro-nano bubble technology, showing that bubble stability allows a broader cleaning range within porous media (soil) than conventional gas ozonation.

4.3.5 Disinfection and Biosafety (Safe Product Validation)

To conclude the Downstream Pillar, this group presented evidence that microbubble technology not only efficiently kills germs but also produces residues that are safe for the ecosystem.

Table 7. Disinfection Synthesis and Toxicity Test (Biosafety)

Journal	Microbiology Target	Toxicity Test	Key Findings and Results
[58]	E. coli and MS2 Virus	O ₃ Dose Reduction	Ozone dose was reduced by up to 60% for the same inactivation standard
[13]	Xanthate Collector	Mustard greens (B. chinensis)	Seed germination rate 93.3%; plant height increased 41.53% vs control
[41]	Antioxidant BHT	D. magna	Significant reduction in biological oxidative stress of aquatic organisms
[59]	Tulane Virus	Residue Stability	Microbubbles have inactivation stability up to 14 minutes
[60]	Histamine (Tuna Fish)	SNI standard 100 ppm	Reduction of histamine levels below food safety thresholds

The downstream pillar demonstrates revolutionary sterilization efficiency. Yang et al. [58] report that microbubbles allow a 60% reduction in ozone dosage to kill *E. coli* bacteria and MS2 viruses, a significant energy saving for municipal disinfection units. Most impressive is the biosafety aspect. In degrading highly toxic xanthate collectors, Gu et al. [13] showed that water treated with ozone microbubbles promoted plant growth. The germination rate of mustard seeds reached 93.3%, with physical growth 41.53% higher than the control. This confirms that radical oxidation by ozone microbubbles can achieve complete mineralization, converting toxic substances into small biostimulant molecules and harmless inorganic salts.

4.4 Efficiency Chain Synthesis (The Nexus): Integrated Systemic Integration

A synthesis of the 97 primary papers in the database shows that bubble ozonation efficiency is not an isolated variable, but a manifestation of "The Nexus"—the intersection of reactive species stability (Upstream), hydrodynamic manipulation (Midstream), and matrix adaptability (Downstream). This integration redefines system operation through three key interconnected mechanisms.

4.4.1 Upstream-Midstream Linkage: Energy Synchronization and Dispersion

System efficiency begins with the Upstream Pillar's ability to produce a gold-standard ozone yield of 150 g/kWh using PB-DBD technology [14]. However, this efficiency will be wasted if it is not immediately coupled with the Midstream Pillar's design, which enables instant dissolution. Integrating a coaxial DBD system with a Venturi injector has been shown to increase ozone dissolution by 13.8 times compared to conventional methods [17]. Here, microphysical variables act as a bridge: upstream plasma discharge causes a 17–25% thermal expansion of the gas [15], which the Midstream Pillar must control to keep the bubble stable above the Debye length scale (~30 µm) and ensure plasma stability within the microbubble [18]. Without this upstream-midstream synchronization, the system would experience massive oxidative power loss before the ozone gas has a chance to interact with the liquid phase [3].

4.4.2 Midstream-Downstream Linkages: From Hydrodynamics to Radical Oxidation

The integrated paradigm shows that the optimal bubble diameter (37–40.6 µm) generated in the Midstream Pillar [8, 10] primarily drives in situ hydroxyl radical ($\bullet$ OH) formation in the Downstream Pillar. Through an internal pressure mechanism (Laplace Pressure), the microbubbles in the midstream pillar store potential energy that is released upon bubble collapse, resulting in an $\bullet$ OH yield of 0.97×10^{-9} M s [22]. This explains why the integrated system achieved 98% ozone utilization efficiency in coal waste [43] and doubled the rate of textile decolorization [44]. The kLa metric fails to capture the transition phenomenon from selective molecular oxidation to non-selective radical oxidation that occurs at these bubble interfaces [40, 41].

4.4.3 Techno-Economic Validation: The Peak of the Efficiency Chain

The final synthesis of this efficiency chain is the economic demonstration in a real water matrix. Integrating this platform resolves operational contradictions under extreme conditions. For example, in a Bayer Liquor matrix with an alkaline pH of 14.4, the integrated system achieved operational cost savings of CNY 2,360.48 per ton of TOC [12]. This success is a cumulative result: high ozone yield upstream → intensive mass transfer in the midstream → interfacial stability at high salinity downstream [48, 49]. This efficiency chain concludes with biosafety validation, where complete pollutant mineralization yields water safe for the ecosystem, as evidenced by a seed germination rate of 93.3% [13].

Table 8. "The Nexus" Efficiency Chain Matrix on the Integrated Platform

Chain Stage	Key Parameters (Input)	Integration Mechanism	Final Result (Output)
Upstream	Electric Field (4.06×10^7 V/m) [14]	Plasma-DBD Intensification	Yield 150 g/kWh
Midstream	Sauter diameter (37–40.6 μm) [8]	Hydrodynamic-Cavitation Coupling	kLa 1.0258 min^{-1} [7]
Downstream	Real Matrix (pH/Salinity/TOC) [12]	In-situ Radical Generation ($\bullet\text{OH}$)	Save 2360 CNY/ton

5. Recommendations and Future Perspectives

Based on a comprehensive synthesis of 97 primary research papers validated through the PRISMA protocol, the integrated microbubble ozonation platform has demonstrated significant technical advantages at the laboratory scale. However, transitioning to industrial implementation requires a shift in research focus toward metric standardization, system modularity, and intelligent control based on operational data.

5.1 Bubble Characterization Standardization: Beyond the Sauter Diameter Metric

A major obstacle to the replicability of current microbubble ozonation research is the lack of uniformity in reporting bubble physical properties.

- **Integration of Holistic Metrics:** The Sauter mean diameter (d_{32}) has proven inadequate for describing the long-term colloidal stability of bubbles, especially in aqueous matrices with high ionic strength. Future research should adopt a routine Zeta Potential measurement protocol to map the bubble surface charge density, as discussed in the atrazine degradation mechanism in Wang et al. [61], which is a determining parameter for coalescence rate and cavitation efficiency.
- **Instrument Standardization:** High-speed imaging technology coupled with automated image-processing algorithms is required to accurately distinguish nanobubbles (217 nm) from microbubbles (37 μm), in accordance with the size distribution identified in John et al. [9]. This size differentiation is crucial because each has different radical-generation mechanisms that enhance the system's oxidizing power [11].

5.2 Scalability and Industrial Integration: Modular Design Recommendations

Industrial scalability challenges often result in unpredictable energy cost overruns during the transition from pilot to full-scale.

- **Modular Design Strategy:** As demonstrated by the multi-orifice generator innovation in Hao et al. [35], a modular configuration offers a linear scalability solution through parallelization of reactor units. This approach increases wastewater discharge capacity without redesigning the entire reactor hydrodynamic system, minimizing the risk of inefficiencies at scale.
- **Retrofitting Optimization:** A sidestream addition (SSA) system is recommended as the most cost-effective integration method for existing industrial installations, maintaining ozone transfer efficiencies above 95% [5]. Prioritize implementation of an inner-cylinder jet reactor, proven to be 8.6 times more compact than a commercial design in Ding et al. [10], to conserve land use in crowded industrial wastewater treatment facilities.

5.3 AI-Based Optimization and Real-Time Sensors: Integrated Precision Control

The "Integrated Platform" paradigm requires dynamic synchronization between upstream operating conditions and downstream pollutant-load fluctuations.

- Operational Data-Driven Sensors: Implementing Oxidation-Reduction Potential (ORP) sensors capable of recording peak values up to 821 mV in pilot systems [21] is highly recommended for instantaneous monitoring of oxidation transition points. Real-time dissolved oxygen (DO) pressure probes are also crucial to prevent energy waste from ozone oversaturation in the reactor.
- Artificial Intelligence (AI) Integration: Future research should use machine learning algorithms to process data from CFD-PBM numerical models [29] and automatically predict optimal bubble diameters. This intelligent control allows the system to dynamically adjust the ozone dose and plasma power based on changes in wastewater temperature and pH, ensuring maximum radical yield while reducing energy consumption to 0.017 kWh/g [6].

6. Conclusions

A comprehensive synthesis of 97 primary research papers from 2000 to 2026 shows that microbubble ozonation has evolved from a mass-transfer enhancement technique into an "Integrated Platform" connecting upstream, midstream, and downstream domains. Based on the quantitative data analysis presented, the following are the main conclusions to address the efficiency challenges of advanced oxidation systems:

6.1 Validation of the Integrated Platform Paradigm (The Nexus)

This research successfully confirmed that system efficiency can no longer be measured solely by the single parameter kLa. Instead, system success is determined by systemic integration:

- Upstream Pillar: Packed-bed DBD technology can produce yields of up to 150 g/kWh [14], which is instantly coupled with a dispersion system to increase ozone dissolution by up to 13.8 times [17].
- Midstream Pillar: Hydrodynamic manipulation through the dual-field UC-RF resulted in a peak volumetric mass transfer coefficient of 1.0258 min^{-1} [7]. Innovative reactor designs such as the inner-cylinder jet showed the system could be 8.6 times more compact without losing dissolution performance [10].
- Downstream Pillar: The platform demonstrated exceptional adaptability to real-world aqueous matrices, including extreme alkaline pH and high salinity, with a $\cdot\text{OH}$ radical yield reaching $0.97 \times 10^{-9} \text{ M s}$ [22].

6.2 Techno-Economic and Environmental Achievements

The integration of these three pillars has a significant impact on the operational sustainability of wastewater treatment:

1. Energy Efficiency: Specific energy consumption (SEC) has been reduced to 0.017 kWh/g [6], far below the standard for conventional ozonation systems.
2. Economic Advantage: In heavy industrial applications (Bayer Liquor), this integrated system recorded significant operational cost savings of 2,360.48 CNY per ton of TOC [12].
3. Treatment Effectiveness: Removal of pharmaceutical contaminants such as Ibuprofen reached 98.4% [22], while decolorization of textile wastewater occurred twice as fast [44].
4. Bio-Safety: Complete mineralization has been shown to produce water safe for the ecosystem, validated by a mustard seed germination rate of 93.3% [13].

6.3 Concluding Remarks

Overall, this paper confirms that the integration paradigm is key to overcoming the thermodynamic limitations of conventional ozone. By optimizing upstream gas stability, midstream hydrodynamic control, and downstream radical oxidation effectiveness, the microbubble ozonation platform is ready for full-scale industrial implementation as an efficient and sustainable green technology solution. Standardizing bubble characterization and integrating AI-based intelligent control are strategic next steps to secure this technology's place in the future water treatment industry. This review traces the evolution of ozonation research by

highlighting a paradigm shift toward microbubble-based systems as an increasingly dominant approach. Bibliometric analysis reveals growing attention to microbubbles as integrative nodes that bridge hydrodynamic phenomena, interfacial processes, and chemical reactivity within ozonation systems. The mechanistic and systemic synthesis presented herein confirms that performance enhancement in microbubble ozonation does not arise from a single isolated mechanism, but from coupled interactions among multiple processes across scales, from ozone generation to gas–liquid interfacial dynamics. By positioning microbubble-based ozonation as an integrative platform, this review provides a coherent conceptual framework for interpreting diverse experimental findings, reducing reliance on single descriptors, and supporting more rational design and integration of ozonation systems. This framework also offers clear directions for future research, particularly in developing ozonation technologies that are more energy-efficient, more predictable during scale-up, and more sustainable for water and wastewater treatment applications.

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