

Review

Recent Advances in High-Gravity Ozonation for Wastewater Treatment

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Abstract

Ozonation is widely used in wastewater treatment, but its efficiency is often limited by the low solubility of ozone and insufficient gas–liquid mass transfer. High-gravity technology offers an effective intensification strategy by enhancing liquid-film renewal, interfacial contact, and micromixing under centrifugal fields. This review summarizes recent advances in high-gravity ozonation for wastewater treatment. The fundamental oxidation pathways of ozonation, the characteristics of typical high-gravity reactors, and recent applications in both homogeneous and heterogeneous systems are discussed. Current studies show that high-gravity ozonation can significantly improve ozone utilization, pollutant degradation, and mineralization efficiency. It was reported that the equilibrium dissolved ozone concentration and ozone decomposition rate constant in heterogeneous catalytic high-gravity systems were 2.5 and 2.6 times higher than those in conventional bubbling reactors, respectively, leading to markedly enhanced pollutant and TOC removal. These findings highlight the potential of high-gravity ozonation for intensified wastewater treatment. Despite these advances, its practical application still faces challenges related to real wastewater adaptability, byproduct and toxicity control, reactor scale-up, catalyst stability, economic feasibility, and energy demand. This review provides a useful reference for the further development and engineering application of high-gravity ozonation technology.

Keywords: high-gravity technology; ozonation; wastewater treatment; process intensification; advanced oxidation processes



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1. Introduction

Clean water is fundamental to human health, social stability, and economic development [1]. With the acceleration of urbanization and the continuous expansion of agricultural activities, water demand has been steadily increasing, while water pollution is becoming increasingly severe, thereby aggravating global water scarcity. It is projected that the global urban population facing water scarcity will increase from 933 million in 2016 to 1.693–2.373 billion by 2050 [2,3]. Meanwhile, industrialization generates large volumes of wastewater containing pollutants and even toxic substances. It has been reported

that approximately 48% of global wastewater is discharged into the environment without treatment, posing serious threats to the ecological environment and public health [4]. Therefore, the development of efficient wastewater treatment and water reuse technologies has become increasingly urgent.

Existing wastewater treatment technologies mainly include physical, chemical, and biological methods [5], while common advanced treatment processes involve membrane separation [6,7], adsorption [8], coagulation–flocculation [9], microbial treatment [10], and chemical oxidation [11]. However, each technology still has certain limitations in terms of applicability, treatment efficiency, operating cost, and engineering sustainability. Advanced oxidation processes (AOPs) can achieve efficient removal of refractory organic pollutants by generating highly reactive radicals [12]. Among them, ozonation is one of the most widely applied oxidation technologies in water treatment. Ozone has been extensively used for disinfection and the degradation of toxic organic pollutants, and ozone-based processes as well as their coupled systems have shown great potential for pollutant degradation, mineralization, and toxicity reduction [13].

Although conventional ozonation has been widely applied in water treatment, its practical performance is still constrained by the low aqueous solubility of ozone, insufficient gas–liquid mass transfer, non-uniform ozone distribution, and the loss of unutilized ozone [14]. In conventional bubble-column or pneumatic bubble reactors, these drawbacks often result in limited pollutant removal [15], low ozone utilization efficiency [16], and even increased risks of by-product formation [17,18]. Therefore, the development of intensified methods capable of enhancing gas–liquid mass transfer, shortening diffusion paths, and improving ozone utilization is of great significance.

To overcome the limitations of conventional ozone reactors, such as low ozone mass transfer efficiency and insufficient gas–liquid contact, high-gravity technology (HiGee) has been introduced into ozonation processes for wastewater treatment. High-gravity technology is a typical process intensification technique, commonly employing a rotating packed bed (RPB) as the core device. By generating a high-gravity field through centrifugal force, the fluid is subjected to a large centrifugal acceleration under rotating conditions, thereby significantly enhancing liquid-film renewal, interfacial contact efficiency, and micromixing intensity, and enabling the synergistic intensification of mass transfer, mixing, and chemical reactions [19]. Owing to its advantages of simple structure, compact design, small footprint, high throughput, and excellent mass transfer performance, high-gravity equipment has been widely applied in absorption [20], desorption [21], extraction [22,23], crystallization [24], and nanomaterial preparation [25], and has provided a new technological approach for intensified ozonation for water treatment. Therefore, the integration of high-gravity technology with ozonation is considered an effective strategy for improving ozone utilization efficiency and wastewater treatment performance.

This review summarizes recent advances in the application of high-gravity technology to ozonation-based wastewater treatment. The review first introduces the fundamental oxidation chemistry of ozonation and the intensification mechanisms enabled by high-gravity fields. Subsequently, typical high-gravity reactor configurations, including rotating packed bed, rotor-stator reactors and rotating zigzag beds, are discussed. Recent applications of homogeneous and heterogeneous high-gravity ozonation systems are then reviewed, with emphasis on ozone utilization, pollutant degradation, mineralization, and catalytic mechanisms. Finally, the major challenges associated with real wastewater treatment, byproduct control, reactor scale-up, catalyst stability, and the economic feasibility and energy demand of industrial application are critically discussed. This review aims to provide a systematic reference for the further development and practical application of high-gravity ozonation technologies.

Previous reviews have discussed high-gravity technologies for wastewater treatment or industrial sewage purification from broad technological perspectives, covering stripping, electrochemical treatment, adsorption, extraction, photocatalysis, and various oxidation processes, with ozonation treated as only one of several application routes [26,27]. In contrast, the present review is specifically dedicated to high-gravity ozonation for wastewater treatment and focuses on the coupling between ozone reaction chemistry and high-gravity process intensification. It systematically examines how high-gravity reactor configurations and operating modes affect ozone dissolution, gas–liquid interfacial renewal, reactive-species generation, and ozone utilization, and further summarizes recent progress in homogeneous O_3 -based systems, including O_3/H_2O_2 , O_3 /persulfate (PS), and Fe^{2+} -assisted processes, as well as heterogeneous catalytic systems based on carbon materials, supported metal catalysts, and structured catalytic packings. Accordingly, this review provides a focused synthesis of high-gravity ozonation by linking ozone reaction pathways with reactor-based mass-transfer intensification and catalytic activation, rather than broadly surveying multiple wastewater-treatment processes enabled by high-gravity technology.

2. Reaction Chemistry of Ozonation

Ozonation in aqueous solution mainly proceeds through two pathways: the direct oxidation by molecular ozone and the indirect oxidation initiated by ozone decomposition [28]. The former is mainly characterized by the selective attack of ozone on specific functional groups in pollutants, whereas the latter achieves the non-selective degradation of pollutants through the generation of reactive species such as $\cdot OH$, $HO_2\cdot$, and $HO_3\cdot$ [29]. In certain coupled systems, reactive radicals such as $SO_4\cdot^-$, $CO_3\cdot^-$, and $Cl\cdot$ can also be further formed.

2.1. Direct and Indirect Oxidation Mechanisms of Ozonation

Under acidic-to-neutral conditions, direct reactions of molecular ozone with pollutants usually dominate; under alkaline conditions, however, ozone is more readily decomposed to generate reactive oxidative species. When the pH exceeds 5, $\cdot OH$ starts to form, and with further increases in pH, both the ozone decomposition rate and the contribution of indirect oxidation increase significantly [30]. This process is generally considered to be a radical chain reaction initiated by $\cdot OH$. In brief, the decomposition of ozone in water can be represented by the following reactions:

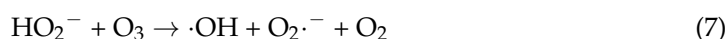


Compared with molecular ozone, $\cdot OH$ exhibits lower reaction selectivity and stronger oxidation capacity, with an oxidation potential of approximately 2.8 V, which is higher than that of ozone (2.07–2.08 V). Therefore, $\cdot OH$ can react with a wide range of organic pollutants at rates close to the diffusion-controlled limit and plays an important role in the removal of refractory organic compounds during ozone-based advanced oxidation processes [31].

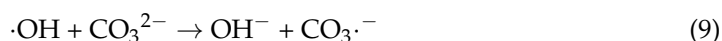
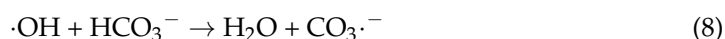
2.2. Reaction Mechanisms of Typical Inorganic/Organic Constituents with O₃ and Radicals

In ozonation systems, coexisting inorganic constituents can regulate the relative contributions of molecular ozone oxidation and radical oxidation by promoting O₃ decomposition, scavenging ·OH, or altering the distribution of secondary reactive species.

H₂O₂/HO₂[−] is a typical promoter of ozone decomposition. The dissociation of H₂O₂ to HO₂[−] can initiate the chain decomposition of ozone and promote ·OH generation, thereby enhancing the contribution of radical oxidation in the system [32]. The decomposition pathway of O₃ in the presence of H₂O₂ is illustrated as follows:



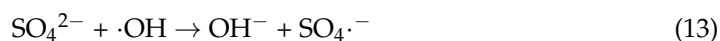
HCO₃[−] and CO₃^{2−} are common ·OH scavengers in ozonation systems. Both species can react with ·OH to generate CO₃·[−]. Compared with ·OH, the oxidation potential of the CO₃·[−]/CO₃^{2−} redox couple is approximately 1.59 V, indicating that CO₃·[−] has a lower oxidation capacity [33]. However, it exhibits higher selectivity and greater persistence in aqueous solution, and may therefore achieve superior performance in the degradation of specific pollutants [34–36]. The reaction pathways of HCO₃[−] and CO₃^{2−} with ·OH are as follows:



The effect of Cl[−] on ozonation systems is relatively complex. Cl[−] can react with ·OH to generate reactive chlorine species, such as Cl· and Cl₂·[−], thereby decreasing the concentration of free ·OH and partially shifting the oxidation process toward pathways involving reactive chlorine species [37]. The redox potentials of Cl· and Cl₂·[−] are approximately 2.4 V and 2.0 V, respectively, indicating that although the presence of Cl[−] can suppress the ·OH-mediated pathway, the generated reactive chlorine species still possess considerable oxidative capacity [38]. The reaction pathways of Cl[−] with ·OH are as follows:



In contrast, SO₄^{2−} generally acts as a background anion in conventional ozonation systems. The reaction of SO₄^{2−} with ·OH can generate SO₄·[−], which possesses a redox potential comparable to or even higher than that of ·OH, along with higher selectivity and a longer lifetime [39,40]. Therefore, it can still exhibit considerable reactivity toward the oxidation of specific organic pollutants. The reaction pathway between SO₄^{2−} and ·OH is as follows:



Overall, coexisting inorganic constituents play an important role in shaping ozonation chemistry by affecting ozone decomposition, the distribution of reactive oxygen species, and the generation of secondary radicals, thereby influencing pollutant oxidation pathways and treatment performance. The major reaction pathways involved in high-gravity ozonation systems are schematically illustrated in Figure 1.

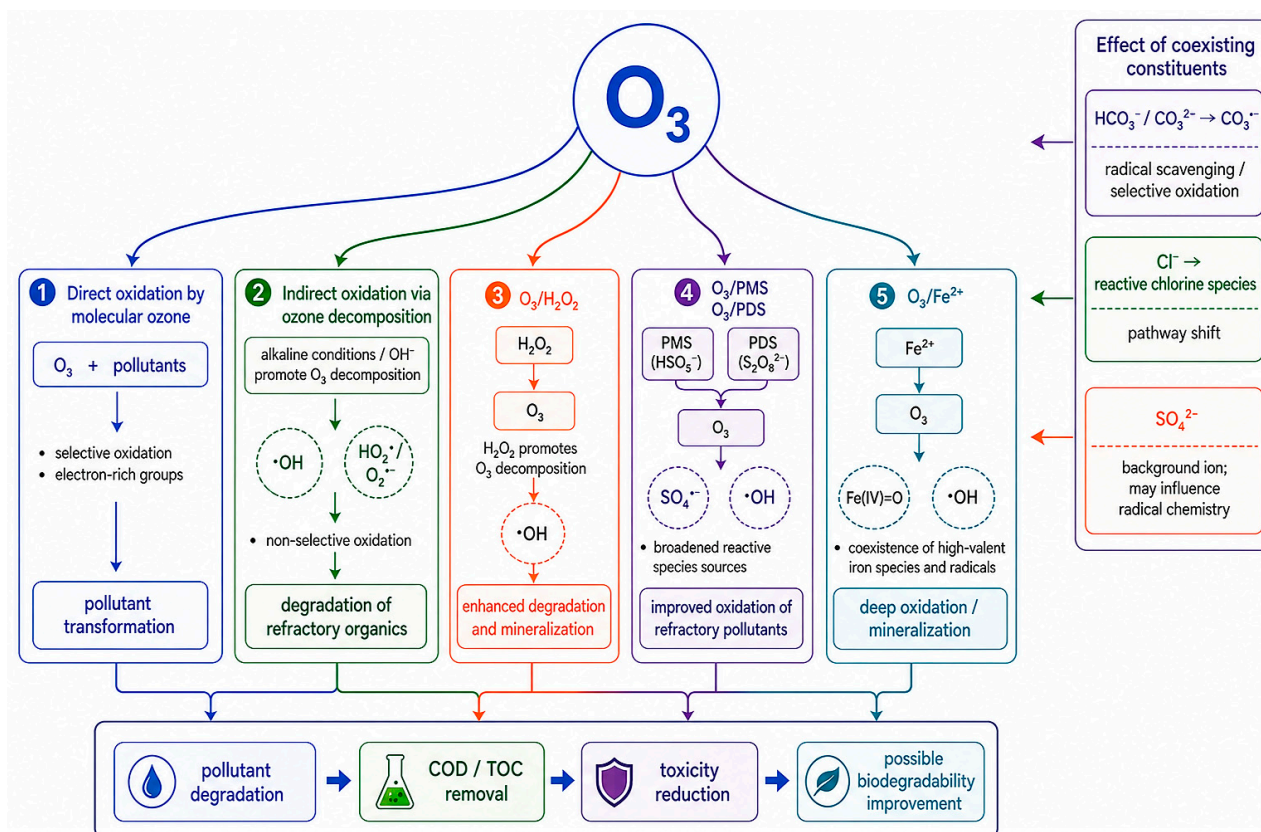


Figure 1. Schematic illustration of the main reaction pathways in high-gravity ozonation systems.

These reaction pathways are closely related to the molecular structures of target pollutants. Pollutants containing electron-rich moieties, such as phenolic, amino, or olefinic groups, can generally react with molecular ozone through direct oxidation, whereas less ozone-reactive or more refractory compounds usually require radical-mediated oxidation, especially through $\cdot\text{OH}$. In high-gravity ozonation systems, ozone-based AOPs, including $\text{O}_3/\text{H}_2\text{O}_2$, O_3 /persulfates, $\text{O}_3/\text{Fe}^{2+}$, and catalytic ozonation, have been applied to the degradation of typical pollutants such as phenolic compounds, antibiotics, nitroaromatic compounds, pharmaceuticals, and other refractory organics, with the reported removal and mineralization efficiencies summarized in the following sections and tables.

3. Typical HiGee Reactors for Ozonation

High-gravity technology is a typical process intensification method that utilizes rotation-induced high centrifugal fields to enhance transport and reaction processes. The intensity of the high-gravity field is commonly described by the high-gravity factor β , which is defined as follows:

$$\beta = a_c/g = \omega^2 r/g \quad (14)$$

where a_c is the centrifugal acceleration, ω is the angular velocity, r is the radial position, and g is the gravitational acceleration. Depending on the rotor radius and rotational speed, the effective centrifugal acceleration in high-gravity reactors can generally reach tens to hundreds of times that of normal gravity. Compared with conventional gas–liquid contactors, high-gravity reactors can significantly reduce liquid film thickness, accelerate gas–liquid interfacial renewal, and intensify fluid turbulence and micromixing, thereby improving gas–liquid mass transfer rates and reaction efficiency [19].

In ozonation systems, the low solubility of O_3 in water and the relatively high gas–liquid mass transfer resistance often limit its utilization efficiency; therefore, the use

of high-gravity reactors offers clear advantages in enhancing ozone mass transfer and promoting the generation of reactive oxygen species [26,27]. Compared with conventional ozonation, high-gravity ozonation introduces additional reactor-related parameters, such as rotational speed, high-gravity factor, packing or rotor configuration, and liquid distribution. In recent years, with the continuous development of high-gravity technology, researchers have developed various high-gravity reactors with different rotating configurations [41,42]. At present, a variety of high-gravity reactors have been applied to ozone-based water treatment processes, mainly including rotating packed beds (RPB), rotor-stator reactors (RSR) and rotating zigzag beds (RZB). The structural characteristics and intensification mechanisms of these typical high-gravity reactors are introduced separately below (Figure 2).

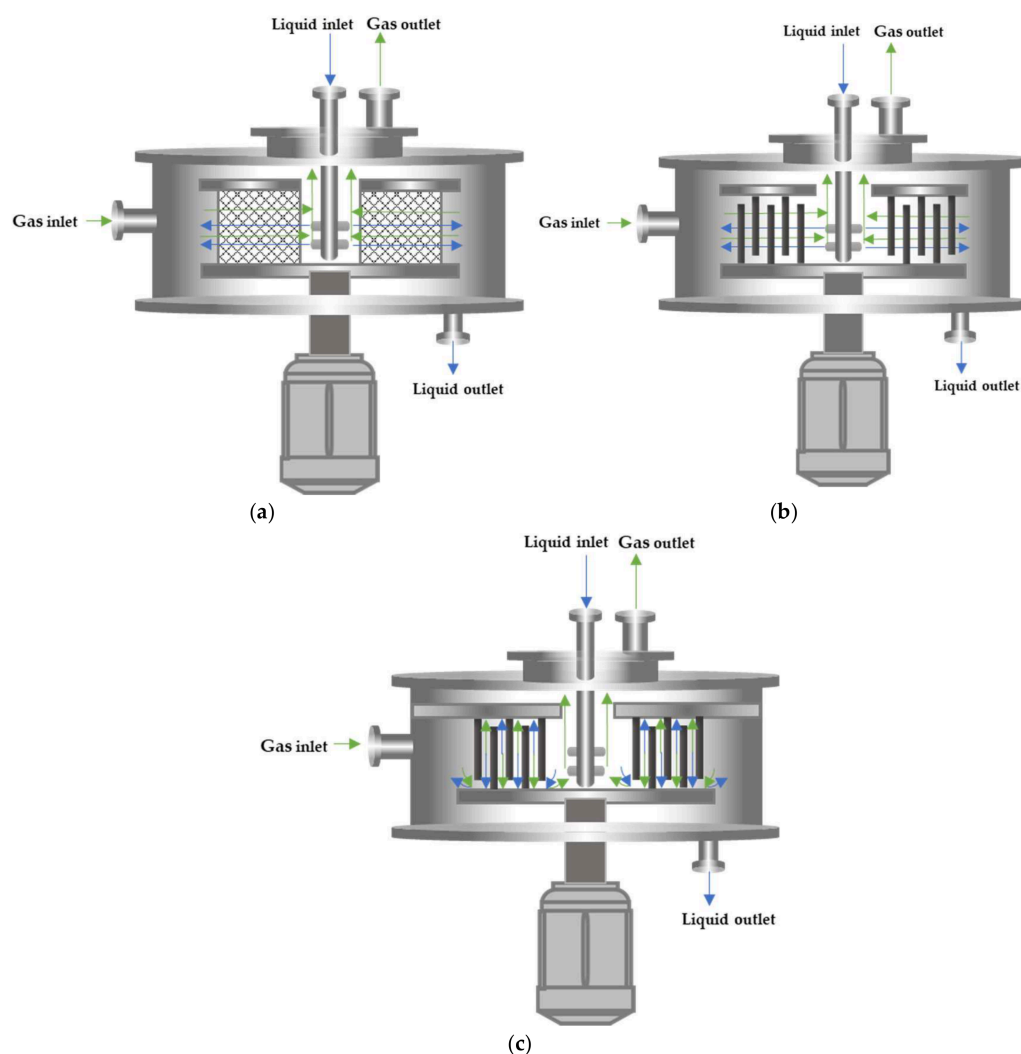


Figure 2. Schematic diagram of the major HiGee reactor configurations used in ozonation systems: (a) rotating packed beds; (b) rotor-stator reactors; (c) rotating zigzag beds.

3.1. Rotating Packed Bed

The RPB is one of the most representative high-gravity reactors. Its basic structure, as shown in Figure 2a, mainly consists of a rotating packed rotor, a casing, a liquid distributor, and gas/liquid inlets and outlets [43,44]. During operation, the liquid flows radially outward through the packing from the inner edge to the outer edge of the rotor under centrifugal force, while the gas typically flows from the outer edge toward the inner edge, thereby forming a radially countercurrent gas–liquid contact pattern within the packing layer. Compared with conventional packed towers, the RPB can significantly reduce liquid

film thickness, accelerate gas–liquid interfacial renewal, and intensify turbulence under a high centrifugal field, thus markedly enhancing gas–liquid mass transfer efficiency [42]. Owing to its compact structure, high mass transfer efficiency, and pronounced process intensification performance, the RPB has become one of the most widely applied and extensively studied reactor configurations in high-gravity technology.

In addition to the conventional RPB, several modified RPB configurations have also been developed in recent years, such as the gas-baffled rotating packed bed (GB-RPB) [45] and the submerged rotating packed bed (SRPB) [46]. These modified configurations generally further enhance ozone mass transfer and reaction performance by regulating gas–liquid flow paths, prolonging gas residence time, or strengthening liquid circulation and interfacial renewal.

3.2. Rotor-Stator Reactor

The basic structure of the RSR is shown in Figure 2b. It typically consists of multiple concentric rotor rings and stator rings arranged alternately along the radial direction, in which ring assemblies with slotted or perforated structures replace the conventional packing. As a result, the RSR features an open structure, adjustable ring configuration, and ease of assembly and disassembly [47]. After entering the RSR, the fluid continuously undergoes rotor capture and acceleration, stator-induced collision and disturbance, and multistage redistribution during its outward radial migration, thereby giving rise to markedly non-uniform, multiscale flow characteristics. Meanwhile, liquid breakup occurs mainly in the high-shear regions near the rotor rings and around the stator, exhibiting typical behaviors such as ligament breakup into droplets and subsequent droplet fragmentation [48,49]. Owing to these structural and hydrodynamic characteristics, the RSR offers advantages including frequent fluid renewal, high micromixing efficiency, operational flexibility, and low susceptibility to clogging.

3.3. Rotating Zigzag Bed

The RZB is a novel rotating contactor developed based on the principle of high gravity. Its basic structure is shown in Figure 2c, and its core section consists of coupled rotating and stationary disks, with rotating baffles and stationary baffles arranged alternately along the radial direction [50]. During operation, the gas and liquid flows countercurrently through the gaps between the rotating and stationary baffles with a zigzag pathway, while the liquid continuously undergoes dispersion, coalescence, and redistribution under the action of centrifugal force. Compared with the conventional RPB, the RZB employs a baffle structure instead of the traditional packing, eliminating the need for a liquid distributor and dynamic seals, while also allowing intermediate feeding in continuous distillation processes [51]. Owing to its unique zigzag configuration, the RZB can effectively prolong the gas–liquid contact path and residence time, and it is also convenient for constructing multistage rotor structures. Therefore, it exhibits good engineering adaptability in mass-transfer separation processes such as continuous distillation [52].

3.4. Comparative Remarks on HiGee Reactors for Ozonation

Although these HiGee reactors can all intensify gas–liquid contact, their applicability in ozonation processes depends strongly on reactor structure and the dominant process limitation. These structural differences affect gas–liquid interfacial renewal, transport paths, and flow resistance, thereby leading to distinct mass-transfer performances, pressure drops, liquid residence times, and energy demands among different HiGee reactors. In RPBs, the rotating packing disperses liquid into thin films, rivulets, and droplets, providing a large and continuously renewed interface for ozone transfer, but the packed zone may also result in short liquid residence time. In RSRs, the alternating rotor and stator rings

repeatedly shear and redistribute the liquid, resulting in rapid liquid breakup, strong interfacial renewal, and efficient micromixing. Those hydrodynamic characteristics can enhance the local redistribution of dissolved ozone and reactive species near the gas–liquid interface, which is beneficial for fast ozone-based reactions. In RZBs, alternating rotating and stationary baffles create zigzag flow paths that can increase liquid holdup and gas–liquid contact time, but may also increase flow resistance and power demand.

To avoid overgeneralized comparison, the main intensification features, advantages, limitations, and suitable ozonation scenarios of typical HiGee reactors are summarized in Table 1. In general, RPBs are more suitable when ozone dissolution and gas–liquid mass transfer are the main limitations, especially in conventional and catalytic ozonation systems. RSRs may be preferred for fast ozone-based AOPs requiring rapid micromixing and interfacial renewal, whereas RZBs may be considered when longer gas–liquid contact and extended flow paths are desired. However, direct comparisons among different HiGee reactors under identical ozonation conditions remain limited. Therefore, future reactor selection should consider not only pollutant removal efficiency, but also ozone utilization, pressure drop, liquid residence behavior, mass-transfer performance, fouling tendency, and scale-up adaptability.

Table 1. Characteristics and selection criteria of typical HiGee reactors for ozonation.

Reactor	Main Intensification Feature	Main Advantages	Main Limitations	Suitable Scenarios in Ozonation	Ref.
RPB	Annular packing disperses liquid into films, rivulets, and droplets, enhancing interfacial renewal and gas–liquid mass transfer	Mature and compact configuration; high mass transfer efficiency; suitable for catalytic packing; widely applied in high-gravity ozonation	Relatively high pressure drop; short liquid residence time; possible liquid maldistribution, splashing, packing fouling	General ozonation and catalytic ozonation systems where ozone dissolution and gas–liquid mass transfer are limiting factor	[42,43,53,54]
RSR	Repeated liquid redistribution, strong shear, rapid droplet breakup, and excellent micromixing generated by alternating rotor and stator rings	Very short micromixing time; strong interfacial renewal; reduced packing fouling; adjustable rotor/stator structure	Complex hydrodynamics; short liquid residence time at high speed; higher energy demand with more layers or higher speed; limited ozonation studies	Fast homogeneous ozone-based AOPs requiring rapid mixing and interfacial renewal	[47–49]
RZB	Zigzag gas–liquid flow channels formed by rotating and stationary baffles, causing repeated dispersion–aggregation and extended contact	Longer gas–liquid contact path; larger liquid holdup; good mass transfer performance; convenient multirotor configuration	Higher pressure drop and power consumption than RPB; complex structure; limited ozonation validation	Ozonation systems requiring extended gas–liquid contact and improved ozone utilization	[50–52]

4. Wastewater Treatment by HiGee Homogeneous Ozonation

In HiGee homogeneous ozonation systems for wastewater treatment, ozone reacts with pollutants in the absence of solid catalysts. Such systems include not only ozonation alone, but also advanced oxidation processes coupled with homogeneous oxidants such

as H_2O_2 , PS, and Fe^{2+} . Compared with conventional ozonation systems, the high-gravity field can significantly intensify gas–liquid mass transfer and improve ozone utilization efficiency, thereby enhancing pollutant removal performance. Therefore, this type of system not only represents the fundamental form of high-gravity ozonation, but also provides an important basis for the subsequent development of heterogeneous catalytic and hybrid oxidation systems.

Representative applications of HiGee homogeneous ozonation systems for wastewater treatment are summarized in Table 2. As shown in the table, current studies have expanded from ozonation alone to various coupled homogeneous systems involving H_2O_2 , PMS/PDS, and Fe^{2+} -based reagents, demonstrating enhanced pollutant degradation, mineralization, and, in some cases, improved biodegradability.

Table 2. Representative applications of HiGee homogeneous ozonation systems in wastewater treatment.

Pollutant	HiGee Ozonation System	Key Operating Conditions	Ozone Utilization Efficiency	Pollutant Removal	COD/TOC Removal	Ref.
BR-46 wastewater	RPB- O_3 /LDP	$C_0 = 300 \text{ mg/L}$; $V_{\text{LDP}} = 200 \text{ mL}$; $\text{O}_3 = 20 \text{ mg/L}$; $Q_G = 75 \text{ L/h}$; $Q_L = 15 \text{ L/h}$; 800 rpm	63.2%	82.6%	COD 29.8%	[55]
High-salinity AR-73 wastewater	RPB- O_3 /LDP	$C_0 = 300 \text{ mg/L}$; $\text{Na}_2\text{SO}_4 = 30 \text{ g/L}$; $V_{\text{LDP}} = 150 \text{ mL}$; $\text{O}_3 = 40 \text{ mg/L}$; $Q_G = 60 \text{ L/h}$; $Q_L = 20 \text{ L/h}$; 800 rpm Inner baffle = 1/3 rotor outer diameter; outer baffle = 5/9 rotor outer diameter; baffle spacing = 20 mm; $Q_L = 60 \text{ L/h}$; $\text{O}_3 = 20 \text{ mg/L}$; $\beta = 30$; initial pH = 6 $C_0 = 10\text{--}30 \text{ mg/L}$; mesh numbers = 12;	75.7%	91.3%	COD 32.4%	[56]
Pesticide-laden wastewater	GB-RPB/ O_3	$N = 300\text{--}500 \text{ rpm}$; $Q_G = 300\text{--}500 \text{ L/h}$; $\text{O}_3 = 50\text{--}150 \text{ mg/L}$; $t = 24 \text{ min}$	~81% (60 min)	—	COD ~71% (60 min)	[45]
SMX wastewater	SRPB/ O_3	$C_0 = 50 \text{ mg/L}$; pH = 6.5; $T = 25 \text{ }^\circ\text{C}$; $\text{O}_3 = 61.3 \text{ mg/L}$; $Q_L = 18 \text{ L/h}$; 1000 rpm $C_0 = 500 \text{ mg/L}$; pH = 9.25; initial COD = 380 mg/L; $\text{O}_3 = 50 \text{ mg/L}$; $Q_G = 36 \text{ L/h}$; $Q_L = 12 \text{ L/h}$; 1000 rpm $C_0 = 300 \text{ mg/L}$; pH = 6.5;	90.1%	94.0–96.8%	—	[57]
<i>o</i> -PDA wastewater	RSR/ O_3	$\text{O}_3 = 30 \text{ mg/L}$; $Q_G = 60 \text{ L/h}$; $Q_L = 12 \text{ L/h}$; 1200 rpm	—	94.6%	COD 61.2%	[58]
AR-73 wastewater	RSR-BCR/ O_3		—	>97%	COD > 30%	[59]
Amaranth wastewater	RZB/ O_3		—	92.8%	COD 14.6%	[60]

Table 2. Cont.

Pollutant	HiGee Ozonation System	Key Operating Conditions	Ozone Utilization Efficiency	Pollutant Removal	COD/TOC Removal	Ref.
<i>E. coli</i> -contaminated water	RPB/O ₃	Ct = 0.0008–0.0014 min·mg·L ^{−1} ; Q _G = 30 L/h; Q _L = 60 L/h; 800 rpm; 22 °C C ₀ = 200 mg/L; H ₂ O ₂ = 5.7 mmol/L;	—	<i>E. coli</i> log inactivation reached 6.8–7.3	—	[61]
Nitrobenzene wastewater	RPB/O ₃ /H ₂ O ₂	O ₃ = 50 mg/L; Q _L = 125 L/h; β = 100; pH = 10.5; Q _G = 75 L/h; t = 10 min C ₀ = 60 mg/L; H ₂ O ₂ = 30 mg/L;	—	76.1%	—	[62]
<i>o</i> -PDA wastewater	RSR/O ₃ /H ₂ O ₂	O ₃ = 51.0 mg/L; Q _L = 20 L/h; Q _G = 240 L/h; pH = 6.5; T = 25 °C; 1000 rpm C ₀ = 150 mg/L; pH = 7.0;	—	94.8%	COD 68.1%	[63]
Tetracycline hydrochloride (TCH) wastewater	RPB/O ₃ /PMS/LDP	O ₃ = 30 mg/L; PMS = 2.25 mmol/L; Q _G = 60 L/h; Q _L = 25 L/h; 600 rpm; V _{LDP} = 200 mL C ₀ = 200 mg/L; pH = 10;	75.9%	92.2%	COD 19.6%	[64]
Nitrobenzene wastewater	RPB/O ₃ /PDS	β = 40; PDS = 2.5 mmol/L; O ₃ = 60 mg/L; Q _G = 75 L/h; Q _L = 100 L/h; t = 30 min C ₀ = 20 mg/L; pH = 10;	—	90.59%	—	[65]
Chloramphenicol wastewater	SRPB/O ₃ /PDS	O ₃ = 30 mg/L; PDS = 100 mg/L; 400 rpm; t = 16 min C ₀ = 200 mg/L; pH = 4; Fe ²⁺ = 1.0 mM;	—	97%	—	[66]
Methyl orange wastewater	RPB/O ₃ /PDS/Fe ²⁺	PDS = 2.0 mM; O ₃ = 40 mg/L; Q _G = 300 L/h; Q _L = 15 L/h; 1000 rpm; 25 °C C ₀ = 200 mg/L; pH = 7.3; Fe ²⁺ = 0.8 mmol/L;	—	88%	COD 38%	[67]
Indigo carmine wastewater	RSR/O ₃ /PDS/Fe ²⁺	PDS = 0.8 mmol/L; O ₃ = 2.5 mg/L; G/L = 1; 600 rpm; 25 °C C ₀ = 200 mg/L; β = 100; pH = 5; Fe ²⁺ = 0.8 mmol/L;	—	96.9%	—	[68]
Aniline wastewater	RPB/O ₃ /Fenton	H ₂ O ₂ = 2.5 mL; O ₃ = 36 mg/L; Q _G = 60 L/h; Q _L = 80 L/h pH = 4; Fe ²⁺ = 0.5 mmol/L; H ₂ O ₂ = 2.5 mmol/L;	85%	100%	TOC 89%	[69]
Coal gasification wastewater	RPB/O ₃ /Fenton + coagulation	O ₃ = 20 mg/L; 800 rpm; Q _G = 90 L/h; Q _L = 15 L/h; pH(coagulation) = 3; poly aluminum sulfate = 100 mg/L	—	87.5%	COD 47.8%	[70]

Because the operating conditions and processes vary among different studies, Table 2 summarizes representative applications and performance indicators rather than providing a direct quantitative comparison among different systems.

4.1. HiGee Ozonation Alone

In HiGee ozonation alone systems, pollutant removal is mainly achieved through the combined effects of direct oxidation by molecular ozone and indirect oxidation by reactive species generated from ozone decomposition. Previous studies have applied this system to the treatment of various wastewaters and typical organic pollutants, and have systematically investigated its removal performance and intensification characteristics.

Early studies mainly focused on the behavior of ozone in conventional RPB. These investigations showed that the decomposition of aqueous ozone in an RPB could be accelerated by increasing pH and rotational speed, suggesting that the high-gravity field not only enhances ozone transfer from the gas phase to the liquid phase, but also affects the relative contribution of direct ozonation and radical-mediated oxidation [71].

On this basis, one emerging intensification strategy has been the utilization of the liquid detention phenomenon (LDP) [55,56]. This phenomenon refers to the retention of a specified volume of liquid at the base of the RPB by regulating the outlet liquid flow (Figure 3). When liquid is detained in the RPB, it will accumulate at the bottom and immerse the lower part of the rotor. Some of the detained liquid will be carried by the rotating rotor to the upper part of the rotor and cavity. Thus, both the liquid residence time and liquid holdup in the RPB increase when the liquid is detained, leading to improved interphase transfer effect. Hydrodynamically, liquid detention prolongs the residence time of the liquid phase and increases the amount of liquid retained within the reactor, thereby maintaining longer gas–liquid contact and providing more time for ozone dissolution, interfacial transfer, and subsequent oxidation reactions. This effect is beneficial for both direct ozone oxidation and indirect oxidation by ozone-derived reactive species. Xu et al. [55] and Shi et al. [56] demonstrated that LDP could markedly improve pollutant removal and ozone utilization. These results indicate that residence-time regulation is an effective way to strengthen the performance of single-ozone HiGee systems, especially when wastewater composition hinders efficient oxidation.

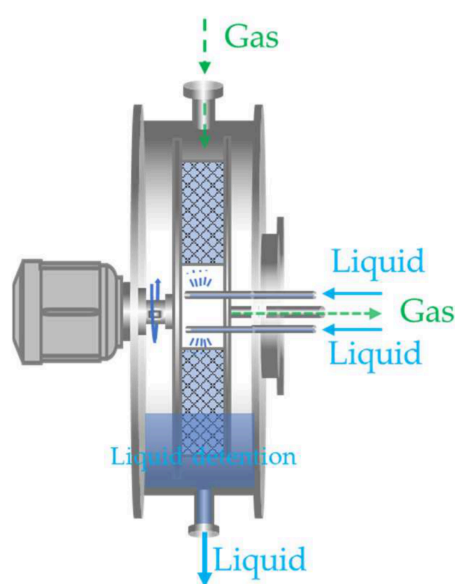


Figure 3. Schematic illustration of LDP in an RPB [64].

Nevertheless, liquid detention reduces the available pathways for gas flow within the RPB, thereby increasing the pressure drop. Moreover, LDP elevates the liquid load in the RPB, which can lead to higher energy consumption for its operation. Consequently, an optimal level of detained liquid must be maintained to balance the benefits of enhanced oxidation against these potential drawbacks.

In addition to operation-mode regulation, structural optimization of reactors has also become an important route for intensification. Modified configurations such as GB-RPB and SRPB have been developed to improve gas distribution, enhance liquid circulation, prolong effective gas residence time, and accelerate interfacial renewal. Studies showed that such improvements could substantially enhance ozone utilization or mass-transfer efficiency, while enabling rapid degradation of refractory pollutants such as pesticide residues and antibiotics [45,57]. Overall, these findings suggest that internal-structure optimization and hydrodynamic regulation have become key strategies for improving the treatment efficiency of HiGee single-ozone systems.

Single-ozone HiGee systems have also been extended beyond the conventional RPB to other intensified reactors, including RSR [58,59] and RZB [60]. Although these reactors differ in structure and flow pattern, they show a consistent intensification trend, namely, improving ozone absorption while maintaining sufficient effective reaction time. This extension indicates that the application of single-ozone HiGee systems is gradually shifting from a single reactor type toward a broader family of intensified gas–liquid contactors.

The application of HiGee single-ozone systems is not limited to the degradation of organic pollutants. Previous studies have also employed RPBs as ozonation disinfection contactors, showing that high microbial inactivation could be achieved even at relatively low Ct values [61]. This result highlights the potential of HiGee single-ozone systems in disinfection process.

Overall, HiGee single-ozone systems have significantly improved ozone utilization and pollutant removal through both operation-mode regulation and reactor-configuration optimization. However, their deep oxidation and mineralization capacity remains inherently limited, because the system still relies primarily on ozone and ozone-derived reactive species generated without additional oxidants. This limitation provides the motivation for introducing H_2O_2 , PMS/PDS, and Fe^{2+} -based reagents, which are discussed in the following sections.

4.2. Applications of the HiGee $\text{O}_3/\text{H}_2\text{O}_2$ System in Water Treatment

To overcome the limitations of single-ozone systems in terms of oxidation selectivity and deep mineralization capacity, hydrogen peroxide has been introduced to construct the $\text{O}_3/\text{H}_2\text{O}_2$ combined system. In this system, H_2O_2 promotes ozone decomposition and accelerates the generation of hydroxyl radicals, thereby enhancing the non-selective oxidation capacity of the process and improving the removal of refractory organic pollutants. Under high-gravity conditions, the intensification of ozone gas–liquid mass transfer and the acceleration of radical reactions can proceed simultaneously, which further increases the applicability of the $\text{O}_3/\text{H}_2\text{O}_2$ system in refractory wastewater treatment.

Existing studies indicate that the high-gravity $\text{O}_3/\text{H}_2\text{O}_2$ homogeneous system has considerable potential for the treatment of refractory organic wastewater. Jiao et al. [62] demonstrated that the treatment of nitrobenzene wastewater in an RPB was strongly influenced by the coupling of oxidant dosage and high-gravity intensity, confirming that process intensification in such systems depends not only on enhanced ozone transfer but also on the coordinated optimization of reaction conditions. Similarly, Arowo et al. [63] employed an RSR to treat *o*-phenylenediamine wastewater and showed that, compared with ozonation alone, the $\text{O}_3/\text{H}_2\text{O}_2$ system could simultaneously improve pollutant degradation, ozone

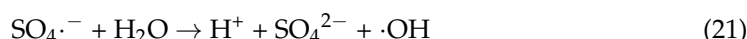
mass-transfer performance, and COD removal, while also leading to lower residual levels of intermediate products. These results suggest that the introduction of H_2O_2 into HiGee ozonation systems does not merely enhance pollutant transformation, but also promotes a more complete oxidation pathway.

Overall, under high-gravity conditions, the $\text{O}_3/\text{H}_2\text{O}_2$ system improves the degradation and mineralization of refractory organic pollutants through the synergistic enhancement of ozone transfer and hydroxyl-radical generation. Nevertheless, its performance remains strongly dependent on oxidant dosage, ozone concentration, and reactor operating conditions. Therefore, although the $\text{O}_3/\text{H}_2\text{O}_2$ system provides a relatively straightforward route for strengthening homogeneous ozonation, further enhancement through other oxidants or Fe^{2+} -assisted systems remains of continued interest.

4.3. Applications of the HiGee O_3 /Persulfate System in Water Treatment

To further enhance the oxidation capacity of ozonation systems toward refractory organic pollutants, researchers have coupled ozone with persulfate-based oxidants to construct O_3 /persulfate combined systems. Persulfate generally includes two types of precursors, namely peroxymonosulfate (PMS) and peroxydisulfate (PDS).

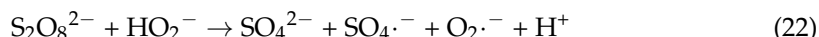
In the O_3 /PMS system, PMS can react with ozone to generate $\text{SO}_4^{\cdot-}$ and $\cdot\text{OH}$ through intermediate reactive species such as $\text{SO}_5^{\cdot-}$ and $\text{O}_3^{\cdot-}$, thereby forming a combined reaction system involving the molecular ozone oxidation, sulfate radical oxidation, and hydroxyl radical oxidation [72,73]. Compared with the ozone-alone system, the introduction of PMS broadens the sources of reactive oxidative species and enhances the indirect oxidation capacity of the system [74]. The mechanistic reactions are as follows:



Zhu et al. [64] developed a liquid-detention-enhanced RPB/ O_3 /PMS system for the treatment of tetracycline hydrochloride (TCH) wastewater. Their results showed that an appropriate detained liquid volume could simultaneously enhance ozone absorption and PMS activation by prolonging liquid-phase residence time and increasing liquid holdup in the reactor. At a detained liquid volume of 200 mL, the ozone absorption efficiency, TCH degradation efficiency, and COD removal efficiency reached 75.9%, 92.2%, and 19.6%, respectively, all higher than those obtained without liquid detention. Quenching experiments further confirmed the participation of both $\cdot\text{OH}$ and $\text{SO}_4^{\cdot-}$ in pollutant oxidation, indicating that liquid detention coupled with the high-gravity O_3 /PMS system can effectively improve the treatment performance for antibiotic wastewater.

In the O_3 /PDS system, PDS has a symmetric structure and higher stability than PMS, and therefore generally requires stronger activation conditions. Under alkaline conditions, ozone decomposition can be promoted, and reactive intermediates such as HO_2^- and $\text{O}_2^{\cdot-}$ may participate in PDS activation, subsequently leading to the formation of $\text{SO}_4^{\cdot-}$. These

reactive species then jointly participate in pollutant oxidation [75]. The corresponding mechanistic reactions are as follows:



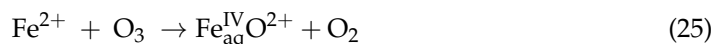
Existing studies indicate that high-gravity homogeneous O_3/PDS systems exhibit considerable potential for the treatment of refractory organic wastewater. Qiao et al. [65] showed that coupling ozone with peroxydisulfate in an RPB markedly enhanced nitrobenzene removal, with the degradation efficiency exceeding 90% under optimized conditions. Yang et al. [66] extended the O_3/PDS process to chloramphenicol wastewater treatment in a submerged RPB and reported that the degradation efficiency reached 97% within 16 min, with an apparent kinetic constant of 0.23 min^{-1} . Taken together, these studies suggest that the O_3/PDS system can simultaneously enhance ozone mass transfer and promote the generation of both $\cdot\text{OH}$ and $\text{SO}_4^{\cdot-}$, thereby strengthening the combined contribution of direct ozone oxidation and indirect radical oxidation to refractory pollutant removal. Nevertheless, its treatment performance remains strongly dependent on solution chemistry and operating parameters, including pH, PDS dosage, ozone concentration, rotational speed, and water-matrix conditions.

4.4. Applications of Fe^{2+} -Assisted HiGee Ozonation System in Water Treatment

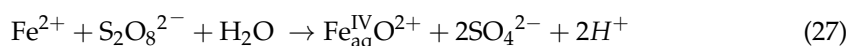
The introduction of Fe^{2+} significantly alters the reaction mechanism of ozonation systems. Traditionally, the $\text{O}_3/\text{Fe}^{2+}$ system has often been attributed to a radical pathway initiated by single-electron transfer, in which Fe^{2+} activates ozone to generate $\text{O}_3^{\cdot-}$, which is subsequently transformed into reactive species such as $\cdot\text{OH}$. The main processes are shown as follows:



However, increasing evidence suggests that the high-valent iron-oxo species Fe(IV)=O is also a key intermediate in this system and may even play a dominant role under certain conditions [76,77]. Its main pathway is shown as follows:



Overall, the reaction between Fe^{2+} and O_3 can generate the high-valent iron-oxo species Fe(IV)=O . Compared with $\cdot\text{OH}$, Fe(IV)=O not only exhibits high oxidation capability and a relatively long lifetime, but also shows greater reaction selectivity. It can participate in the oxidation of organic compounds through multiple pathways, including oxygen-atom transfer, hydrogen-atom transfer, hydride transfer, outer-sphere electron transfer, and electrophilic addition [78,79]. For example, the reaction pathways associated with PMS and PDS are shown as follows:



Meanwhile, $\cdot\text{OH}$ may still be generated through competing single-electron pathways or formed secondarily during the subsequent decay of Fe(IV)=O . Therefore, the $\text{O}_3/\text{Fe}^{2+}$ system should not be simply described as a process in which Fe^{2+} promotes ozone to produce $\cdot\text{OH}$; rather, it should be regarded as a composite oxidation system in which high-valent iron species and free radicals coexist.

It should be noted that the participation of high-valent iron-oxo species such as Fe(IV)=O in Fe^{2+} -assisted HiGee ozonation remains difficult to verify experimentally. Previous studies have demonstrated that $\text{Fe}_{\text{aq}}^{\text{IV}}\text{O}^{2+}$ can be generated in $\text{Fe}^{2+}/\text{O}_3$ systems and can oxidize substrates through oxygen-atom-transfer pathways; however, these evidences were mainly obtained in conventional aqueous systems or microdroplet systems rather than in HiGee reactors. In high-gravity reactors, rapid ozone mass transfer, short liquid residence time, intense micromixing, $\text{Fe}^{2+}/\text{Fe}^{3+}$ cycling, $\cdot\text{OH}$ generation, and possible Fe(IV)=O formation coexist, making it challenging to distinguish radical and non-radical pathways. Therefore, Fe(IV)=O should currently be regarded as a possible reactive species rather than a confirmed dominant oxidant in Fe^{2+} -assisted HiGee ozonation systems. Further studies using selective probe compounds, isotope labeling, and in situ spectroscopic characterization are needed to clarify its contribution.

In practical applications, high-gravity Fe^{2+} -assisted ozonation systems have expanded from the conventional O_3/Fenton process to more complex multi-oxidant systems such as $\text{O}_3/\text{PS}/\text{Fe}^{2+}$, while the reactor configuration has also evolved from the classical RPB to other intensified devices such as the RSR. Existing studies consistently show that the high-gravity field can markedly enhance ozone transfer into the liquid phase and strengthen its synergistic reactions with Fe^{2+} , H_2O_2 , or persulfate. As a result, both pollutant degradation and mineralization can be effectively promoted in refractory organic wastewater treatment.

For dye-containing wastewater, previous studies have shown that the introduction of Fe^{2+} and persulfate into high-gravity ozonation systems can produce a clear synergistic effect beyond that of simpler oxidation routes. Representative work in RPBs and RSRs demonstrated that the combined $\text{O}_3/\text{PS}/\text{Fe}^{2+}$ process outperformed either ozone alone or Fe^{2+} /persulfate-based oxidation, indicating that the coexistence of ozone, Fe^{2+} , and persulfate-derived reactive species can be effectively amplified by the favorable mass-transfer and micromixing environment provided by high-gravity reactors [67,68]. In some cases, the oxidation step also improved the subsequent biological treatment performance, further highlighting the practical value of this coupled strategy.

For aromatic amine wastewater, Fe^{2+} -assisted high-gravity ozonation has also shown strong potential for deep oxidation [69]. In RPB-intensified O_3/Fenton treatment of aniline wastewater, rapid pollutant removal was achieved together with substantial TOC reduction, indicating that high-gravity conditions are beneficial not only for accelerating pollutant transformation but also for promoting subsequent mineralization. Moreover, for complex industrial wastewater such as coal gasification wastewater, the integration of O_3/Fenton in an RPB with coagulation could simultaneously enhance COD removal, decolorization, and biodegradability, suggesting that such systems can create more favorable conditions for downstream treatment rather than serving only as a standalone oxidation unit [70].

Overall, Fe^{2+} -assisted high-gravity ozonation systems have shown considerable potential for enhancing ozone mass transfer, improving oxidant utilization, promoting pollutant mineralization, and increasing wastewater biodegradability. They therefore represent one of the most promising homogeneous intensification routes in high-gravity ozonation for water treatment. Nevertheless, their treatment performance is still jointly influenced by multiple factors, including Fe^{2+} concentration, dose of auxiliary oxidants, pH, temperature, and reactor operating parameters. Further optimization is therefore still required according to the characteristics of specific wastewaters.

4.5. Comparative Remarks on HiGee Homogeneous Ozonation Systems

Taken together, HiGee homogeneous ozonation systems show a clear evolution from ozone-alone processes to multi-oxidant systems involving H_2O_2 , PMS/PDS, and Fe^{2+} -based reagents. Ozone-alone systems mainly rely on enhanced gas–liquid mass transfer and

ozone decomposition, and are therefore suitable for improving pollutant transformation and disinfection efficiency. However, their mineralization capacity is often limited when treating refractory organic pollutants. The introduction of H_2O_2 provides a relatively simple way to promote $\cdot\text{OH}$ generation, whereas PMS/PDS-based systems further broaden the reactive-species spectrum by involving both $\cdot\text{OH}$ and $\text{SO}_4\cdot^-$. Fe^{2+} -assisted systems are more complex because high-valent iron species and radical pathways may coexist, which can enhance deep oxidation but also increases the sensitivity of the process to pH, reagent dosage, and water-matrix composition.

Despite the promising performance reported in these studies, several limitations should be noted. First, most investigations were conducted using simulated wastewater containing single target pollutants, and the adaptability of these systems to real wastewater remains insufficiently verified. Second, the relative contributions of ozone transfer, radical generation, and direct molecular ozone oxidation are often not quantitatively distinguished. Third, performance evaluation has mainly focused on pollutant removal, COD/TOC reduction, or ozone utilization, whereas byproduct evolution, toxicity variation, and process stability have received comparatively less attention. Therefore, future studies should establish more comprehensive evaluation frameworks by combining kinetic analysis, reactive-species identification, ozone-utilization assessment, byproduct identification, toxicity testing, and process-stability evaluation under realistic water-matrix conditions.

5. Wastewater Treatment by HiGee Heterogeneous Ozonation

Heterogeneous catalytic ozonation systems represent an important extension of high-gravity ozonation for wastewater treatment. Compared with homogeneous systems, they promote ozone activation and the generation of reactive species at the interface through solid catalysts, and thus offer several advantages, including high catalytic activity, broad applicability, easy separation and recovery, and a lower risk of secondary pollution. Under high-gravity conditions, where mass transfer and micromixing are intensified, the interaction between ozone and the catalyst surface can be further amplified, thereby enabling more efficient degradation and mineralization of pollutants.

Representative applications of high-gravity heterogeneous catalytic ozonation systems in water treatment are summarized in Table 3. The catalysts mainly include activated-carbon-based catalysts, metal-based-supported catalysts, and monolithic catalysts. These systems have demonstrated considerable potential for enhancing pollutant degradation, mineralization, and, in some cases, the simultaneous removal of multiple contaminants.

Table 3. Representative applications of HiGee heterogeneous catalytic ozonation systems in wastewater treatment.

Pollutant	HiGee Ozonation System	Key Operating Conditions	Pollutant Removal	COD/TOC Removal	Ref.
Phenol wastewater	RPB/ O_3 /activated carbon(AC)	Phenol = 100 mg/L; AC = 25 g/L; $\beta = 40$; $\text{O}_{3,\text{in}} = 90 \text{ mg/L}$; $Q_G = 60 \text{ L/h}$; $Q_L = 80 \text{ L/h}$; pH = 11; T = 25 °C NB = 100 mg/L; $\beta = 20$;	100% (10 min)	TOC 91% (40 min)	[80]
Nitrobenzene (NB) wastewater	RPB/ O_3 /Mn-Fe/ZSM-5	$\text{O}_3 = 25 \text{ mg/L}$; $C_{0,\text{TOC}} = 70 \text{ mg/L}$; $Q_L = 60 \text{ L/h}$; $Q_G = 60 \text{ L/h}$; pH = 6	99.99% (40 min)	TOC 72% (40 min)	[81]

Table 3. Cont.

Pollutant	HiGee Ozonation System	Key Operating Conditions	Pollutant Removal	COD/TOC Removal	Ref.
Formaldehyde wastewater	RPB/O ₃ /H ₂ O ₂ /MgO/ γ -Al ₂ O ₃	Formaldehyde = 2200 mg/L; catalyst = 3MgO/ γ -Al ₂ O ₃ ; pH = 14; β = 40; H ₂ O ₂ = 15 mL/L; O ₃ = 0.14 g/L; Q _L = 90 L/h; Q _G = 100 L/h	99.85% (60 min)	TOC 97.37% (60 min)	[82]
Phenol wastewater	RPB/O ₃ /Mn-CoO _x / γ -Al ₂ O ₃	Phenol = 100 mg/L; β = 104; O ₃ = 80 mg/L; Q _L = 80 L/h; Q _G = 60 L/h; pH = 6	100% (60 min)	TOC 95.01% (45 min)	[83]
High-salt phenol wastewater	RPB/O ₃ /Co-Mn/ γ -Al ₂ O ₃	Phenol = 100 mg/L; NaCl = 10 g/L; β = 40; Q _L = 80 L/h; O ₃ = 70 mg/L; pH = 6	98.40% (9 min)	TOC 90.02% (80 min)	[84]
Composite wastewater containing phenol and Cr(VI)	RPB/O ₃ /Fe-Mn/AC	Phenol = 100 mg/L; Cr(VI) = 30 mg/L; catalyst dosage = 10 g/L; β = 40; Q _L = 5.13 m/h; O ₃ = 50 mg/L; Q _G = 60 L/h; pH = 6; T = 25 °C	Cr(VI) 98.9% phenol: 100%	TOC 98.5% (60 min)	[85]
SMX wastewater	RPB/O ₃ /Ce-Co/CH	SMX = 100 mg/L; β = 30; Q _L = 100 L/h; O ₃ = 35 mg/L; pH = 6	100% (7 min)	TOC 68.6% (60 min)	[86]

Because catalyst dosage, ozone concentration, and reactor operation parameters were different across studies, Table 3 presents the typical operating conditions and treatment performance as reported in the literature.

5.1. Activated Carbon and Carbon-Based Catalysts

Activated carbon-catalyzed ozonation is generally considered to arise from the synergistic effects of surface adsorption, electron transfer, and the generation of reactive oxygen species. Previous studies have shown that activated carbon can significantly promote ozone decomposition, and its catalytic activity is closely related to its surface chemical properties and pore structure characteristics [87]. In general, activated carbons with larger specific surface areas, more developed microporous structures, and stronger surface basicity are more favorable for ozone activation. The catalytic mechanism is commonly attributed to the enrichment of ozone on the activated carbon surface, followed by electron transfer through surface electron-donating sites or specific functional groups, which leads to the formation of reactive species such as O₂^{·−}, HO₂[·], and ·OH and thereby promotes the oxidative degradation of organic pollutants. Meanwhile, activated carbon can also enhance interfacial contact between ozone and pollutants through its adsorption capacity [88].

Activated carbon, as a representative carbon-based catalyst, has shown promising potential in high-gravity heterogeneous ozonation systems for wastewater treatment. In phenolic wastewater treatment, using activated carbon simultaneously as the catalyst and packing material in a RPB enabled rapid pollutant degradation and markedly enhanced mineralization compared with conventional ozonation systems [80]. This improvement reflects the synergistic effect between high-gravity-enhanced ozone mass transfer and activated-carbon-catalyzed ozone decomposition. Mechanistic analyses further indicated

that both direct ozone oxidation and indirect oxidation by reactive species such as $\cdot\text{OH}$ and $\text{O}_2\cdot^-$ participated in the reaction.

These results suggest that activated carbon can function as both a catalytic and structural component in high-gravity reactors, thereby effectively strengthening ozone utilization and the oxidative removal of refractory organic pollutants.

5.2. Supported Metal-Based Catalysts

Supported metal-based catalysts are among the most extensively investigated catalytic materials in high-gravity heterogeneous ozonation systems because of their tunable compositions, adjustable active sites, and relatively good structural stability. Metals or metal oxides such as Fe, Mn, Co, Cu, and Mg are commonly dispersed on supports including $\gamma\text{-Al}_2\text{O}_3$, ZSM-5, and activated carbon, forming active interfaces rich in surface hydroxyl groups, Lewis acid sites, oxygen vacancies, and multivalent redox couples. These active sites can promote ozone adsorption, interfacial electron transfer, and catalytic decomposition, thereby enhancing the generation of reactive oxygen species such as $\cdot\text{OH}$ and $\text{O}_2\cdot^-$ [89,90]. Meanwhile, the introduction of supports not only improves the dispersion and structural stability of active metal species, but also enhances the transport of ozone and pollutants to the catalytic interface and their interfacial contact efficiency [91]. Under high-gravity conditions, intensified gas–liquid–solid contact can further amplify these catalytic processes and thus improve the degradation and mineralization of refractory organic pollutants.

For example, Fe-Mn-Cu/ $\gamma\text{-Al}_2\text{O}_3$ significantly enhanced both the overall ozone decomposition rate constant and the volumetric mass transfer coefficient in comparison with a conventional bubbling reactor [92], while Mn-Fe/ZSM-5 further demonstrated efficient nitrobenzene removal and mineralization, with quenching experiments confirming the dominant role of $\cdot\text{OH}$ in the reaction process [81].

Among these materials, $\gamma\text{-Al}_2\text{O}_3$ -supported metal catalysts have shown particularly strong versatility in the degradation and mineralization of refractory organics under high-gravity conditions. When coupled with the $\text{O}_3/\text{H}_2\text{O}_2$ process, MgO/ $\gamma\text{-Al}_2\text{O}_3$ achieved nearly complete formaldehyde removal together with high TOC reduction and good cyclic stability, indicating that supported catalysts can improve both oxidation efficiency and catalyst reusability [82]. Likewise, Mn-CoO_x/ $\gamma\text{-Al}_2\text{O}_3$ exhibited excellent catalytic performance in phenol wastewater treatment, enabling rapid pollutant degradation and substantial mineralization [83]. Mechanistic analyses further showed that $\cdot\text{OH}$ was the key reactive species, while oxygen vacancies, surface oxygen species, and bimetallic redox cycling contributed to the enhanced activation and decomposition of ozone.

Supported metal-based catalysts have also shown strong adaptability under more complex water-quality conditions. It was found that Co-Mn/ $\gamma\text{-Al}_2\text{O}_3$ maintained relatively high degradation and mineralization performance in high-salinity phenol wastewater, and salt accumulation on the catalyst surface and within its pores was an important factor affecting catalytic performance under saline conditions [84]. In addition, Fe-Mn/AC has been extended to high-gravity coupled catalytic ozonation-adsorption systems for the simultaneous removal of phenol and Cr(VI), demonstrating a clear synergistic effect between organic pollutant oxidation and heavy-metal removal [85]. Moreover, mechanistic studies on Fe-MnO_x/AC further showed that high-gravity conditions can markedly enhance both the self-decomposition and catalytic decomposition of ozone, while increasing the contribution of $\cdot\text{OH}$ relative to conventional bubbling reactors [93].

Overall, the advantages of supported metal-based catalysts in high-gravity ozonation systems lie not only in their abundant active sites and tunable catalytic performance, but also in their pronounced synergy with high-gravity-enhanced mass transfer, interfacial

renewal, and micromixing, thereby enabling more efficient degradation and mineralization of refractory organic pollutants in wastewater.

5.3. Monolithic and Structured Catalysts

Previous studies have shown that the intensification effect of monolithic and structured catalysts in heterogeneous ozonation systems arises primarily not from pollutant adsorption, but from the promotion of ozone activation on their regularly structured surfaces. Representative monolithic catalysts, such as ceramic honeycomb (CH) and cordierite monoliths, can facilitate ozone decomposition through surface hydroxyl sites and enhance the generation of reactive species such as $\cdot\text{OH}$, thereby improving pollutant degradation and mineralization [94]. Further studies have indicated that metal loading can strengthen ozone activation by increasing the density of surface hydroxyl groups, introducing active phases, and regulating surface acid-base properties. In particular, when the solution pH is close to the catalyst the pH at the point of zero charge (pH_{PZC}), surface hydroxyl groups are generally more favorable for participating in ozone decomposition and radical initiation [95,96]. Therefore, the advantages of monolithic and structured catalysts lie not only in providing a stable structured reaction interface but also in their ability to continuously enhance ozone activation through surface-site regulation.

In recent years, monolithic and structured catalysts have attracted increasing attention in high-gravity heterogeneous ozonation systems. Compared with conventional granular catalyst packings, these materials offer advantages such as lower pressure drop, improved structural stability, and greater potential for scale-up in RPB. A representative study employed a Ce-Co/CH monolithic catalyst as the functional packing in an RPB for the treatment of sulfamethoxazole (SMX)-containing wastewater [86]. The results showed that Ce-Co oxides could be uniformly loaded onto the ceramic foam support without destroying its original mesoporous structure, while the coupling of RPB and Ce-Co/CH markedly enhanced both ozone mass transfer and catalytic decomposition. As a result, complete SMX removal was achieved within a short reaction time, accompanied by substantially improved mineralization compared with the conventional bubbling reactor. Mechanistic analyses further indicated that $\cdot\text{OH}$ and oxygen vacancies were the main reactive species and active sites in the system, whereas the redox cycling between $\text{Co}^{2+}/\text{Co}^{3+}$ and $\text{Ce}^{3+}/\text{Ce}^{4+}$ as well as the synergistic interaction between Ce and Co were favorable for sustained ozone activation and pollutant mineralization.

However, the long-term operational stability of monolithic and structured catalysts in high-gravity reactors still deserves careful consideration, especially for practical wastewater treatment. Although monoliths intrinsically offer low initial flow resistance because of their open-channel structure and high open frontal area, their hydraulic performance remains sensitive to flow distribution and channel geometry [97]. Under real wastewater conditions, suspended solids, natural organic matter, inorganic salts, and other coexisting components may gradually deposit on catalyst surfaces or within the structured channels, leading to active-site coverage, channel blockage, and deterioration of gas–liquid–solid contact efficiency. From the perspective of catalyst deactivation, such fouling is a common mechanical cause of activity loss, and a progressive increase in pressure drop may also occur during prolonged operation [98]. Therefore, beyond short-term pollutant removal performance, future studies should place greater emphasis on long-term stability, fouling resistance, pressure-drop evolution, and practical regeneration strategies, such as hydraulic washing, chemical cleaning, thermal treatment, and catalyst reloading, particularly for scale-up and continuous operation under realistic wastewater conditions.

Overall, monolithic and structured catalysts possess important structural and catalytic advantages that make them promising as functional packing in high-gravity reactors.

Their stable structured interfaces and surface-active sites can effectively enhance ozone activation and pollutant degradation, but issues related to long-term stability, fouling resistance, pressure-drop evolution, and regeneration still require further investigation for practical application.

5.4. Comparative Remarks on HiGee Heterogeneous Catalytic Ozonation Systems

Overall, HiGee heterogeneous catalytic ozonation systems integrate the mass-transfer intensification of high-gravity reactors with interfacial ozone activation on solid catalysts. Compared with homogeneous systems, their major advantages lie in catalyst recoverability, interfacial reaction regulation, and the possibility of constructing multifunctional catalytic packings. Carbon-based catalysts, especially activated carbon, can simultaneously provide adsorption sites and promote ozone decomposition, making them suitable for enhancing pollutant enrichment and oxidative degradation. Supported metal-based catalysts offer more tunable active sites, such as surface hydroxyl groups, oxygen vacancies, Lewis acid sites, and multivalent redox couples, and thus generally exhibit stronger catalytic activity toward refractory organic pollutants. In contrast, monolithic and structured catalysts are particularly attractive for high-gravity reactors because they can serve as both catalytic interfaces and structured packing materials, potentially reducing catalyst loss and improving reactor operability.

Nevertheless, the current development of HiGee heterogeneous catalytic ozonation is still at an early stage. Many studies emphasize initial catalytic activity and pollutant removal, whereas long-term stability, metal leaching, catalyst fouling, regeneration behavior, and pressure-drop changes during continuous operation are less investigated. In addition, the roles of adsorption, catalytic ozone decomposition, radical generation, and non-radical oxidation pathways are sometimes difficult to distinguish, especially in complex wastewater matrices. Future research should therefore focus on the rational design of catalysts that are not only highly active but also mechanically stable, regenerable, and compatible with high-gravity hydrodynamics. Particular attention should be paid to structured catalytic packings, long-term continuous operation, catalyst deactivation mechanisms, and the coupling of catalytic performance with reactor-scale mass-transfer behavior.

6. Challenges and Outlook

Although high-gravity ozonation technology has demonstrated clear advantages in enhancing ozone mass transfer and improving pollutant degradation and mineralization, its transition from laboratory research to engineering application still faces several important challenges. Most existing studies have been conducted using simulated wastewater and laboratory-scale reactors, and systematic understanding remains insufficient regarding its adaptability to real wastewater, byproduct formation and toxicity evolution, scale-up behavior of reactors, and the long-term stability and regenerability of catalysts. In addition, the economic feasibility and energy demand of high-gravity ozonation for industrial-scale application remain largely unexplored. Therefore, based on the current research progress, it is necessary to further identify the key limitations of high-gravity ozonation systems and propose future research directions toward practical wastewater treatment applications.

6.1. Challenges

Insufficient adaptability to real wastewater remains an important challenge for the engineering application of high-gravity ozonation technology. Existing studies have largely been conducted using simulated wastewater or single-target pollutant systems, which cannot adequately reflect the actual reaction behavior under the complex coexisting-component conditions of real wastewater. Recent reviews have pointed out that inorganic

ions and organic constituents in real wastewater can markedly influence the catalytic ozonation process through reactive-species scavenging, competitive reactions, and occupation of active sites, thereby reducing pollutant removal efficiency and increasing system complexity [99]. For example, Wang et al. [100] reported that, during Bisphenol A (BPA) ozonation in an RPB, Cl^- had little effect on BPA degradation, HCO_3^- promoted BPA removal by increasing solution alkalinity, whereas fulvic acid inhibited BPA degradation due to ozone competition and pH variation. This indicates that wastewater matrix components may not only suppress ozonation, but also alter pollutant speciation, oxidant competition, and the relative contribution of direct ozone oxidation and radical-mediated pathways. Therefore, systematically evaluating the mass transfer behavior, reactive-species evolution, and pollutant transformation patterns of high-gravity ozonation systems under real wastewater conditions remains a key issue that needs to be addressed in this field.

The formation of byproducts and the associated toxicity risk remain important challenges that cannot be overlooked in the further development of high-gravity ozonation technology for wastewater treatment. Existing studies have shown that, while ozonation intensification can enhance pollutant degradation and mineralization, it may also induce the formation of various intermediates, some of which may exhibit even higher toxicity than the parent compounds. Taking SMX ozonation as an example, although the intensified ozonation process significantly improves removal performance, some of the generated hydroxylated intermediates display higher toxicity, indicating that high removal efficiency does not necessarily correspond to low environmental risk [101]. More importantly, systematic monitoring of typical regulated or highly concerned ozonation byproducts, such as bromate and N-nitrosodimethylamine (NDMA), remains largely insufficient in current high-gravity ozonation studies. Under complex water-quality conditions, especially in the presence of bromide or nitrogen-containing precursors, ozonation may lead to the formation of bromate, NDMA, or brominated organic byproducts, thereby increasing potential cytotoxicity and genotoxicity [102]. These findings suggest that future research on high-gravity ozonation systems should not be limited to the evaluation of pollutant removal and mineralization performance, but should also place greater emphasis on the systematic identification and control of key intermediate evolution, byproduct formation patterns, and toxicity variation.

Uncertainties in treatment performance after reactor scale-up and in the associated scale-up rules also remain issues that deserve attention as high-gravity ozonation moves toward engineering application. Existing studies have shown that, during scale-up, high-gravity reactors may undergo changes in liquid distribution, local flow behavior, mass transfer efficiency, and radial utilization [103,104]. However, current investigations have focused mainly on the hydrodynamic and mass transfer characteristics of high-gravity reactors themselves, whereas direct scale-up studies for ozonation-based wastewater treatment remain relatively limited. Since the performance of high-gravity ozonation systems is strongly dependent on gas–liquid mass transfer, interfacial renewal, and local flow features, there is still a lack of systematic understanding of whether high ozone utilization efficiency and pollutant removal performance can be maintained after scale-up. Therefore, the scale-up behavior and scale effects of reactors for high-gravity ozonation wastewater treatment require further investigation.

Long-term catalyst stability and regenerability remain important issues that cannot be neglected as high-gravity catalytic ozonation systems move toward engineering application. Although some catalysts are able to maintain relatively good activity during short-term cycling tests, deactivation may still occur under prolonged operation due to active-site coverage, surface deposition, pore blockage, and structural changes, thereby impairing ozone activation and pollutant removal performance. In complex wastewater systems,

coexisting salts, organic matter, and suspended impurities may further aggravate catalyst surface fouling and performance deterioration. Therefore, beyond the initial catalytic activity investigation, future studies should place greater emphasis on the systematic evaluation of catalyst lifetime, deactivation mechanisms, and regeneration strategies.

Economic and energy considerations remain insufficiently explored in the field of high-gravity ozonation. At present, most studies are still conducted at the laboratory scale and mainly focus on ozone mass transfer, pollutant degradation, ozone utilization, and mineralization efficiency, whereas industrial applications and systematic techno-economic evaluations are rarely reported. Therefore, it is still difficult to draw a clear conclusion on whether high-gravity ozonation is economically superior to conventional ozonation or other advanced oxidation processes. Future studies should pay more attention to the key factors affecting economic feasibility and energy demand, including ozone generation, rotor power consumption, liquid circulation, gas supply, pressure drop, reactor fabrication, catalyst cost and lifetime, maintenance requirements, and scale-up reliability. Standardized indicators such as specific ozone consumption, electrical energy per order, energy consumption per unit COD or TOC removal, and life-cycle cost should also be reported to support more reliable economic comparisons.

6.2. Outlook

In the future, the development of high-gravity ozonation technology for wastewater treatment should shift from performance verification under laboratory conditions toward systematic investigations oriented to engineering application. On the one hand, deeper understanding is needed under real wastewater conditions with respect to efficient ozone utilization, treatment performance, byproduct evolution, and toxicity risk control. On the other hand, targeted studies should be carried out focusing on catalytic material design, catalyst stability as well as reactor configuration optimization and scale-up behavior. In addition, the economic feasibility and energy demand of high-gravity ozonation should be systematically evaluated by considering ozone generation, rotor power consumption, liquid circulation, gas supply, pressure drop, catalyst lifetime, and maintenance requirements.

Meanwhile, the integration of experimental studies, mechanistic analysis, and reactor modeling will be important for the further development of high-gravity ozonation. Computational fluid dynamics and multiphase modeling can be used to clarify local gas–liquid flow behavior, liquid distribution, interfacial renewal, mass transfer, and reaction-zone characteristics in high-gravity reactors. In addition, data-driven methods, such as response-surface methodology and machine-learning models, may support the prediction and optimization of treatment performance under complex operating conditions. In the longer term, the combination of validated mechanistic models, online monitoring of key operating variables, and data-driven prediction may provide a basis for digital-twin-assisted reactor optimization and intelligent process control. However, these approaches remain insufficiently developed for high-gravity ozonation and require further validation using reliable hydrodynamic, mass-transfer, and real-wastewater treatment data.

7. Conclusions

High-gravity ozonation has emerged as a promising intensification technology for water treatment by effectively overcoming the mass transfer limitations of conventional ozonation. Through the introduction of a high-gravity field, ozone dissolution, gas–liquid interfacial renewal, liquid-film thinning, and micromixing can be significantly intensified, thereby improving ozone utilization and promoting the generation and utilization of reactive oxidative species. On this basis, various high-gravity reactors, represented by RPB,

RSR and RZB have been developed and applied in wastewater treatment, demonstrating distinct advantages in process intensification and equipment compactness.

From the perspective of application systems, both homogeneous and heterogeneous high-gravity ozonation processes have shown considerable potential. In homogeneous systems, single-ozone processes, their coupled systems constructed with H_2O_2 , PMS/PDS, and Fe^{2+} , as well as process-intensification strategies such as liquid detention, can all achieve efficient pollutant degradation and mineralization through the synergistic enhancement of ozone mass transfer and reactive-species generation, and in some cases improve the biodegradability of wastewater. In heterogeneous systems, activated carbon, supported metal-based catalysts, and monolithic/structured catalysts have further expanded the application scope of high-gravity ozonation by strengthening interfacial ozone activation and enhancing the removal of refractory pollutants. Among these systems, immobilized heterogeneous systems based on structured or monolithic catalysts appear particularly promising for engineering application, because they can integrate catalytic ozone activation, intensified gas–liquid mass transfer, and catalyst immobilization within the same reactor.

Although these advances demonstrate the technical potential of high-gravity ozonation, its transition from laboratory research to practical application still faces several limitations. Most existing studies have been conducted using simulated wastewater and laboratory-scale reactors, and systematic understanding remains insufficient regarding real wastewater adaptability, byproduct formation and toxicity evolution, reactor scale-up behavior, and the long-term stability and regenerability of catalysts. The absence of long-term, continuous validation of high-gravity ozonation systems under real wastewater conditions represents the most critical barrier to their industrial adoption. In addition, the economic feasibility and energy demand of high-gravity ozonation remain largely unexplored, especially considering rotor power consumption, pressure drop, ozone generation, reactor fabrication, catalyst lifetime, and maintenance requirements. Future studies should move beyond laboratory-scale performance verification and focus more on long-term continuous operation under real wastewater conditions, reactor optimization, catalytic material design, process integration, and techno-economic assessment. With continued progress in these areas, high-gravity ozonation is expected to play an increasingly important role in the efficient treatment of refractory wastewater and the development of compact intensified water treatment technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	activated carbon
AOPs	advanced oxidation processes
AR-73	Acid Red 73
BCR	bubble column reactor
BPA	Bisphenol A
BR-46	Basic Red 46

CH	ceramic honeycomb
COD	chemical oxygen demand
GB-RPB	gas-baffled rotating packed bed
HiGee	high-gravity technology
LDP	liquid detention phenomenon
NB	Nitrobenzene
NDMA	N-nitrosodimethylamine
<i>o</i> -PDA	<i>o</i> -phenylenediamine
PDS	peroxydisulfate
PMS	peroxymonosulfate
PS	persulfate
RPB	rotating packed bed
RSR	rotor-stator reactor
RZB	rotating zigzag bed
SMX	sulfamethoxazole
SRPB	submerged rotating packed bed
TCH	tetracycline hydrochloride
TOC	total organic carbon
ZSM-5	Zeolite Socony Mobil-5
Symbols	
β	high-gravity factor
a_c	centrifugal acceleration
g	gravitational acceleration
ω	angular velocity
r	radial position
C_0	initial concentration
C_t	Concentration–time value
pH_{PZC}	pH at the point of zero charge
Q_G	gas flow rate
Q_L	liquid flow rate

References

1. UN World Water Development Report 2024. Available online: <https://www.unwater.org/publications/un-world-water-development-report-2024> (accessed on 26 March 2026).
2. Wang, M.; Bodirsky, B.L.; Rijnveld, R.; Beier, F.; Bak, M.P.; Batool, M.; Droppers, B.; Popp, A.; Van Vliet, M.T.H.; Strokal, M. A Triple Increase in Global River Basins with Water Scarcity Due to Future Pollution. *Nat. Commun.* **2024**, *15*, 880. [\[CrossRef\]](#)
3. He, C.; Liu, Z.; Wu, J.; Pan, X.; Fang, Z.; Li, J.; Bryan, B.A. Future Global Urban Water Scarcity and Potential Solutions. *Nat. Commun.* **2021**, *12*, 4667. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Jones, E.R.; van Vliet, M.T.H.; Qadir, M.; Bierkens, M.F.P. Country-Level and Gridded Estimates of Wastewater Production, Collection, Treatment and Reuse. *Earth Syst. Sci. Data* **2021**, *13*, 237–254. [\[CrossRef\]](#)
5. Kato, S.; Kansha, Y. Comprehensive Review of Industrial Wastewater Treatment Techniques. *Environ. Sci. Pollut. Res.* **2024**, *31*, 51064–51097. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Sanchis-Perucho, P.; Aguado, D.; Ferrer, J.; Seco, A.; Robles, Á. A Comprehensive Review of the Direct Membrane Filtration of Municipal Wastewater. *Environ. Technol. Innov.* **2024**, *35*, 103732. [\[CrossRef\]](#)
7. Ilyas, A.; Vankelecom, I.F.J. Designing Sustainable Membrane-Based Water Treatment via Fouling Control through Membrane Interface Engineering and Process Developments. *Adv. Colloid Interface Sci.* **2023**, *312*, 102834. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Satyam, S.; Patra, S. Innovations and Challenges in Adsorption-Based Wastewater Remediation: A Comprehensive Review. *Heliyon* **2024**, *10*, e29573. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Teh, C.Y.; Budiman, P.M.; Shak, K.P.Y.; Wu, T.Y. Recent Advancement of Coagulation–Flocculation and Its Application in Wastewater Treatment. *Ind. Eng. Chem. Res.* **2016**, *55*, 4363–4389. [\[CrossRef\]](#)
10. Singh, D.; Singh, D.; Mishra, V.; Kushwaha, J.; Sengar, M.; Sinha, S.; Singh, S.; Giri, B.S. Strategies for Biological Treatment of Waste Water: A Critical Review. *J. Clean. Prod.* **2024**, *454*, 142266. [\[CrossRef\]](#)
11. Von Gunten, U. Oxidation Processes in Water Treatment: Are We on Track? *Environ. Sci. Technol.* **2018**, *52*, 5062–5075. [\[CrossRef\]](#) [\[PubMed\]](#)

12. Hübner, U.; Spahr, S.; Lutze, H.; Wieland, A.; Rüting, S.; Gernjak, W.; Wenk, J. Advanced Oxidation Processes for Water and Wastewater Treatment—Guidance for Systematic Future Research. *Heliyon* **2024**, *10*, e30402. [[CrossRef](#)] [[PubMed](#)]
13. Das, P.P.; Dhara, S.; Samanta, N.S.; Purkait, M.K. Advancements on Ozonation Process for Wastewater Treatment: A Comprehensive Review. *Chem. Eng. Process.-Process Intensif.* **2024**, *202*, 109852. [[CrossRef](#)]
14. Graça, C.A.L.; Lima, R.B.; Pereira, M.F.R.; Silva, A.M.T.; Ferreira, A. Intensification of the Ozone-Water Mass Transfer in an Oscillatory Flow Reactor with Innovative Design of Periodic Constrictions: Optimization and Application in Ozonation Water Treatment. *Chem. Eng. J.* **2020**, *389*, 124412. [[CrossRef](#)]
15. Elaissoui Elmehiani, M.E.A.; Seladji, F.; Aguedal, H.; Alaoui, C.; Gherdaoui, C.E.; Goel, G.; So, M.; Liu, B.; Iddou, A.; Terashima, M. Enhancing Ozonation Technology: A Case Study on Full-Scale Airlift Reactor Upgrades in the Existing Wastewater Treatment Plant's Ozonation Tank Using CFD. *J. Water Process Eng.* **2024**, *66*, 106023. [[CrossRef](#)]
16. Herrmann, S.; Dietz, K.; Wilms, L.; Wessling, M. Bubble-Less Photocatalytic Ozonation with Ceramic Membranes and Static Mixers Enhances the Total Organic Carbon Removal and Degradation of Iodinated X-Ray Contrast Agents. *J. Environ. Chem. Eng.* **2024**, *12*, 112995. [[CrossRef](#)]
17. Herrmann, S.; Padligur, M.C.; Bieneck, C.J.; Wessling, M. Modeling of Tubular Membrane Contactors for Ozonation of Water Reveals Reduced Bromate Formation with Static Mixers. *Chem. Eng. Sci.* **2024**, *291*, 119924. [[CrossRef](#)]
18. Morrison, C.M.; Hogard, S.; Pearce, R.; Mohan, A.; Pisarenko, A.N.; Dickenson, E.R.V.; von Gunten, U.; Wert, E.C. Critical Review on Bromate Formation during Ozonation and Control Options for Its Minimization. *Environ. Sci. Technol.* **2023**, *57*, 18393–18409. [[CrossRef](#)] [[PubMed](#)]
19. Zhao, H.; Shao, L.; Chen, J.-F. High-Gravity Process Intensification Technology and Application. *Chem. Eng. J.* **2010**, *156*, 588–593. [[CrossRef](#)]
20. Feng, L.; Li, H.; Zhang, M.; Wu, T.; Shi, L.; Xiang, Y.; Shao, L. CO₂ Absorption with Polyethyleneimine Solution Intensified by a Rotating Packed Bed with Liquid Detention. *Fuel* **2025**, *381*, 133318. [[CrossRef](#)]
21. Yuan, M.-H.; Chen, Y.-H.; Tsai, J.-Y.; Chang, C.-Y. Removal of Ammonia from Wastewater by Air Stripping Process in Laboratory and Pilot Scales Using a Rotating Packed Bed at Ambient Temperature. *J. Taiwan Inst. Chem. Eng.* **2016**, *60*, 488–495. [[CrossRef](#)]
22. Karmakar, S.; Bhowal, A.; Das, P. A Comparative Study of Liquid-Liquid Extraction in Different Rotating Bed Contactors. *Chem. Eng. Process.-Process Intensif.* **2018**, *132*, 187–193. [[CrossRef](#)]
23. Zhu, Y.-G.; Fei, X.-F.; Li, Y.-B.; Sun, B.-C.; Chu, G.-W.; Chen, J.-F. Extraction of Platinum at High Phase Ratio via a Rotating Packed Bed Integrated with Falling Film. *Sep. Purif. Technol.* **2024**, *333*, 125918. [[CrossRef](#)]
24. Li, H.; Ren, H.; An, Y.; Liu, Y.; Yuan, Z. Preparation of Ultrafine Nitroguanidine by One-Step Crystallization in an Impinging Stream-Rotating Packed Bed. *Ind. Eng. Chem. Res.* **2023**, *62*, 5141–5149. [[CrossRef](#)]
25. He, X.; Wang, Z.; Pu, Y.; Wang, D.; Tang, R.; Cui, S.; Wang, J.-X.; Chen, J.-F. High-Gravity-Assisted Scalable Synthesis of Zirconia Nanodispersion for Light Emitting Diodes Encapsulation with Enhanced Light Extraction Efficiency. *Chem. Eng. Sci.* **2019**, *195*, 1–10. [[CrossRef](#)]
26. Jiao, W.; Luo, S.; He, Z.; Liu, Y. Applications of High Gravity Technologies for Wastewater Treatment: A Review. *Chem. Eng. J.* **2017**, *313*, 912–927. [[CrossRef](#)]
27. Huang, B.; Feng, S.-J.; Chen, H.; Zhang, W.; Fu, C. Applications of High-Gravity Technologies in Industrial Sewage Purification: A Review. *Process Saf. Environ. Prot.* **2025**, *194*, 1180–1193. [[CrossRef](#)]
28. Hoigné, J.; Bader, H. The Role of Hydroxyl Radical Reactions in Ozonation Processes in Aqueous Solutions. *Water Res.* **1976**, *10*, 377–386. [[CrossRef](#)]
29. Muthukumar, M. Studies on the Effect of Inorganic Salts on Decolouration of Acid Dye Effluents by Ozonation. *Dye. Pigment.* **2004**, *62*, 221–228. [[CrossRef](#)]
30. Rice, R.G. Applications of Ozone for Industrial Wastewater Treatment—A Review. *Ozone Sci. Eng.* **1996**, *18*, 477–515. [[CrossRef](#)]
31. von Gunten, U. Ozonation of Drinking Water: Part I. Oxidation Kinetics and Product Formation. *Water Res.* **2003**, *37*, 1443–1467. [[CrossRef](#)] [[PubMed](#)]
32. Staehelin, J.; Hoigne, J. Decomposition of Ozone in Water: Rate of Initiation by Hydroxide Ions and Hydrogen Peroxide. *Environ. Sci. Technol.* **1982**, *16*, 676–681. [[CrossRef](#)]
33. Huie, R.E.; Clifton, C.L.; Neta, P. Electron Transfer Reaction Rates and Equilibria of the Carbonate and Sulfate Radical Anions. *Int. J. Radiat. Appl. Instrum. Part C Radiat. Phys. Chem.* **1991**, *38*, 477–481. [[CrossRef](#)]
34. Wang, J.; Wang, S. Reactive Species in Advanced Oxidation Processes: Formation, Identification and Reaction Mechanism. *Chem. Eng. J.* **2020**, *401*, 126158. [[CrossRef](#)]
35. Sbardella, L.; Velo-Gala, I.; Comas, J.; Rodríguez-Roda Layret, I.; Fenu, A.; Gernjak, W. The Impact of Wastewater Matrix on the Degradation of Pharmaceutically Active Compounds by Oxidation Processes Including Ultraviolet Radiation and Sulfate Radicals. *J. Hazard. Mater.* **2019**, *380*, 120869. [[CrossRef](#)] [[PubMed](#)]
36. Li, Y.; Li, L.; Chen, Z.-X.; Zhang, J.; Gong, L.; Wang, Y.-X.; Zhao, H.-Q.; Mu, Y. Carbonate-Activated Hydrogen Peroxide Oxidation Process for Azo Dye Decolorization: Process, Kinetics, and Mechanisms. *Chemosphere* **2018**, *192*, 372–378. [[CrossRef](#)] [[PubMed](#)]

37. Jayson, G.G.; Parsons, B.J.; Swallow, A.J. Some Simple, Highly Reactive, Inorganic Chlorine Derivatives in Aqueous Solution. Their Formation Using Pulses of Radiation and Their Role in the Mechanism of the Fricke Dosimeter. *J. Chem. Soc. Faraday Trans. 1* **1973**, *69*, 1597. [[CrossRef](#)]
38. Chen, C.; Du, Y.; Zhou, Y.; Wu, Q.; Zheng, S.; Fang, J. Formation of Nitro(so) and Chlorinated Products and Toxicity Alteration during the UV/Monochloramine Treatment of Phenol. *Water Res.* **2021**, *194*, 116914. [[CrossRef](#)] [[PubMed](#)]
39. Wang, J.; Wang, S. Activation of Persulfate (PS) and Peroxymonosulfate (PMS) and Application for the Degradation of Emerging Contaminants. *Chem. Eng. J.* **2018**, *334*, 1502–1517. [[CrossRef](#)]
40. Berruti, I.; Inmaculada Polo-López, M.; Oller, I.; Flores, J.; Luisa Marin, M.; Bosca, F. Sulfate Radical Anion: Laser Flash Photolysis Study and Application in Water Disinfection and Decontamination. *Appl. Catal. B Environ.* **2022**, *315*, 121519. [[CrossRef](#)]
41. Cortes Garcia, G.E.; van der Schaaf, J.; Kiss, A.A. A Review on Process Intensification in HiGee Distillation. *J. Chem. Technol. Biotechnol.* **2017**, *92*, 1136–1156. [[CrossRef](#)]
42. Wang, Z.; Yang, T.; Liu, Z.; Wang, S.; Gao, Y.; Wu, M. Mass Transfer in a Rotating Packed Bed: A Critical Review. *Chem. Eng. Process.-Process Intensif.* **2019**, *139*, 78–94. [[CrossRef](#)]
43. Rao, D.P.; Bhowal, A.; Goswami, P.S. Process Intensification in Rotating Packed Beds (HIGEE): An Appraisal. *Ind. Eng. Chem. Res.* **2004**, *43*, 1150–1162. [[CrossRef](#)]
44. Munjal, S.; Duduković, M.P.; Ramachandran, P. Mass-Transfer in Rotating Packed Beds—II. Experimental Results and Comparison with Theory and Gravity Flow. *Chem. Eng. Sci.* **1989**, *44*, 2257–2268. [[CrossRef](#)]
45. Cheng, T.; Miao, F.; Shang, R.; Liu, Y.; Jiao, W. Gas Flow in a New Type of Rotating Packed Bed with Gas Baffles. *Chem. Eng. Sci.* **2025**, *307*, 121353. [[CrossRef](#)]
46. Yang, Z.-Y.; Xu, H.-Z.; Li, Y.-B.; Banaga, A.B.; Chu, G.-W.; Chen, J.-F. Local Gas Holdup, Bubble Size Distribution, and Bubble Velocity in a Submerged Rotating Packed Bed Reactor. *Ind. Eng. Chem. Res.* **2024**, *63*, 14391–14402. [[CrossRef](#)]
47. Chu, G.-W.; Song, Y.-H.; Yang, H.-J.; Chen, J.-M.; Chen, H.; Chen, J.-F. Micromixing Efficiency of a Novel Rotor–Stator Reactor. *Chem. Eng. J.* **2007**, *128*, 191–196. [[CrossRef](#)]
48. Ouyang, Y.; Wang, S.; Xiang, Y.; Zhao, Z.; Wang, J.; Shao, L. CFD Analyses of Liquid Flow Characteristics in a Rotor-Stator Reactor. *Chem. Eng. Res. Des.* **2018**, *134*, 186–197. [[CrossRef](#)]
49. Li, Y.; Wang, S.; Sun, B.; Arowo, M.; Zou, H.; Chen, J.; Shao, L. Visual Study of Liquid Flow in a Rotor-Stator Reactor. *Chem. Eng. Sci.* **2015**, *134*, 521–530. [[CrossRef](#)]
50. Wang, G.Q.; Xu, Z.C.; Yu, Y.L.; Ji, J.B. Performance of a Rotating Zigzag Bed—A New HIGEE. *Chem. Eng. Process.-Process Intensif.* **2008**, *47*, 2131–2139. [[CrossRef](#)]
51. Wang, G.Q.; Xu, O.G.; Xu, Z.C.; Ji, J.B. New HIGEE-Rotating Zigzag Bed and Its Mass Transfer Performance. *Ind. Eng. Chem. Res.* **2008**, *47*, 8840–8846. [[CrossRef](#)]
52. Li, Y.; Ji, J.; Yu, Y.; Xu, Z.; Li, X. Hydrodynamic Behavior in a Rotating Zigzag Bed. *Chin. J. Chem. Eng.* **2010**, *18*, 34–38. [[CrossRef](#)]
53. Liu, H.-S.; Lin, C.-C.; Wu, S.-C.; Hsu, H.-W. Characteristics of a Rotating Packed Bed. *Ind. Eng. Chem. Res.* **1996**, *35*, 3590–3596. [[CrossRef](#)]
54. Shi, X.; Xiang, Y.; Wen, L.-X.; Chen, J.-F. CFD Analysis of Liquid Phase Flow in a Rotating Packed Bed Reactor. *Chem. Eng. J.* **2013**, *228*, 1040–1049. [[CrossRef](#)]
55. Xu, P.; Wu, T.; Xiang, Y.; Yun, J.; Shao, L. Enhanced Treatment of Basic Red 46 by Ozonation in a Rotating Packed Bed with Liquid Detention. *Processes* **2023**, *11*, 1345. [[CrossRef](#)]
56. Shi, L.; Feng, L.; Wu, T.; Xiang, Y.; Yun, J.; Shao, L. Ozonation of the Acid Red 73 Dye Wastewater with High-Salinity in a Rotating Packed Bed. *Ozone Sci. Eng.* **2025**, *48*, 3–15. [[CrossRef](#)]
57. Yang, Z.-Y.; Li, Z.-H.; Wang, L.-L.; Li, Y.-B.; Chu, G.-W.; Chen, J.-F. Intensification of Sulfamethoxazole Degradation in a Submerged Rotating Packed Bed Reactor. *Ind. Eng. Chem. Res.* **2025**, *64*, 1449–1459. [[CrossRef](#)]
58. Arowo, M.; Li, Y.; Chu, G.; Sun, B.; Chen, J.; Shao, L. Treatment of Wastewater Containing O-Phenylenediamine by Ozone in a Rotor-Stator Reactor. *Water Sci. Technol.* **2016**, *73*, 1357–1363. [[CrossRef](#)] [[PubMed](#)]
59. Fan, J.; Fan, F.; Wang, W.; Zhang, H.; Wang, L.; Chang, J.; Liang, Q.; Wang, D.; Liu, Z.; Shao, L. Treatment of Acid Red 73 Wastewater by the O₃/RSR-BCR Process. *Chem. Eng. Process.-Process Intensif.* **2021**, *160*, 108296. [[CrossRef](#)]
60. Wu, T.; Zhang, H.; Liu, Z.; Liu, T.; Jiang, P.; Arowo, M.; Shao, L. Amaranth Wastewater Treatment by Intensified Ozonation in a Rotating Zigzag Bed. *J. Water Process Eng.* **2022**, *49*, 102984. [[CrossRef](#)]
61. Liu, T.; Wang, D.; Liu, H.; Zhao, W.; Wang, W.; Shao, L. Rotating Packed Bed as a Novel Disinfection Contactor for the Inactivation of E. Coli by Ozone. *Chemosphere* **2019**, *214*, 695–701. [[CrossRef](#)] [[PubMed](#)]
62. Jiao, W.; Yu, L.; Feng, Z.; Guo, L.; Wang, Y.; Liu, Y. Optimization of Nitrobenzene Wastewater Treatment with O₃/H₂O₂ in a Rotating Packed Bed Using Response Surface Methodology. *Desalin. Water Treat.* **2016**, *57*, 19996–20004. [[CrossRef](#)]
63. Arowo, M.; Zhao, Z.; Li, G.; Chu, G.; Sun, B.; Shao, L. Ozonation of o-Phenylenediamine in the Presence of Hydrogen Peroxide by High-Gravity Technology. *Chin. J. Chem. Eng.* **2018**, *26*, 601–607. [[CrossRef](#)]

64. Zhu, Y.; Sun, H.; Deng, Y.; Xiang, Y.; Yun, J.; Shao, L. Process Intensification of Tetracycline Hydrochloride Degradation via Ozone/Peroxymonosulfate in a High-Gravity Rotating Packed Bed. *Processes* **2026**, *14*, 758. [[CrossRef](#)]
65. Qiao, J.; Luo, S.; Yang, P.; Jiao, W.; Liu, Y. Degradation of Nitrobenzene-Containing Wastewater by Ozone/Persulfate Oxidation Process in a Rotating Packed Bed. *J. Taiwan Inst. Chem. Eng.* **2019**, *99*, 1–8. [[CrossRef](#)]
66. Yang, Z.; Yang, Z.; Li, Y.; Chu, G.; Chen, J. Enhanced Degradation of Chloramphenicol Wastewater in a Submerged Rotating Packed Bed Reactor: O₃/PDS Synergistic Oxidation. *Chin. J. Chem. Eng.* **2025**, *82*, 176–184. [[CrossRef](#)]
67. Ge, D.; Zeng, Z.; Arowo, M.; Zou, H.; Chen, J.; Shao, L. Degradation of Methyl Orange by Ozone in the Presence of Ferrous and Persulfate Ions in a Rotating Packed Bed. *Chemosphere* **2016**, *146*, 413–418. [[CrossRef](#)] [[PubMed](#)]
68. Zhao, Z.; Wang, L.; Fan, J.; Song, Y.; Chu, G.; Shao, L. Degradation of Indigo Carmine by Coupling Fe(II)-Activated Sodium Persulfate and Ozone in a Rotor-Stator Reactor. *Chem. Eng. Process.-Process Intensif.* **2020**, *148*, 107791. [[CrossRef](#)]
69. Qin, Y.; Luo, S.; Geng, S.; Jiao, W.; Liu, Y. Degradation and Mineralization of Aniline by O₃/Fenton Process Enhanced Using High-Gravity Technology. *Chin. J. Chem. Eng.* **2018**, *26*, 1444–1450. [[CrossRef](#)]
70. Ma, H.; Zhao, Z.; Shi, Y.; Xiao, H.; Han, R.; Wang, L.; Shao, L. Advanced Treatment of Coal Gasification Wastewater by O₃/Fenton in a Rotating Packed Bed in Tandem with Coagulation. *Chem. Eng. Process.-Process Intensif.* **2022**, *170*, 108664. [[CrossRef](#)]
71. Yang, P.; Luo, S.; Liu, H.; Jiao, W.; Liu, Y. Aqueous Ozone Decomposition Kinetics in a Rotating Packed Bed. *J. Taiwan Inst. Chem. Eng.* **2019**, *96*, 11–17. [[CrossRef](#)]
72. Yang, Y.; Jiang, J.; Lu, X.; Ma, J.; Liu, Y. Production of Sulfate Radical and Hydroxyl Radical by Reaction of Ozone with Peroxymonosulfate: A Novel Advanced Oxidation Process. *Environ. Sci. Technol.* **2015**, *49*, 7330–7339. [[CrossRef](#)] [[PubMed](#)]
73. Lu, H.; Chen, X.; Cong, Q.; Li, Q.; Wang, X.; Zhong, S.; Deng, H.; Yan, B. Research Progress of Ozone/Peroxymonosulfate Advanced Oxidation Technology for Degrading Antibiotics in Drinking Water and Wastewater Effluent: A Review. *Molecules* **2024**, *29*, 1170. [[CrossRef](#)] [[PubMed](#)]
74. Deniere, E.; Alagappan, R.P.; Langenhove, H.V.; Hulle, S.V.; Demeestere, K. The Ozone-Activated Peroxymonosulfate Process (O₃/PMS) for Removal of Trace Organic Contaminants in Natural and Wastewater: Effect of the (in)Organic Matrix Composition. *Chem. Eng. J.* **2022**, *430*, 133000. [[CrossRef](#)]
75. Abu Amr, S.S.; Aziz, H.A.; Adlan, M.N.; Bashir, M.J.K. Pretreatment of Stabilized Leachate Using Ozone/Persulfate Oxidation Process. *Chem. Eng. J.* **2013**, *221*, 492–499. [[CrossRef](#)]
76. Loegager, T.; Holcman, J.; Sehested, K.; Pedersen, T. Oxidation of Ferrous Ions by Ozone in Acidic Solutions. *Inorg. Chem.* **1992**, *31*, 3523–3529. [[CrossRef](#)]
77. Pestovsky, O.; Bakac, A. Aqueous Ferryl(IV) Ion: Kinetics of Oxygen Atom Transfer to Substrates and Oxo Exchange with Solvent Water. *Inorg. Chem.* **2006**, *45*, 814–820. [[CrossRef](#)] [[PubMed](#)]
78. Wang, Z.; Qiu, W.; Pang, S.; Guo, Q.; Guan, C.; Jiang, J. Aqueous Iron(IV)–Oxo Complex: An Emerging Powerful Reactive Oxidant Formed by Iron(II)-Based Advanced Oxidation Processes for Oxidative Water Treatment. *Environ. Sci. Technol.* **2022**, *56*, 1492–1509. [[CrossRef](#)] [[PubMed](#)]
79. Gu, A.Y.; Musgrave, C.; Goddard, W.A.; Hoffmann, M.R.; Colussi, A.J. Role of Ferryl Ion Intermediates in Fast Fenton Chemistry on Aqueous Microdroplets. *Environ. Sci. Technol.* **2021**, *55*, 14370–14377. [[CrossRef](#)] [[PubMed](#)]
80. Zhang, J.; Shao, S.; Ding, X.; Li, Z.; Jing, J.; Jiao, W.; Liu, Y. Removal of Phenol from Wastewater by High-Gravity Intensified Heterogeneous Catalytic Ozonation with Activated Carbon. *Environ. Sci. Pollut. Res.* **2022**, *29*, 34830–34840. [[CrossRef](#)] [[PubMed](#)]
81. Li, Z.; Jing, J.; Gao, K.; Ren, G.; Zhang, J.; Jiao, W.; Liu, Y. Degradation of Nitrobenzene by High-Gravity Intensified Heterogeneous Catalytic Ozonation with Mn-Fe/ZSM-5 Catalysts. *Chem. Eng. Process.-Process Intensif.* **2021**, *169*, 108642. [[CrossRef](#)]
82. Du, L.; Li, P.; Gao, W.; Ding, X.; Jiao, W.; Liu, Y. Enhancement Degradation of Formaldehyde by MgO/γ-Al₂O₃ Catalyzed O₃/H₂O₂ in a Rotating Packed Bed. *J. Taiwan Inst. Chem. Eng.* **2021**, *118*, 29–37. [[CrossRef](#)]
83. Miao, F.; Zhang, S.; Sun, X.; Li, Y.; Shang, R.; Wu, W.; Jiao, W.; Liu, Y. Degradation of Phenol with Mn-CoOX/γ-Al₂O₃ Catalytic Ozonation Enhanced by High Gravity Technology. *Chem. Eng. Sci.* **2023**, *280*, 119036. [[CrossRef](#)]
84. Miao, F.; Cheng, T.; Wang, L.; Li, K.; Bao, M.; Ma, C.; Nie, K.; Liu, Y.; Jiao, W. Treatment of High-Salt Phenol Wastewater by High-Gravity Technology Intensified Co-Mn/γ-Al₂O₃ Catalytic Ozonation: Treatment Efficiency, Inhibition and Catalytic Mechanism. *Chem. Eng. Sci.* **2024**, *292*, 120019. [[CrossRef](#)]
85. Zhang, J.; Shao, S.; Guo, Q.; Duan, X.; Liu, Y.; Jiao, W. Co-Removal of Phenol and Cr(VI) by High Gravity Coupled Heterogeneous Catalytic Ozonation-Adsorption. *Sep. Purif. Technol.* **2025**, *358*, 130297. [[CrossRef](#)]
86. Cheng, T.; Liu, Y.; Miao, F.; Duan, X.; Liu, Y.; Jiao, W. Catalytic Ozonation Degradation of Sulfamethoxazole by High Gravity Coupled Monolithic Catalyst Ce-Co/CH: Efficacy, Mechanism, Pathways and Toxicity. *Chem. Eng. J.* **2025**, *515*, 163553. [[CrossRef](#)]
87. Faria, P.C.C.; Órfão, J.J.M.; Pereira, M.F.R. Ozone Decomposition in Water Catalyzed by Activated Carbon: Influence of Chemical and Textural Properties. *Ind. Eng. Chem. Res.* **2006**, *45*, 2715–2721. [[CrossRef](#)]
88. Sánchez-Polo, M.; von Gunten, U.; Rivera-Utrilla, J. Efficiency of Activated Carbon to Transform Ozone into OH Radicals: Influence of Operational Parameters. *Water Res.* **2005**, *39*, 3189–3198. [[CrossRef](#)] [[PubMed](#)]

89. Chen, W.; He, H.; Liang, J.; Wei, X.; Li, X.; Wang, J.; Li, L. A Comprehensive Review on Metal Based Active Sites and Their Interaction with O₃ during Heterogeneous Catalytic Ozonation Process: Types, Regulation and Authentication. *J. Hazard. Mater.* **2023**, *443*, 130302. [[CrossRef](#)] [[PubMed](#)]
90. Yan, L.; Bing, J.; Wu, H. The Behavior of Ozone on Different Iron Oxides Surface Sites in Water. *Sci. Rep.* **2019**, *9*, 14752. [[CrossRef](#)] [[PubMed](#)]
91. Wang, J.; Chen, H. Catalytic Ozonation for Water and Wastewater Treatment: Recent Advances and Perspective. *Sci. Total Environ.* **2020**, *704*, 135249. [[CrossRef](#)] [[PubMed](#)]
92. Jiao, W.; Wei, X.; Shao, S.; Liu, Y. Catalytic Decomposition and Mass Transfer of Aqueous Ozone Promoted by Fe-Mn-Cu/ γ -Al₂O₃ in a Rotating Packed Bed. *Chin. J. Chem. Eng.* **2022**, *45*, 133–142. [[CrossRef](#)]
93. Zhao, Z.; Liu, Y.; Yu, X.; Wang, C.; Li, B.; Liu, Y.; Jiao, W. Self-Decomposition and Catalytic Decomposition of Ozone in a High-Gravity Rotating Packed Bed. *Chem. Eng. Sci.* **2025**, *305*, 121120. [[CrossRef](#)]
94. Zhao, L.; Ma, J.; Sun, Z. Oxidation Products and Pathway of Ceramic Honeycomb-Catalyzed Ozonation for the Degradation of Nitrobenzene in Aqueous Solution. *Appl. Catal. B Environ.* **2008**, *79*, 244–253. [[CrossRef](#)]
95. Zhao, L.; Ma, J.; Sun, Z.; Liu, H. Mechanism of Heterogeneous Catalytic Ozonation of Nitrobenzene in Aqueous Solution with Modified Ceramic Honeycomb. *Appl. Catal. B Environ.* **2009**, *89*, 326–334. [[CrossRef](#)]
96. Zhao, L.; Sun, Z.; Ma, J.; Liu, H. Enhancement Mechanism of Heterogeneous Catalytic Ozonation by Cordierite-Supported Copper for the Degradation of Nitrobenzene in Aqueous Solution. *Environ. Sci. Technol.* **2009**, *43*, 2047–2053. [[CrossRef](#)] [[PubMed](#)]
97. Williams, J.L. Monolith Structures, Materials, Properties and Uses. *Catal. Today* **2001**, *69*, 3–9. [[CrossRef](#)]
98. Bartholomew, C.H. Mechanisms of Catalyst Deactivation. *Appl. Catal. A Gen.* **2001**, *212*, 17–60. [[CrossRef](#)]
99. Tian, M.; Chang, J.; Ding, J.; Yin, Y. Impact of Coexisting Components on the Catalytic Ozonation of Emerging Contaminants in Wastewater. *Sep. Purif. Technol.* **2025**, *362*, 131847. [[CrossRef](#)]
100. Wang, L.; Yun, J.; Zhang, H.; Si, J.; Fang, X.; Shao, L. Degradation of Bisphenol a by Ozonation in Rotating Packed Bed: Effects of Operational Parameters and Co-Existing Chemicals. *Chemosphere* **2021**, *274*, 129769. [[CrossRef](#)] [[PubMed](#)]
101. Zhang, J.; Lv, S.; Yu, Q.; Liu, C.; Ma, J.; Jia, M.; Fang, S. Degradation of Sulfamethoxazole in Microbubble Ozonation Process: Performance, Reaction Mechanism and Toxicity Assessment. *Sep. Purif. Technol.* **2023**, *311*, 123262. [[CrossRef](#)]
102. Wu, Q.-Y.; Zhou, Y.-T.; Li, W.; Zhang, X.; Du, Y.; Hu, H.-Y. Underestimated Risk from Ozonation of Wastewater Containing Bromide: Both Organic Byproducts and Bromate Contributed to the Toxicity Increase. *Water Res.* **2019**, *162*, 43–52. [[CrossRef](#)] [[PubMed](#)]
103. Groß, K.; De Beer, M.; Dohrn, S.; Skiborowski, M. Scale-up of the Radial Packing Length in Rotating Packed Beds for Deaeration Processes. *Ind. Eng. Chem. Res.* **2020**, *59*, 11042–11053. [[CrossRef](#)]
104. Dhaneesh, K.P.; Ranganathan, P. A Comprehensive Review on the Hydrodynamics, Mass Transfer and Chemical Absorption of CO₂ and Modelling Aspects of Rotating Packed Bed. *Sep. Purif. Technol.* **2022**, *295*, 121248. [[CrossRef](#)]

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