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Review

The Combination of Micro-Nano Bubbles and Other Technologies for Emerging Contaminants' Elimination in Water Treatment

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Abstract

With the widespread application of new chemicals, the concentration of emerging contaminants (ECs), such as antibiotics, per- and polyfluoroalkyl substances (PFAS), microplastics, and new pesticides, in aquatic environments is on the rise. ECs such as those examined in the studies exhibit high toxicity, persistence, and a propensity for bioaccumulation, which can lead to significant risks for ecosystems and human health. Traditional water treatment technologies exhibit limited removal capabilities for ECs, whereas micro-nano bubbles (MNBs) exhibit great potential in the field of ECs treatment, due to their unique physicochemical properties. This article systematically reviews the research progress on the treatment of ECs using MNBs combined with other technologies, including physical methods (adsorption enhancement), chemical methods (ozonation, persulfate oxidation, photocatalysis, and material catalysis) and biological methods (microbial synergy). This review summarizes the research progress and mechanisms of MNBs combination technologies, outlining the critical knowledge gaps and future research perspectives to advance the rational design and engineering application of MNBs for ECs' elimination in water treatment.

Keywords: micro-nano bubbles; emerging contaminants; advanced oxidation processes; material catalysis; microbial synergy

1. Introduction

The United States Environmental Protection Agency defines emerging contaminants (ECs) as "chemicals or other substances found in natural rivers as a result of improved analytical and detection levels that are not subject to management standards and may be harmful to aquatic life". These primarily include pharmaceuticals and personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFAS), microplastics (MPs), new pesticides, and so on [1]. These substances are characterized by their low environmental concentrations (ng/L–μg/L), high biological toxicity, potential for migration and transformation, and resistance to natural degradation, making these compounds a major focus and challenge in global water-pollution control. The primary sources of these natural or synthetic compounds include untreated wastewater, treated effluents from domestic, industrial, agricultural, and hospital treatment plants, sewer leaks/overflows, and landfill leachate discharges [2]. Conventional water treatment processes, such as coagulation–sedimentation and biological degradation technologies

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show limited capacity in removing these trace ECs, making it difficult to meet increasingly stringent water-quality standards and ecological health requirements. Consequently, methods like activated carbon adsorption, membrane filtration and advanced oxidation processes are commonly employed to remove ECs from water bodies [3]. However, problems such as low treatment efficiency, high costs and the risk of secondary pollution associated with these technologies warrant further attention.

Against this backdrop, the MNB technology has gradually emerged as an effective gas–liquid interface approach for improving pollutant removal or degradation in the current research. MNBs are bubble systems with diameters typically ranging from tens of nanometers to one hundred micrometers. Additionally, MNBs with millimeter-sized bubbles exhibit extremely low rising velocities, in the order of μm/s to mm/s. This allows them to remain suspended in water for hours or even days, significantly extending the contact times of gas–liquid reactions. MNBs with specific surface areas above 1000 m^2/g offer extensive interfaces that are highly effective for pollutant adsorption, radical generation and microbial attachment, making them valuable in environmental remediation and other applications. Moreover, MNBs often carry a negative surface charge with a zeta potential between −17 and −45 mV, allowing them to attract and accumulate cationic pollutants through electrostatic interactions. The collapse (or cavitation) of MNBs directly generates substantial quantities of ROS. Indeed, studies have demonstrated that MNBs, whether filled with air or pure O_2, can facilitate ROS production, thereby driving the oxidative transformation of aqueous pollutants. This phenomenon is hypothesized to occur via hydrodynamic cavitation (often triggered by external energy inputs such as ultrasonication). During the final stage of bubble implosion, known as the Rayleigh collapse, extreme yet transient conditions (pressures up to ∼10 MPa and temperatures approaching ∼5000 K) are reached, favoring the homolytic cleavage of water molecules into hydroxyl radicals (•OH) [4]. Currently, MNB technology has expanded from fundamental property research to various engineering fields including water treatment, soil remediation, biomedicine and aquaculture [5]. Moreover, MNBs can be flexibly combined with technologies such as adsorption, oxidation (ozone, persulfate), photocatalysis, biological treatment, and material catalysis, for improving the efficiency of aqueous chemical treatment and detoxification [6,7]. This addresses the limitations of single technologies, for instance, preventing particle agglomeration when combined with nZVI (Zero-valent iron nanoparticles) or alleviating DO (dissolved oxygen) deficiency when combined with microorganisms.

Grounded in the evolving research landscape of micro/nanobubble (MNB)-integrated technologies for the abatement of emerging contaminants (ECs), this review offers a critical and systematic overview of recent progress in three interrelated areas: enhanced adsorption processes, advanced oxidation strategies (including ozonation, persulfate activation, photocatalysis, and catalytic materials), and synergistic microbial degradation pathways. With an emphasis on mechanistic insights and technological scalability, this work seeks to provide a holistic reference for both fundamental understanding and practical deployment of MNB-based systems in aquatic environments, contributing to the conceptualization of next-generation, resource-efficient, and environmentally sustainable water treatment solutions.

2. Review Methodology

The literature search was conducted by using three major databases, including Web of Science, Scopus and PubMed, to ensure comprehensive and authoritative literature coverage. The primary search terms included “micro-nano bubbles”, “emerging contaminants” and “technology”, along with related synonyms such as “adsorption”, “ozonation”, “persulfate oxidation”, “photocatalysis”, “zero-valent iron” and “microbial synergy”. The initial search yielded 980 records. During screening, duplicates and studies such as system-

atic reviews, preprints, book chapters and non-English publications were excluded. The remaining articles were evaluated for eligibility based on title and abstract relevance. Ultimately, 54 studies were included in the quantitative synthesis. The search covers literature published from January 2010 to December 2025, with a focus on research results published after 2018 (covering the stage of rapid technological development in the field), ensuring that the review content is both fundamental and frontier.

3. Generation and Characteristics of Micro-Nano Bubbles

3.1. Primary Generation Techniques for Micro-Nano Bubbles

The generation of MNBs involves the efficient dispersion of gas into microscopic units, which can be achieved through a variety of physical and physicochemical methods. Currently, three MNB production technologies, including the hydraulic shear method, the gas dissolution and release method, and the ultrasonic cavitation method, are relatively mature (Table 1). The hydrodynamic shear method utilizes devices such as Venturi tubes or rotary shear generators to expose gas–liquid mixtures as high-velocity flow, generating intense shear forces for tearing the gas into micro-nano sized bubbles. Xiong et al. [8] constructed an MNB generator by connecting a self-made Venturi tube in series with a static mixer, and the generated micro-nano bubbles have a minimum particle size range of 150~240 nm. This technology is distinguished by low equipment cost, simple operation, and the ability to enable continuous production. Owing to its capacity for continuous operation and economic efficiency, this technology is ideally applicable to large-volume waste streams, including municipal sewage and intensive aquaculture effluents. Moreover, it ensures adequate dissolved oxygen levels to sustain subsequent biological treatments, such as activated sludge processes targeting COD (Chemical Oxygen Demand) and ammonia nitrogen removal. Additionally, the gas dissolution–release method refers to a process in which the target gas (e.g., oxygen or ozone) is completely dissolved into a supersaturated aqueous solution under elevated pressure. Then, the gas is released in the form of MNBs through rapid depressurization. It is noted that the higher the dissolved gas concentration, the larger the size of the generated MNBs. For instance, stable ozone MNBs can enhance advanced oxidation processes, thereby creating conditions for the subsequent degradation of recalcitrant pollutants. Notably, the ultrasonic cavitation method relies on the formation of localized low-pressure zones during ultrasound propagation in aqueous media. These dynamic pressure variations drive the oscillation, expansion, and subsequent disintegration of minute bubbles into MNBs. Cho et al. [9] designed a special device to generate nanobubbles, which included a double-sided palladium-plated electrode and an ultrasonic device with a frequency of 20 kHz and an output power of 200 W. By employing this device, they successfully generated nanobubbles with a particle size of around 750 nm and explored the impacts of ultrasonic power and ultrasonic exposure time on the particle size of nanobubbles. The results indicated that the particle size of nanobubbles exhibited a slight increase as the ultrasonic power rose. And the influence of ultrasonic exposure time on the particle size of nanobubbles was more notable: the particle size of nanobubbles increased significantly as the ultrasonic exposure time was prolonged.

The properties of the solution, including surfactants, hydrophilic and hydrophobic particles, inorganic salts, pH value, and temperature, significantly influence micro-nano bubbles in the solution. Within a defined concentration range, the bubble size exhibits a progressive decline with increasing surfactant concentration [10–12]. Adding hydrophilic particles to a high-concentration hydrophobic particle solution results in a decrease in bubble size [13]. The zeta potential of MNBs quantifies the electrostatic potential at the boundary between the adsorbed interfacial layer and the diffuse layer, referenced to the ionic equilibrium at the outer edge of the diffuse layer. It serves as a key parameter for

elucidating the colloidal stability and inter-bubble interaction mechanisms of MNBs [14]. Similar to the influencing factors of particle size distribution, the zeta potential of MNBs is greatly influenced by solution properties, such as the type and concentration of surfactants in the solution, solution temperature, pH, etc. The generation of •OH after the bursting of micro-nano bubbles might be due to the high concentration of positive and negative charges stored within the double layer of micro-nano bubbles. The collapse of micro-nano bubbles results in a rapid discharge of accumulated charges, which in turn triggers the production of a significant number of free radicals [15]. The generation of •OH by MNBs is influenced by solution properties, including the presence of metal catalysts, as evidenced by research on the formation of these radicals and their application in odor removal from cutting fluids [16]. However, its production capacity remains relatively limited, rendering it more appropriate for laboratory-scale investigations and the pretreatment of small-volume, specialized waste streams [17].

Table 1. Differences in Generation Technologies among MNBs.

	Hydraulic Shear Method	Gas Dissolution–Release Method	Ultrasonic Cavitation Method
Principle	Using a Venturi tube and high-speed rotating shear force to tear gas into MNBs.	Under high pressure, the gas is supersaturated and dissolved in water, and rapid pressure reduction causes the gas to precipitate in MNBs.	Ultrasonic waves generate local negative pressure, causing bubbles to oscillate, grow, rupture and split into MNBs.
Bubble size	100 nm–50 μm	50 nm–5 μm	20 nm–800 nm
Application	Municipal sewage, aquaculture wastewater and large-scale continuous aeration.	Precision water treatment, efficient dissolution of ozone or oxygen and medical or industrial wastewater.	Laboratory research, small-batch special wastewater and mechanism research.
Costs	Simple equipment, low energy consumption, and low operating costs. Suitable for large-scale engineering.	Simple equipment, low energy consumption, and low operating costs. Suitable for large-scale engineering.	High controllability and fine particle size. Low production capacity, high energy consumption, not suitable for large-scale production.

3.2. Physicochemical Properties of Micro-Nano Bubbles

The advantages of MNBs stem from their unique properties, including a large surface area, slow rising speed, self-pressurization, surface charge, generation of free radicals under specific condition and high gas-dissolution rate. The physicochemical properties resulting from their small particle size enable strategic matching with various wastewater-treatment scenarios, thereby overcoming the limitations of conventional processes in terms of mass-transfer efficiency, reaction duration, gas utilization, and pollutant adsorption/degradation. Moreover, the ascent velocity of MNBs is significantly lower than that of ordinary bubbles, influenced by both liquid viscosity and buoyancy. A bubble with a diameter of 10 μm has a rise velocity of merely about 0.01 cm/s, enabling it to stay in the liquid for several hours or an even longer period. This effectively stops gas from escaping through flotation prior to its participation in reactions. This long residence characteristic is particularly advantageous for the treatment of industrial wastewater, especially when it contains persistent organic compounds. Technologies like microbubble ozonation coupled with ultrafiltration membrane separation, as well as multi-scale microbubble ozonation, have demonstrated effectiveness in achieving high removal efficiencies for these contaminants, allowing sufficient time for complete reactions [18]. The self-pressurization dissolution characteristic stems from surface tension effects; as the particle size decreases, the internal pressure of the bubble rises, facilitating efficient gas dissolution into the liquid and substantially enhancing gas utilization. This property is crucial for oxygen-deficient scenarios such as the remediation of black and odorous water bodies and the aerobic polishing of anaerobically treated effluent,

which makes it suitable for the pretreatment of wastewater, thereby creating favorable conditions for subsequent deep purification [19].

4. ECs' Elimination by MNBs with Other Technologies

MNBs have become a promising multifunctional platform for enhancing the elimination of new ECs in water. As shown in Figure 1, MNBs can be combined with three mechanisms to improve treatment performance: enhancing adsorption by increasing the affinity of pollutants through its larger specific surface area, improving oxidation through synergistic effects with advanced oxidation processes, and boosting the synergistic effect of microbial degradation of pollutants by promoting microbial activity and abundance.

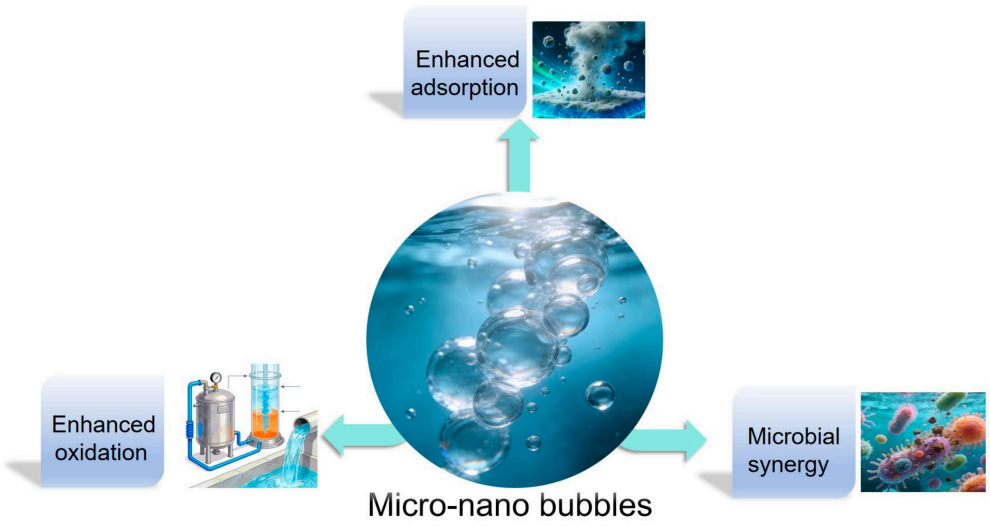


Figure 1. Three types of technologies for MNBs.

4.1. Adsorption Enhancement by MNBs

Traditional adsorption processes are often constrained by three primary limitations: inefficient mass transfer, agglomeration of adsorbent particles, and insufficient interfacial interactions. These issues make it difficult to meet the requirements for deep removal of low-concentration ECs. According to Table 2, the MNB-adsorbent synergistic system can effectively overcome these bottlenecks, according to these previous studies. Luo et al. constructed a synergistic adsorption system combining carbon-based adsorbents and MNBs for the efficient removal of legacy perfluoroalkyl and polyfluoroalkyl substances (PFAS) from water, boosting the interfacial aggregation and molecular transfer of PFAS onto the adsorbent surfaces, which significantly improved the PFAS adsorption capacity, especially at a high initial concentration (50 mg/L), while demonstrating that acidic conditions and lower ionic strength further facilitated the MNB-driven removal efficiency [20]. Furthermore, the pollutant enrichment at the gas–liquid interface and the surface-charge regulation of MNBs can further optimize the mass-transfer and adsorption processes [21]. Jiang et al. [22] employed hydrodynamic cavitation to generate MNBs and synergized them with amino-functionalized graphene (GR-NH_2). Under conditions of pH 6.5 and 25 °C, MNBs increased the local concentration of PFOS (Perfiuorooctanesulfonic acid, belonging to a type of PFAS) on the GR-NH_2 surface by 10 times, through interfacial enrichment effects, enhancing the adsorption capacity from 180 mg/g to 250 mg/g, and the adsorption equilibrium time can be reduced from 24 h to just 6 h. Molecular dynamics simulations revealed that MNBs did not directly adhere to the GR-NH_2 surface, according to Figure 2. Instead, following the interfacial enrichment of PFAS at the MNB solution interface, PFAS molecules migrated toward the GR-NH_2 surface in conjunction with the bubbles, ultimately achieving

immobilization via a cooperative "bubble–PFAS–adsorbent" mechanism. MNBs capture PFAS molecules via their surface negative potential (−15~−25 mV), thereby forming a 'bubble–PFAS' complex. During the slow ascent of the bubbles, they collide with GR-NH_2, transferring PFAS to the surface of the adsorbent via the interfacial enrichment effect. Stable fixation is attained through hydrogen bonding and hydrophobic interactions, thereby completing the collaborative removal pathway of the "bubble–PFAS–adsorbent". Experimental results demonstrated that the negative surface charge of MNBs and the protonated amino groups of GR-NH_2 generated an electrostatic synergy. Simultaneously, the C-F chain of PFAS has strong oleophobicity, and the affinity between traditional non-polar carbon-based materials and the C-F chain is relatively weak, resulting in insufficient adsorption binding force. However, in actual wastewater-treatment scenarios, although this synergistic system efficiently removes PFAS, its application relies on stable conditions of pH 6.5 and 25 °C. The pH of actual wastewater often fluctuates, easily disrupting the protonation state of GR-NH_2 amino groups and the interfacial enrichment effect of MNBs. Subsequent research could optimize GR-NH_2 through acid–base resistant modification to maintain electrostatic synergy with MNBs across a wider pH range [22]. Notably, Kang et al. constructed a synergistic system combining quaternized cellulose nonwoven adsorption and MNBs for the enhanced selective removal of PFAS from water, boosting the PFAS removal rate from 68% to 95% and raising the adsorption capacity to 272.5 mg/g^{-1} [23]. Furthermore, this integration significantly improved the selective capture of PFAS in complex water matrices through the dual action of electrostatic attraction by the quaternized cellulose and hydrophobic enrichment at the MNBs' gas–liquid interface.

Table 2. Pollutant removal by adsorption with MNBs: a comparative study.

Category	Processes	Pollutants	Efficiency	Role of MNBs	Ref.
Adsorption	Adsorption on carbon-based adsorbents in MNBs	PFAS	For PFOS, the capacities significantly improved from 73.3 to 161.7 mg g^{-1} for CNTs, from 199.8 to 369.6 mg g^{-1} for graphene, and from 147.6 to 231.7 mg g^{-1} for GAC.	Boosting the interfacial aggregation and molecular transfer of PFAS onto the adsorbent surfaces.	[20]
	MNBs with amino-functionalized graphene	PFAS	PFAS removal rate: 90.3%.	Enrichment of pollutants, enhancement of electrostatic synergy, and optimization of adsorption stability.	[22]
	Quaternized cellulose nonwoven adsorption and MNBs	PFAS	Boosting the PFAS removal rate from 68% to 95% and raising the adsorption capacity to 272.5 mg/g^{-1}.	The dual action of electrostatic attraction by the quaternized cellulose and hydrophobic enrichment at the MNBs' gas–liquid interface.	[23]
	Micro-nano bubble flotation adsorption for removal of microplastics	Microplastics	MNB collaboration: 68.9% −73.3%; 62% achieved in 16 min.	Adsorption of hydrophobic microplastics and synergistic buoyancy with large bubbles enhance enrichment efficiency.	[24]

In addition to assisting in the adsorption and removal of ECs such as PFAS, MNBs can also play a key role in the removal of microplastics. Wang et al. [24] established a flotation system using MNBs for effective enrichment and removal of microplastics in aqueous solutions and laundry wastewater, and increased the removal efficiency of microplastics from 55.6% −57.8% to 68.9% −73.3%, achieving a maximum enrichment efficiency of about 62% within 16 min, while achieving synchronous removal of detergent residues. Notably, the synergistic effect between MNBs and biochar adsorbents can also be extended to the removal of other organic pollutants, like 2,4-dichlorophenoxyacetic acid. By coupling inter-

facial catalysis with adsorption, the efficient fixation and transformation of pollutants can be realized, offering a reference for the functional enhancement of physical adsorption technology [25,26]. However, most of the research has been conducted on single pollutants under ideal experimental conditions (with a fixed pH and in a pure aqueous solution), and there is a lack of verification regarding the interference from coexisting ions and natural organic matter in actual wastewater regarding interfacial enrichment and electrostatic synergism.

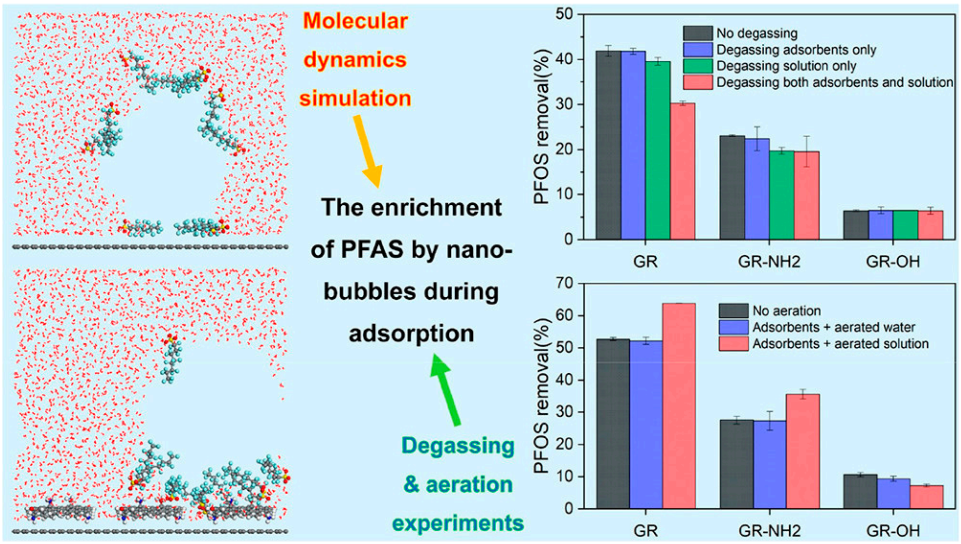


Figure 2. PFOS removal performance and molecular dynamics simulations in the GR-NH_2 and MNBs system.

4.2. Advanced Oxidation Processes' Enhancement by MNBs

The chemical oxidation technology can degrade ECs through the strong reactive oxygen species (ROS, such as •OH, $^1O_2$, SO_4•$^-$) generation. Traditional processes are frequently constrained by low oxidant solubility, limited ROS generation, and the formation of by-products. As demonstrated in Table 3, the application of MNBs in water treatment encompasses a wide range of chemical oxidation processes.

4.2.1. Ozonation Enhancement by MNBs

MNBs significantly enhance the efficiency of ozonation through oxidant solubilization, ROS activation or mass-transfer enhancement, as evidenced by studies on wastewater-treatment effectiveness [27]. Ozone MNBs represent an innovative wastewater-treatment technology that leverages the high surface area and extended contact time of micro-nano bubbles to significantly enhance the remediation efficiency for a wide range of pollutants. The efficiency of ozone MNBs, as judged by the volumetric ozone-gas mass transfer at the gas–liquid interface, can reach 1.3, up to 19 times that of conventional ozone technology [28]. Generally, ozone is a highly potent oxidant capable of converting both organic pollutants into their respective by-products. MNBs can significantly enhance the utilization rate of ozone and reduce the amount of ozone required per unit of pollutant treatment, thereby minimizing the risk of by-product generation. Notably, bromate (BrO_3^-) could be produced through the oxidation of bromide ions (Br^-) in water by O_3, and the maximum concentration of bromate can reach 27.5 μg/L [29]. Therefore, it is still necessary to optimize process parameters based on the characteristics of the water matrix, to control potential toxicity [30]. The application of ozone MNBs in water treatment and chemical processes indicates a significant reduction in chemical usage and energy consumption. Thus, MNB ozonation technology shows great potential in supplementing or potentially replacing conventional ozonation systems, to improve pollutant removal.

Ozone MNBs demonstrate superior degradation capabilities and lower toxicity in the treatment of oxytetracycline (OTC) compared to traditional ozonation methods. Research by Tang et al. [31] identifies the fact that the often-overlooked $^1O_2$ serves as a crucial reactive species within the ozone MNB system, as determined by probe and electron paramagnetic resonance methods (Figure 3). Subsequently, the mechanism of OTC oxidation by ozone MNBs was systematically studied, with a focus on the oxidation processes and the removal of organic compounds. Owing to the high reactivity between OTC and $^1O_2$, ozone MNBs enhanced the selectivity and anti-interference ability for OTC in complex matrix production wastewater. The generation of •OH after the bursting of MNBs in the presence of ozone is due to the high concentration of positive and negative charges stored within the double layer of the MNBs. The bursting of the bubbles leads to the instantaneous release of a large number of charges, which in turn stimulates the generation of free radicals [32]. As MNBs rise in water, their size gradually decreases. Subsequently, over a wide pH range, high concentrations of OH^- adsorb at the gas–water interface, resulting in a negative charge at this interface. Consequently, counter-ions (H^+) are rapidly attracted to the gas–water interface, leading to the formation of an electrical double layer and a rapid increase in zeta potential. The drastic environmental changes that trigger the instantaneous collapse of bubbles under spatial confinement may induce the diffusion of elevated chemical potential [32,33], leading to ozone decomposition and further generating substantial amounts of $^1O_2$, which can effectively remove OTC from water. However, the generation of $^1O_2$ relies on the gas–water interface double layer, and pH fluctuations in actual wastewater may affect this process. Subsequent development of pH-adaptive regulated MNB-generation systems could further enhance the stability of this technology.

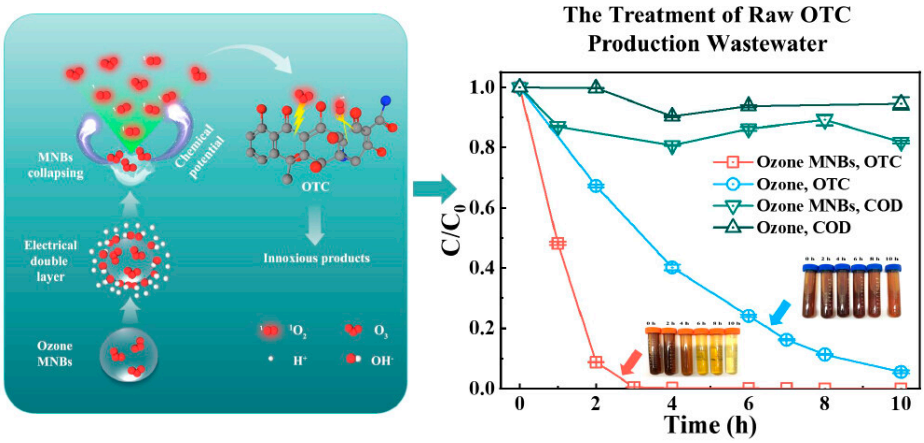


Figure 3. Ozone micro-nano-bubble-enhanced selective degradation of OTC from production wastewater and the generation of $^1O_2$.

4.2.2. Persulfate Activation Enhancement by MNBs

The technology of MNB-assisted persulfate (PMS/PDS) systems degrade recalcitrant ECs by utilizing the generation of SO_4•$^-$ with a high redox potential (2.5−3.1 V). However, single PMS/PDS activation systems are facing too many challenges; for instance, the conventional Fe(II)/persulfate system tends to undergo Fe(II) agglomeration, which shields active sites. Moreover, the herbicide acetochlor exhibits high dispersion in water, thereby reducing the likelihood of contact with active species. Fortunately, Zhang B et al. introduced MNBs into this system [34], precisely addressing these issues: the high mass-transfer efficiency of MNBs effectively enhances the dispersion of Fe(II) within the solution, thereby preventing its agglomeration; the surface negative charge (zeta potential ranging from −17 to −45 mV) is capable of adsorbing acetochlor molecules, thereby forming a local high-concentration zone at the gas–liquid interface. In turn, this promotes the reaction between Fe(II) and persulfate,

as well as the targeted attack of $SO_4\bullet^-$ on acetochlor. Experimental results showed that the removal rate of the synergistic system's efficiency in degrading acetochlor was found to be 32% higher than that of the Fe(II)/persulfate system alone, and the rate of membrane flux decay was reduced by 45%. The fundamental reason lies in the fact that MNBs can reduce the deposition of pollutants and sludge flocs on the membrane surface, thereby achieving the dual goals of pollutant removal and membrane-fouling mitigation.

In addition to chemical activation, MNBs also demonstrate significant suitability in thermal-activation persulfate systems. Thermal activation is a traditional method which employs heating to facilitate persulfate decomposition and generate active species. Nevertheless, in conventional thermal-activation systems, the solubility of persulfate is restricted, and its contact time with pollutants is brief, resulting in low utilization of active species. For addressing this, Yang Y et al. [35] used thermally activated persulfate combined with MNB aeration to treat wastewater containing azo dyes. MNBs, through their self-pressurization dissolution characteristic, enhance the solubility of persulfate in water. This is because their extremely slow rise velocity extends the contact time with the thermally activated system, thereby facilitating the thermal decomposition of persulfate to produce more $SO_4\bullet^-$ and •OH. At 50 °C, with a persulfate dosage of 2 mmol/L and MNB gas flow rate of 30 mL/min, the removal rate of the azo dye (with an initial concentration of 100 mg/L) reached 94.7%, which was 28% higher than that of the group without MNB aeration. Meanwhile, the TOC (Total Organic Carbon) removal rate increased by 35%, which confirms that MNBs not only facilitate dye-molecule degradation, but also boost the mineralization of the dye through active species, thereby reducing the accumulation of intermediate products.

When the persulfate activation pathway is upgraded to catalyst-assisted activation, MNBs are able to further enhance the catalytic efficiency via interfacial synergy. The biochar-supported FeCo metal–organic framework derivative (FeCo-MOFs/BC)/PDS system, as detailed by Ye J et al. [36], has demonstrated effective degradation of pollutants. Efficient activation relies on the catalyst design and preparation. However, in the traditional system, the three-phase contact efficiency among tetracycline, the catalyst, and PDS remains constrained by mass-transfer limitations, and the leaching and cycling efficiency of metal ions from the catalyst surface is inadequate. The introduction of MNBs precisely overcomes this limitation: their interfacial enrichment effect induces the aggregation of tetracycline and FeCo-MOFs/BC at the gas–liquid interface, significantly increasing the collision probability between the catalyst's active sites and the pollutants/PDS. Simultaneously, the shock waves generated during MNB collapse promoted the leaching of Fe^{2+} and Co^{2+} from the catalyst surface, further activating PDS to generate active species. In the presence of MNBs, the removal rate of tetracycline with an initial concentration of 20 mg/L and a catalyst dosage of 0.5 g/L reached 92.3% after 60 min of reaction, marking a 31% increase, compared to the group without MNBs.

MNBs are capable of enhancing performance in various persulfate activation systems by optimizing mass transfer, enriching interfaces, or facilitating the generation of active species. Current research has not thoroughly investigated the interference of natural organic matter and coexisting ions in practical wastewater matrices on the utilization rate of active species and the leaching of catalyst metals, and there is a lack of energy-consumption optimization data for large-scale applications. The precise matching of the catalyst's characteristics with the activation pathway is crucial for the effective degradation of organic pollutants. In the future, adjusting MNB parameters, including the generation method, particle size, and concentration, according to the persulfate activation method (e.g., Fe(II) activation, thermal activation, catalytic activation) could further release the synergistic potential and promote the large-scale application of this technology.

4.2.3. Photocatalysis Enhancement by MNBs

Photocatalysis utilizes semiconductor materials to absorb light energy, generating photogenerated electron-hole pairs, which subsequently produce active species like •OH and $\bullet O_2^-$ to degrade pollutants. However, traditional photocatalysis faces bottlenecks, including the high recombination rate of photogenerated charge carriers, the insufficient supply of O_2 (an electron scavenger), and the low mass-transfer efficiency. These bottlenecks pose challenges for traditional photocatalysis in achieving a balance between efficiency and economy during actual wastewater treatment. MNBs can precisely overcome these pain points through the synergistic mechanism of O_2 solubilization, interfacial enrichment and charge-carrier separation promotion, and have demonstrated potential ranging from laboratory-scale experiments to large-scale applications in scenarios such as municipal wastewater treatment, dye degradation, and disinfection.

In the advanced treatment of municipal secondary effluent, the problems of insufficient O_2 supply and inefficient mass transfer in traditional photocatalysis are particularly pronounced, as this process requires the removal of small molecular organics while demanding high environmental friendliness. Fan W et al. [37] applied the combination of MNBs and photocatalysis to this scenario, precisely addressing these two major issues: MNBs enhanced the dissolved oxygen concentration in water to a range of 7–9 mg/L, which is considered beneficial for promoting microbial activity and accelerating the decomposition of organic matter. And the presence of adequate oxygen, functioning as an electron scavenger, significantly diminishes the recombination of photoinduced electron-hole pairs. Simultaneously, their surface negative charge could adsorb small molecular organics in the effluent, forming a high-concentration zone at the gas–liquid interface, thereby significantly enhancing the photocatalytic degradation efficiency. Ultimately, when exposed to visible-light irradiation (3000 lux) and an MNB gas flow rate of 20 mL/min, the COD removal rate reached 68%, and the UV_{254} level decreased by 57%. Throughout the process, no excessive chemical dosing was required, fully meeting the environmental-friendliness requirements for municipal wastewater treatment.

The high efficiency observed in laboratory experiments, such as in the case of photobromination reactions, needs validation at scale to be truly effectively implemented. The 10-L pilot-scale MNB-enhanced photocatalytic system was developed by Zhao M et al. [38], providing crucial support for scaling up this technology. This system use ZnO as the photocatalyst and salicylic acid (SA) as the model pollutant. And the effectiveness of the MNB/ZnO/UV system was systematically compared with those of the MNB/UV, MNB/ZnO and ZnO/UV degradation systems. The authors reported that optimal performance was achieved under neutral pH conditions, with a catalyst dosage of 0.3 g/L and an air intake rate of 0.1 L/min. In the degradation of SA, the MNB/ZnO/UV system attained a kinetic constant of 0.04126 min^{-1}, representing a 4.5-fold enhancement compared to the conventional ZnO/UV system. This marked improvement in degradation efficiency is primarily attributed to the fact that air MNBs not only enhanced gas–liquid mass-transfer efficiency, but also significantly increased dissolved oxygen concentrations. More importantly, energy consumption was reduced by 40% compared to traditional photocatalytic systems. This energy advantage originates from MNBs reducing the gas–liquid mass-transfer resistance, which in turn decreases the energy needed for aeration and stirring, thus laying the foundation for the economic feasibility of industrial-scale promotion. The mechanism of photocatalysis by MNB enhancement in the above scenarios can be further elucidated through the microscopic experiments conducted by Fan W et al. [39]. A core shortcoming of traditional photocatalysis is the easy recombination of photogenerated charge carriers (Figure 4). This study, through PL spectroscopy (photoluminescence spectroscopy) and transient photocurrent tests, found that MNBs could increase the separation

efficiency of photogenerated electrons by 52%, and this is because the pollutants adsorbed by MNBs serve as hole scavengers, creating a dual scavenging synergy with O_2 acting as electron scavengers, thereby fundamentally reducing charge carrier recombination. The degradation of bisphenol A was significantly accelerated by the MNB-photocatalysis system, with a degradation rate constant (k) of 0.045 min^{-1}, which was 2.3 times higher than that of the control group lacking MNBs, as reported in recent studies. And LC-MS analysis clarified the fact that, after hydroxylation of the benzene ring and carbon bridge cleavage, bisphenol A could ultimately mineralize into CO_2 and H_2O, demonstrating that MNBs not only enhance mass-transfer efficiency, but also bolster the degradation and mineralization capabilities of photocatalysis at the reaction mechanism level [40]. The potential of MNBs for enhancing photocatalysis not only resides in the dual scavenging synergy, but can also be further unlocked through dynamic parameter adjustments tailored to pollutant types. For instance, by employing 100–150 nm MNBs to target small organics in municipal wastewater, with priority given to O_2, mass transfer can be enhanced by using smaller 50–80 nm MNBs for dyes, which strengthens interfacial enrichment and achieves precise performance improvement. Furthermore, by combining the interfacial adsorption characteristics of MNBs with membrane separation, the loss of catalysts such as TiO_2/graphene can be reduced, which not only lowers costs, but also avoids secondary pollution, thereby addressing a key challenge in catalyst recycling for industrial applications [41]. However, the impact of weather and fluctuations in water quality (such as pH, temperature, and pollutant concentration variations) on the interfacial enrichment of MNBs, O_2 solubilization efficiency, and photogenerated carrier separation in practical applications, has not been considered. Meanwhile, it remains unclear how to adapt to dynamic water quality and lighting conditions in real-world scenarios through technical optimization.

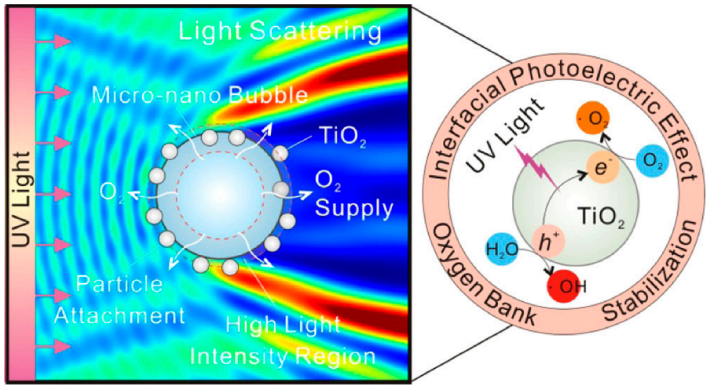


Figure 4. Enhanced photocatalytic water decontamination by MNBs.

4.2.4. Zero-Valent Nano-Iron Catalysis Enhancement by MNBs

In recent years, the combination of zero-valent nano iron (nZVI) and MNBs has attracted widespread attention as a novel approach for pollutant degradation. Nanoparticles of nZVI have demonstrated exceptional reactivity in environmental remediation, effectively degrading a range of organic pollutants, such as pharmaceutical compounds, as evidenced by recent studies [42]. However, the challenges of agglomeration and limited dispersion of nZVI particles in water have been a significant barrier to their practical application [43]. Research has been conducted to address these issues, such as optimizing the nZVI particles through various methods to enhance their dispersion and stability. On the other hand, MNBs, with their unique properties, make them ideal carriers for delivering nZVI to target pollutants [44]. MNBs provide numerous active sites for pollutant degradation. When these bubbles collapse, they generate shock waves and highly reactive species (e.g., •OH), thereby enhancing the degradation efficiency. The combination of nZVI and MNBs offers several

advantages for pollutant degradation. Firstly, the utilization of nZVI enables the generation of •OH radicals with strong oxidizing capacity. Secondly, the utilization of MNBs offers a means to efficiently transport nZVI particles to target pollutants, thereby increasing the contact area and enhancing degradation efficiency [45]. Moreover, MNBs can enhance mass transfer, which facilitates the diffusion of pollutants and further promotes their degradation. Chi et al.'s research [46] explored the degradation of tetracycline in wastewater, utilizing a system combining MNBs with nZVI. This approach aligns with other studies that have investigated the effectiveness of various composite materials in degrading tetracycline, such as the preparation and application of tin-based composites, carbon nitride composites, and magnetic modified activated carbon coupled with a heterogeneous Fenton system. A stable and efficient tetracycline remover was prepared by loading nano-zero-valent iron particles onto phosphoric acid-activated biochar. Understanding how tetracycline degrades in the MNBs/nZVI system is crucial for devising effective strategies to remove pharmaceutical compounds during wastewater treatment. Chi et al.'s study revealed that, under MNB-only conditions, when the gas flow rate of MNBs was 30 mL/min, the tetracycline removal rate changed minimally, suggesting a weak removal capability with MNBs alone. Similarly, the tetracycline removal rate after 2 h was only 34.90% when using nZVI-BC (biochar) alone, indicating that nZVI-BC alone has limited capability to degrade tetracycline. When MNBs are used alone, treating high-concentration tetracycline wastewater is challenging, and the process needs to be conducted at an appropriate temperature [47]. However, under conventional bubble (CB) conditions, the removal efficiency of tetracycline by the CB/nZVI-BC system has been shown to improve, as evidenced by similar systems, such as MNBs/nZVI, which achieved a removal rate of 82.81%. After 2 h of reaction with conventional bubble aeration, the degradation rate of tetracycline by the CB/nZVI-BC system achieved a degradation rate of 52.21%, which indicates that conventional bubble aeration enhanced the degradation of tetracycline by nZVI-BC. This can be attributed to the fact that conventional bubble aeration improved the contact efficiency between nZVI-BC and the solution [48]. When the initial tetracycline concentration was 20 mg/L, the MNBs/nZVI-BC system achieved the highest removal rate, reaching 82.81% after 2 h of reaction. This performance surpassed that of the systems using MNBs alone, nZVI-BC alone, and CB/nZVI-BC alone, owing to the synergistic effect between MNBs and nZVI-BC for tetracycline. Additionally, Chi et al.'s study also investigated the effect of different MNB gas flow rates on tetracycline degradation. At gas flow rates of 10 mL/min and 60 mL/min, the lowest removal rates were observed, reaching 62.35% and 62.71%, respectively, with corresponding rate constants (k) as low as 0.00555 min^{-1} and 0.00517 min^{-1}. However, when the gas flow rate was adjusted to 30 mL/min, the removal rate increased to 82.81%, and k increased to 0.00988 min^{-1}. At this gas flow rate, the reaction vessel contained a substantial number of stable and continuous MNBs, resulting in a milky-looking micro-bubble solution. As the reaction proceeded, the pH of the MNB/nZVI-BC system gradually increased, owing to the oxidation of Fe^{2+} and the production of •OH resulting from MNB collapse. Meanwhile, the degradation products, small organic acids, kept the electrochemical system in a slightly acidic environment. To regulate the degradation rate of tetracycline, it is recommended that an ozone-saturated solvent be added for solubilization, minimizing the bursting of MNBs, and elevating the environmental pH, thereby regulating the degradation rate [49]. Subsequently, via a series of reactions, the organic compounds were ultimately broken down and partly transformed into CO_2 and H_2O. On the other hand, due to iron oxidation and ferric hydroxide formation, tetracycline molecules and intermediate compounds were trapped and precipitated as sludge, separating them from the aqueous solution; the increase in TOC removal rate indicated that MNBs promoted the occurrence of iron–carbon electrochemical reactions, leading to the generation of more •OH in the system [50]. As the reaction time

increased, tetracycline molecules and intermediate compounds were removed through this mechanism. The optimization of the MNBs/nZVI-BC system can be achieved through dynamic adaptation and resource cycling: for example, adjusting the MNB gas flow rate according to different tetracycline concentrations, slightly increasing to 35–40 mL/min for high concentrations to strengthen free radical supply, and avoiding the mass-transfer limitations of a fixed flow rate. Furthermore, by utilizing the magnetic properties of nZVI in combination with a weak magnetic field, rapid separation can be achieved by ferric hydroxide pollutant flocs. And it can simultaneously recover nZVI-BC for reuse, thereby reducing sludge production, lowering material costs, and maintaining environmental health. However, existing research is confined to single tetracycline pollutants and ideal experimental conditions, and there is a lack of data regarding the long-term oxidative deactivation of nZVI and its adaptability to multiple pollutants. It is recommended that the verification of complex matrices and long-term stability testing are given priority, in order to expand the scope of pollutant applicability.

Table 3. Pollutant degradation by AOPs with MNBs.

Category	Processes	Pollutants	Efficiency	Role of MNBs	Ref.
Advanced oxidation processes	MNBs with Ozone	Butylated hydroxytoluene (BHT)	BHT: 70%	Strengthening ozone gas–liquid mass transfer and promoting pollutant oxidative decomposition.	[28]
	MNBs with Ozone	Organic-polluted wastewater	COD: more than 63% at 14 h	Solubilizing ozone, improving its stability and increasing oxidation efficiency.	[30]
	MNBs with Ozone	Oxycline (OTC)	OTC: 99.5%	Generating singlet oxygen, intensifying ozone mass transfer and promoting targeted degradation.	[31]
	MNBs with Ozone	Photoresist	Enhancing the removal rate by more than 30%	Improving ozone stability, increasing dissolution efficiency and facilitating reactive species generation.	[32]
	MNBs with Fe(II)/persulfate with sludge membrane system	Acetochlor	AC: 92.3%, the removal rate has increased by 32%	Dispersing Fe(II), enriching pollutants, and alleviating membrane fouling.	[34]
	MNBs with thermally activated persulfate	Azo dye (100 vmg/L)	Removal rate: 94.7% (an increase of 28%)	Improving persulfate solubility, prolonging contact time and intensifying mineralization.	[35]
	MNBs with persulfate	Tetracycline (20 mg/L)	The removal rate within 60 min was 92.3% (up 31%)	Enriching pollutants and catalysts, enhancing metal ion leaching, and promoting cycling.	[36]
	MNBs with photocatalysis	Small-molecule organic substances in municipal secondary effluent	COD was 68% and UV254 decreased by 57%	Increasing O_2 solubilization, concentrating organics and suppressing charge carrier recombination.	[37]
	MNBs with TiO_2/Graphene Photocatalysis (Pilot)	Rhodamine B (50 mg/L)	Removal rate >90% (for 8 consecutive hours)	Optimizing gas–liquid contact, minimizing mass-transfer resistance, and cutting energy consumption.	[38]
	MNBs with photocatalysis	Bisphenol A	The degradation rate has increased by 2.3 times	Establishing a “Dual-Capture” synergy and intensifying mineralization.	[40]
	MNBs with Zero-valent nano-iron biochar	Tetracycline	The removal rate within 2 h was 82.81%	Dispersing nanoscale iron, generating radicals through particle decomposition, and enhancing triphase contact.	[46]
	MNBs system	Tetracycline	TC: 82.66% at 100 min Efficient degradation	Intensifying mass-transfer–oxidation synergy and boosting degradation stability.	[47]

4.3. Microbial Synergy Processes by MNBs

As demonstrated in Table 4, the synergy between MNBs and microorganisms can also significantly improve pollutant removal rates. By constructing an MNB–microorganisms synergistic system, the biological treatment effectiveness is significantly enhanced, and this system exhibits unique advantages, especially in the treatment of recalcitrant ECs [51,52]. The introduction of MNBs provides new solutions for addressing bottlenecks in biological treatment, such as insufficient dissolved oxygen DO and low microbial activity. Their optimization of the microalgal growth environment, such as enhancing DO and CO_2 supply to boost photosynthetic efficiency, further gives this technology cross-scenario application potential in microalgae production, wastewater treatment, and carbon capture. While biological processes degrade ECs partly via microbial metabolism, and are advantageous in terms of low cost and eco-friendliness, they are subject to multiple limiting factors. EC-induced toxicity often reduces the viability of functional microbial consortia, as exemplified by antibiotic-mediated suppression of microbial activity. Moreover, conventional aeration fails to maintain adequate DO levels (generally <4 mg/L), thereby constraining aerobic metabolic efficiency. Additionally, the limited co-metabolic versatility of microorganisms impedes the direct utilization and mineralization of structurally complex and persistent ECs [53]. The metabolic degradation of ECs by microorganisms is mostly a partial transformation process. Some transformation products may retain or even enhance the toxicity of the parent pollutants. Therefore, it is necessary to consider both the pollutant removal rate and the evolution of product toxicity throughout the degradation process. The marked increase was observed in aerobic microorganisms post-MNB aeration, enhancing the self-purification capacity of the water. MNBs offer a comprehensive solution to the aforementioned constraints by optimizing DO availability, enhancing microbial vitality, and promoting metabolic efficiency. Benefiting from superior mass-transfer characteristics, MNBs can elevate dissolved oxygen levels to 7–9 mg/L, thereby creating favorable conditions for the sustained and efficient functioning of aerobic microorganisms. The negatively charged surfaces of these entities facilitate the adsorption of free pollutants in aqueous systems, thereby alleviating the toxic stress exerted on microbial communities. Consequently, a localized enrichment zone for both pollutants and microorganisms is established at the gas–liquid interface. The interface significantly enhances the co-metabolic degradation of recalcitrant substances, as evidenced by the effectiveness of microbial co-metabolism in treating difficult-to-degrade organic compounds. Therefore, microbial synergy strategies leveraging MNBs have proven highly effective in a wide range of environmental remediation contexts, most notably in mitigating highly toxic antibiotic wastewater and reclaiming pesticide-contaminated soils characterized by chemical persistence.

The MNBs and microbial synergy technology demonstrate varying effects on different ECs across diverse scenarios. In the treatment scenario of antibiotic pollutants in wastewater, ofloxacin, due to its high toxicity, significantly inhibits microbial activity. The removal rate of ofloxacin by traditional immobilized *Chlorella vulgaris* was only 55.3% [54]. This challenge can be precisely addressed through the dual functionality of MNBs, which concurrently provide toxicity buffering and an energy supply. According to Figure 5, the sediment subjected to MNB aeration showed a significant alteration in bacterial community structure. MNB aeration exhibited a stronger selectivity for microorganisms, effectively inhibiting anaerobic species generation in water, and leading to aerobic species as the dominant strains. Zhang et al. [55] achieved relatively ideal treatment results by constructing MNBs with a *Chlorella vulgaris* synergistic system. The experimental results showed that when the initial concentration of ofloxacin was 100 μg/L, the MNBs–*Chlorella vulgaris* synergistic system increased the removal rate to 84.7%, representing a 29.4% improvement compared to the traditional *Chlorella vulgaris* system. The fundamental reason is that the negatively charged surface

of MNBs electrostatically attracts ofloxacin molecules, creating a local high-concentration zone at the gas–liquid interface. This adsorption behavior reduces the concentration of free ofloxacin in the solution, thereby alleviating its toxic effects on *Chlorella vulgaris*; simultaneously, the high mass-transfer efficiency of MNBs elevates the dissolved oxygen concentration in the water to 7–9 mg/L, supplying sufficient energy for the metabolism of *Chlorella vulgaris* and facilitating its growth and the co-metabolic degradation of ofloxacin. HPLC-MS analysis revealed that the degradation pathway of ofloxacin encompassed piperazine ring cleavage and defluorination. However, the adsorption of ofloxacin by MNBs relies on electrostatic interactions, and the surface charge of MNBs can be affected by solution pH. For water matrices containing antibiotics, it is also crucial to monitor the potential impact of this synergistic system on antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARG) in the water. It is important to be vigilant, because some degradation processes of antibiotics may induce the enrichment of ARB and the horizontal transfer of ARG, posing secondary environmental risks. Subsequent studies could investigate modulating the zeta potential of MNBs by altering the gas type (e.g., CO_2-MNBs) to improve their pollutant adsorption capacity under varying pH conditions. In the remediation scenario of soil contaminated with recalcitrant pesticides, traditional microbial remediation encounters the dual challenges of inadequate DO supply and low bioavailability of pollutants. The MNBs equipped with microbial synergy technology can precisely tackle these two major challenges, through the dual mechanisms of deep oxygen supply and enhanced bioavailability. Jing et al. [56] developed an MNBs system incorporating Pseudomonas synergistic effects for the remediation of soil contaminated with the pesticide atrazine. The experimental results demonstrated that after 30 days of remediation, the atrazine removal rate in the MNBs with the Pseudomonas group reached 78.5%, marking a 32.7% improvement over the traditional Pseudomonas group. The fundamental reason is that MNBs, through their large specific surface area and long residence time, can penetrate deep into the soil, providing sufficient dissolved oxygen for aerobic Pseudomonas. The degradation of atrazine is facilitated by reactive species such as •OH, which are generated during the collapse of metal nano-biostructures. These radicals break down atrazine into smaller molecular substances that are more readily utilized by microorganisms like Pseudomonas, thereby enhancing the pollutant's bioavailability. Real-time quantitative PCR analysis indicated that the abundance of Pseudomonas in the MNBs–Pseudomonas group was 2.3 times that of the traditional Pseudomonas group, confirming that MNBs can promote the growth of functional microorganisms. However, the penetration depth of MNBs in the soil is restricted, and subsequent research could explore integrating electrokinetic remediation to drive MNBs deeper into the soil, thereby further expanding the remediation scope.

The improvement mechanism of microbial treatment by MNBs can be further elucidated through the microscopic experiments conducted by Zhou et al. [57]. This study revealed that MNBs could upregulate the expression of key enzyme genes involved in the metabolic pathway of *Chlorella vulgaris* for ofloxacin by utilizing transcriptomics, thereby enhancing its co-metabolic degradation capacity for ofloxacin. Simultaneously, the expression of antioxidant enzyme genes was upregulated, which improved the resistance of *Chlorella vulgaris* to oxidative stress. This indicates that MNBs not only enhance the external environment, but also modulate the internal metabolic processes of microorganisms at the molecular level, thereby fundamentally improving the efficiency of biological treatment. The MNBs, in enhancing microbial treatment, can be further released through the dynamic parameter adjustment adapted to pollutant type. For instance, 100–150 nm MNBs are optimally deployed for antibiotic wastewater treatment, where they primarily enhance DO supply and buffer toxicity. Conversely, smaller 50–80 nm MNBs are utilized for soil pesticide remediation to improve subsurface penetration and contaminant bioavailability,

thereby enabling the precise optimization of treatment efficacy. Furthermore, the synergistic effect of microbial nanobionics with microorganisms can be harnessed in conjunction with plant–microbial remediation strategies, to establish a comprehensive system integrating MNBs, microorganisms and plants. This integrated approach is expected to enhance the stability and efficiency of remediation processes, addressing the key shortcoming of single-technology limitations for large-scale promotion.

Table 4. Pollutant elimination by microbial synergy processes with MNBs.

Category	Processes	Pollutants	Efficiency	Role of MNBs	Ref.
Microbial synergy processes	MNBs with Microorganisms	Gaseous chlorobenzene	Reduction in start-up time by 2 days and a 13.5% increase in overall degradation rate.	Boosting mass-transfer efficiency and activating microbial metabolism.	[52]
	MNBs with ozone and anaerobic digestion	Ibuprofen	IBU: 99% at 70 min	Promoting ibuprofen degradation and ameliorating the subsequent digestion conditions.	[53]
	MNBs	Pollutants from urban black and odorous river water	Biological oxygen demand: 54.4% chemical oxygen demand: 39.0%.	Replenishing dissolved oxygen and boosting natural pollutant degradation.	[54]
	MNBs with Microalgae	Wastewater pollutants and CO_2	COD: 42% NH_3-N: 21% UV: 42%.	Enhancing the microalgal growth environment, boosting photosynthetic efficiency, and strengthening pollutant removal.	[55]
	MNBs with immobilized Chlorella	Ofloxacin	The removal rate increased from 55.3% to 89.5%.	Stimulating EPS secretion via elevating CO_2 supply, thereby establishing a toxicity buffer.	[56]
	MNB irrigation	Thiamethoxam in the soil	The degradation rate within 30 days increased from 52% to 88%.	Increasing soil dissolved oxygen, stimulating degrading microorganisms, and enhancing soil aeration.	[57]

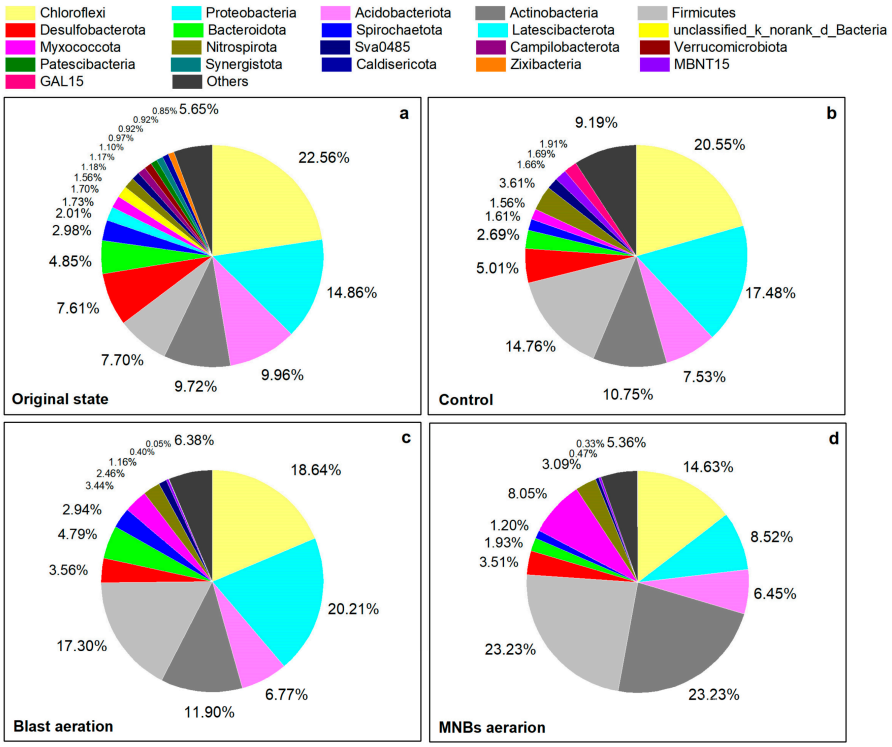


Figure 5. Composition of microbial community at the phylum level for the sediment from original state (**a**), control (**b**), blast aeration (**c**) and MNB aeration. (**d**) (The relative abundance of less than 0.01% is uniformly indicated by others) [54].

MNB–microbial synergy technology has precisely overcome the three major bottlenecks in biological treatment, which lie in DO optimization, toxicity buffering and co-metabolism promotion. However, at present, the matching between MNB-generation parameters and specific pollutants is still relatively general, necessitating further refinement. Looking ahead, the synergy between the precise domestication of functional microorganisms and the tailored parameters of MNBs is poised to enhance the efficiency of this technology in tackling complex pollution challenges.

5. Conclusions

This review systematically elaborates the research progress on the treatment of ECs using MNBs technology in combination with other methods. MNBs exhibit significant potential in environmental cleanup, due to their unique physicochemical properties, including a large specific surface area, extended residence time, high mass-transfer efficiency, negative surface charge, and the ability to generate ROS, as demonstrated in various ecological restoration projects. MNBs combined with physical adsorption technology can elevate the removal efficiency of ECs via mechanisms including interfacial enrichment and compatibility optimization. MNBs, when combined with chemical oxidation technologies (ozonation, persulfate oxidation, photocatalysis, and material catalysis), can enhance the degradation efficiency of ECs through mechanisms such as oxidant solubilization, ROS activation and mass-transfer enhancement. The combination of biological methods can enhance the removal efficiency of ECs through mechanisms including DO optimization, enhancement of microbial activity, and promotion of co-metabolism.

Although MNB technology has yielded certain results in treating ECs, there remain some issues that warrant further research: (1) Current MNB generation technologies remain constrained by high operational costs, substantial energy consumption, and limited bubble stability. Future research efforts should therefore prioritize the development of more efficient and economically viable MNB generation strategies, while simultaneously enhancing bubble stability to prolong their residence time in aqueous systems. (2) The specific mechanisms of MNBs in enhancing physical, chemical, and biological processes, especially at the molecular level, require further in-depth investigation. For instance, the interaction mechanisms among MNBs, pollutants, catalysts and microorganisms should be clarified via advanced characterization techniques and theoretical calculations. (3) Most current studies are conducted under laboratory conditions with simulated wastewater. The effectiveness of MNB technology in treating complex real wastewater with multiple pollutants and interfering substances requires verification. Further research is required to understand the effects of water quality parameters, such as pH and co-existing ion concentration. (4) The comprehensive assessment of MNB technology's large-scale application should consider its economic feasibility and potential environmental benefits, as demonstrated by similar projects that have integrated advanced technologies to enhance production efficiency and reduce environmental impact. This involves evaluating energy consumption, operational costs, potential secondary pollution, and long-term ecological impacts.

In conclusion, MNB technology, as a newly emerging water-treatment technology, shows great potential for the remediation of ECs. Through continuous technological innovation and in-depth mechanism research, MNB technology is expected to play a pivotal role in the realm of water environmental protection in the future.

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Abbreviations

The following abbreviations are used in this manuscript:

ECs	Emerging contaminants
PFAS	Per- and polyfluoroalkyl substances
MNBs	Micro-nano bubbles
PPCPs	Pharmaceuticals and personal care products
EDCs	Endocrine-disrupting chemicals
MPs	Microplastics
nZVI	Zero-valent iron nanoparticles
DO	Dissolved oxygen
COD	Chemical Oxygen Demand
PFOS	Perfluorooctane sulfonate
PFOA	Perfluorooctanoic Acid
GAC	Coal-based granular activated carbon
OTC	Oxytetracycline
PL spectroscopy	Photoluminescence spectroscopy
CB	Conventional bubble
BHT	Butylated hydroxytoluene
ARB	Antibiotic-resistant bacteria
ARG	Antibiotic resistance genes
EPS	Expandable Polystyrene
MBBR	Moving-Bed Biofilm Reactors
TOC	Total Organic Carbon
PMS/PDS	Peroxymonosulfate/Peroxydisulfate
BC	Biochar
TC	Tetracycline
ROS	Reactive oxygen species
qPCR	Quantitative Real-time Polymerase Chain Reaction

References

1. Noorani, K.R.P.M.; Flora, G.; Surendarnath, S.; Stephy, G.M.; Amesho, K.T.; Chinglenthoiba, C.; Thajuddin, N. Recent advances in remediation strategies for mitigating the impacts of emerging pollutants in water and ensuring environmental sustainability. *J. Environ. Manag.* **2024**, *351*, 119674.
2. Wang, J.; Wang, S. Removal of pharmaceuticals and personal care products (PPCPs) from wastewater: A review. *J. Environ. Manag.* **2016**, *182*, 620–640. [CrossRef]
3. Chen, Q.; Xin Jie, Z.; Guo, Y.; Zhou, Q. Research progress of micro-nano-bubbles in environmental remediation field. *Front. Environ. Sci.* **2025**, *13*, 1623566.
4. Zheng, T.; Wang, J.; Wang, Q.; Nie, C.; Shi, Z.; Wang, X.; Gao, Z. A bibliometric analysis of micro/nano-bubble related research: Current trends, present application, and future prospects. *Scientometrics* **2016**, *109*, 53–71. [CrossRef]
5. Zhao, S.; Wu, J.; Li, Y. Advances in the Research on the Properties and Applications of Micro-Nano Bubbles. *Processes* **2025**, *13*, 2106. [CrossRef]
6. Khuntia, S.; Majumder, S.K.; Ghosh, P. Microbubble-aided water and wastewater purification: A review. *Chem. Rev.* **2012**, *28*, 91–221. [CrossRef]
7. Agarwal, A.; Ng, W.J.; Liu, Y. Principle and applications of microbubble and nanobubble technology for water treatment. *Chemosphere* **2011**, *84*, 1175–1180. [CrossRef] [PubMed]

8. Xiong, Y.; Peng, F. Optimization of cavitation venturi tube design for pico and nano bubbles generation. *J. Min. Sci. Technol.* **2015**, *25*, 523–529. [CrossRef]
9. Cho, S.-H.; Kim, J.-Y.; Chun, J.-H.; Kim, J.-D. Ultrasonic formation of nanobubbles and their zeta-potentials in aqueous electrolyte and surfactant solutions. *Colloids Surf. A Physicochem. Eng. Asp.* **2005**, *269*, 28–34. [CrossRef]
10. Levitsky, I.; Tavor, D.; Gitis, V. Generation of Two-Phase Air-Water Flow with Fine Microbubbles. *Chem. Eng. Technol.* **2016**, *39*, 1537–1544. [CrossRef]
11. Parmar, R.; Majumder, S.K. Terminal rise velocity, size distribution and stability of microbubble suspension. *Asia-Pac. J. Chem. Eng.* **2015**, *10*, 450–465. [CrossRef]
12. Fan, M.; Tao, D.; Luo, Z. Nanobubble generation and its application in froth flotation (part I): Nanobubble generation and its effects on properties of microbubble and millimeter scale bubble solutions. *Min. Sci. Technol.* **2010**, *20*, 1–19. [CrossRef]
13. Finch, J.A.; Nesset, J.E.; Acuna, C. Role of frother on bubble production and behaviour in flotation. *Miner. Eng.* **2008**, *21*, 949–957. [CrossRef]
14. Michailidi, E.D.; Bomis, G.; Varoutoglou, A.; Kyzas, G.Z.; Mitrikas, G.; Mitropoulos, A.C.; Efthimiadou, E.K.; Favvas, E.P. Bulk nanobubbles: Production and investigation of their formation/stability mechanism. *J. Colloid Interface Sci.* **2020**, *564*, 371–380. [CrossRef] [PubMed]
15. Haris, S.; Qiu, X.; Klammler, H.; Mohamed, M.M. The use of micro-nano bubbles in groundwater remediation: A comprehensive review. *Groundw. Sustain. Dev.* **2020**, *11*, 100463. [CrossRef]
16. Marui, T. An introduction to micro/nano-bubbles and their applications. *Syst. Cybern. Inform.* **2013**, *11*, 68–73.
17. Monira, S.; Pramanik, B.K. Micro-Nanobubble Integrated Dissolved Air Flotation: A High-Efficiency Strategy for Microplastic Mitigation in Wastewater. *ACS ES T Water* **2026**, *6*, 3153–3161. [CrossRef]
18. You, K.; Liu, E.; Wu, X.; Cheng, D. Progress of researches on synergetic mechanism of micro-nano-bubble-assisted ozonation. *Water Sci. Technol.* **2025**, *92*, 340–362. [CrossRef] [PubMed]
19. Kyzas, G.Z.; Bomis, G.; Kosheleva, R.I.; Efthimiadou, E.K.; Favvas, E.P.; Kostoglou, M.; Mitropoulos, A.C. Nanobubbles effect on heavy metal ions adsorption by activated carbon. *Chem. Eng. J.* **2019**, *356*, 91–97. [CrossRef]
20. Luo, Y.; Fu, K.; Wang, D.; Luo, J. Nanobubble-Driven Interfacial Interactions of Carbon-Based Adsorbents with Legacy PFAS: Impact of Concentration, pH, and Coexisting Ions. *Environ. Sci. Technol.* **2025**, *59*, 6900–6914. [CrossRef] [PubMed]
21. Xiao, Z.; Aftab, T.B.; Li, D. Applications of micro-nano bubble technology in environmental pollution control. *Micro Nano Lett.* **2019**, *14*, 782–787. [CrossRef]
22. Jiang, X.; Wang, W.; Yu, G.; Deng, S. Contribution of nanobubbles for PFAS adsorption on graphene and OH-and NH2-functionalized graphene: Comparing simulations with experimental results. *Environ. Sci. Technol.* **2021**, *55*, 13254–13263. [PubMed]
23. Kang, Y.; Song, F.; Lin, J.; Wang, N.; Zhu, L. Enhanced selective adsorption of perfluoroalkyl substances through an integration of quaternized cellulose nonwoven and micro-nano-bubbles. *Sep. Purif. Technol.* **2025**, *365*, 132598. [CrossRef]
24. Wang, J.; Wang, Z.; Pei, F.; Wang, X. Enrichment of microplastic pollution by micro-nanobubbles. *Chin. Phys. B* **2022**, *31*, 118104. [CrossRef]
25. Sakr, M.; Mohamed, M.M.; Maraqa, M.A.; Hamouda, M.A.; Hassan, A.A.; Ali, J.; Jung, J. A critical review of the recent developments in micro–nano bubbles applications for domestic and industrial wastewater treatment. *Alex. Eng. J.* **2022**, *61*, 6591–6612. [CrossRef]
26. Ova, D.; Ovez, B. 2,4-Dichlorophenoxyacetic acid removal from aqueous solutions via adsorption in the presence of biological contamination. *J. Environ. Chem. Eng.* **2013**, *1*, 813–821. [CrossRef]
27. Malik, S.N.; Ghosh, P.C.; Vaidya, A.N.; Mudliar, S.N. Hybrid ozonation process for industrial wastewater treatment: Principles and applications: A review. *J. Water Process Eng.* **2020**, *35*, 101193. [CrossRef]
28. Achar, J.; Nam, G.; Jung, J.; Klammler, H.; Mohamed, M.M. Microbubble ozonation of the antioxidant butylated hydroxytoluene: Degradation kinetics and toxicity reduction. *Environ. Res.* **2020**, *186*, 109496. [CrossRef] [PubMed]
29. Yan, P.; Feng, C.; Li, M.; Shen, J.; Chen, Z.; Ma, F.; Kang, J.; Zhu, X.; Li, Y.; Cheng, Y. Enhanced durable water purification via UV-triggered ozone micro-nano bubbles process: Exposure of free radicals and control of disinfection byproducts. *Chem. Eng. J.* **2025**, *526*, 171258.
30. Xia, Z.; Hu, L. Treatment of Organics Contaminated Wastewater by Ozone Micro-Nano-Bubbles. *Water* **2019**, *11*, 55.
31. Tang, L.; Zhou, S.; Li, F.; Sun, L.; Lu, H. Ozone Micronano-bubble-Enhanced Selective Degradation of Oxytetracycline from Production Wastewater: The Overlooked Singlet Oxygen Oxidation. *Environ. Sci. Technol.* **2022**, *57*, 18550–18562. [CrossRef] [PubMed]
32. Takahashi, M.; Ishikawa, H.; Asano, T.; Horibe, H. Effect of microbubbles on ozonized water for photoresist removal. *Phys. Chem.* **2012**, *116*, 12578–12583. [CrossRef]
33. Takahashi, M.; Chiba, K.; Li, P. Formation of hydroxyl radicals by collapsing ozone microbubbles under strongly acidic conditions. *Phys. Chem.* **2007**, *111*, 11443–11446. [CrossRef]
34. Zhang, B.; Yue, X.; Tang, H.; Qi, R.; Shi, W. Enhanced Fe (II)/persulfate process with micro-nano bubbles for highly efficient mitigation of membrane fouling and synergistic removal of acetochlor in an aerobic granular sludge membrane system. *Sep. Purif. Technol.* **2025**, *379*, 135098. [CrossRef]

35. Yang, Y.; Yao, X.; Wu, S.; Wang, X.; Feng, L.; Feng, X.; Ma, Y. Enhanced treatment of azo dyes in wastewater using heat-activated persulfate with micro-nano bubble aeration. *Chem. Eng. Res. Des.* **2023**, *197*, 24–37. [CrossRef]
36. Ye, J.; Ling, Z.; Li, C.; Dai, M.; Chen, Q.; Gu, Y.; Yang, C. Micro-nanobubble-assisted tetracycline degradation by biochar-supported FeCo-metal-organic framework derivatives/persulfate system. *Colloids Surf. A Physicochem. Eng. Asp.* **2025**, *718*, 136911. [CrossRef]
37. Fan, W.; Zhou, Z.; Wang, W.; Huo, M.; Zhang, L.; Zhu, S.; Yang, W.; Wang, X. Environmentally friendly approach for advanced treatment of municipal secondary effluent by integration of micro-nano bubbles and photocatalysis. *J. Clean. Prod.* **2019**, *237*, 117828. [CrossRef]
38. Zhao, M.; Cui, H.; Wang, C.; Song, Q. Development of a 10-litre pilot scale micro-nano bubble (MNB)-enhanced photocatalytic system for wastewater treatment. *Environ. Technol.* **2024**, *45*, 6200–6209. [CrossRef] [PubMed]
39. Fan, W.; Li, Y.; Wang, C.; Duan, Y.; Huo, Y.; Januszewski, B.; Sun, M.; Huo, M.; Elimelech, M. Enhanced photocatalytic water decontamination by micro-nano bubbles: Measurements and mechanisms. *Environ. Sci. Technol.* **2021**, *55*, 7025–7033. [CrossRef] [PubMed]
40. Rivas, F.J.; Encinas, Á.; Acedo, B.; Beltrán, F.J. Mineralization of bisphenol A by advanced oxidation processes. *J. Chem. Technol. Biotechnol. Int. Res. Process Environ. Clean Technol.* **2009**, *84*, 589–594.
41. Molinari, R.; Argurio, P.; Szymański, K.; Darowna, D.; Mozia, S. Photocatalytic membrane reactors for wastewater treatment. In *Current Trends and Future Developments on (Bio-) Membranes*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 83–116.
42. Wang, X.; Zhang, B.; Ma, J.; Ning, P. Novel synthesis of aluminum hydroxide gelcoated nano zero-valent iron and studies of its activity in flocculation-enhanced removal of tetracycline. *Environ. Sci.* **2020**, *89*, 194–205. [CrossRef]
43. Zhang, L.; Song, Z.; Dong, T.; Fan, X.; Peng, Y.; Yang, J. Mitigating mechanism of nZVI-C on the inhibition of anammox consortia under long-term tetracycline hydrochloride stress: Extracellular polymeric substance properties and microbial community evolution. *J. Hazard. Mater.* **2023**, *452*, 131035. [CrossRef] [PubMed]
44. Song, M.; Hu, X.; Gu, T.; Zhang, W.-X.; Deng, Z. Nanocelluloses affixed nanoscale zero-valent iron (nZVI) for nickel removal: Synthesis, characterization and mechanisms. *J. Environ. Chem. Eng.* **2022**, *10*, 107466. [CrossRef]
45. Li, S.; Wang, W.; Liang, F.; Zhang, W.-X. Heavy metal removal using nanoscale zero-valent iron (nZVI): Theory and application. *J. Hazard. Mater.* **2017**, *322*, 163–171. [CrossRef] [PubMed]
46. Chi, C.; Huo, B.; Liang, Z.; Hu, C.; Sun, Q.; Zhou, S. Study on tetracycline degradation in wastewater based on zero-valent nano iron assisted micro-nano bubbles. *Alex. Eng. J.* **2024**, *86*, 577–583. [CrossRef]
47. Evode, N.; Zhang, X.; Chai, X.; Gu, J.; Zhao, S.; Yutao, L. Performance test and analysis of tetracycline degradation using a Micro-Nano Bubble system. *J. Environ. Manag.* **2024**, *363*, 121328. [CrossRef]
48. Duan, Y.; Han, P.; Zhang, R.; Ren, P.; Shi, W.; Wong, N.H.; Sunarso, J.; Liu, S.; Yu, J. A CuO-modified ultrafiltration ceramic membrane inducing micro-nano bubble collapse to generate hydroxyl radicals for enhancing pollutant removal. *Appl. Surf. Sci.* **2024**, *651*, 159271. [CrossRef]
49. Zhao, K.; Padervand, M.; Ren, H.; Jia, T.; Guo, Q.; Yang, L.; Wang, C. Enhancing tetracycline removal efficiency through ozone micro-nano bubbles: Environmental implication and degradation pathway. *ACS ES T Eng.* **2024**, *4*, 1860–1870. [CrossRef]
50. Cao, J.; Xiong, Z.; Lai, B. Effect of initial pH on the tetracycline (TC) removal by zero-valent iron: Adsorption, oxidation and reduction. *Chem. Eng. J.* **2018**, *343*, 492–499. [CrossRef]
51. Shao, S.; Wu, X. Microbial degradation of tetracycline in the aquatic environment: A review. *Crit. Rev. Biotechnol.* **2020**, *40*, 1010–1018. [CrossRef] [PubMed]
52. Zhang, M.; Liao, C.; Zhang, Z.; Lu, L.; Chen, J.; Chen, D. Enhancing biodegradation of gaseous chlorobenzene by introducing micro-nano bubbles (MNBs): Performance and mechanisms. *J. Hazard. Mater.* **2025**, *494*, 138745. [CrossRef] [PubMed]
53. Zhou, S.; Qiao, L.; Jia, Y.; Khanal, S.K.; Sun, L.; Lu, H. Micro-nano bubble ozonation for effective treatment of ibuprofen-laden wastewater and enhanced anaerobic digestion performance. *Water Res.* **2025**, *273*, 123006. [CrossRef] [PubMed]
54. Xu, Q.; Zhou, Z.; Chai, X. Micro-and nano-bubbles enhanced the treatment of an urban black-odor river. *Sustainability* **2023**, *15*, 16695. [CrossRef]
55. You, X.; Yang, L.; Chu, H.; Zhang, L.; Hong, Y.; Lin, Y.; Zhou, X.; Zhang, Y. Micro-nano-bubbles and their application in microalgae production: Wastewater treatment, carbon capture and microalgae separation. *Algal Res.* **2024**, *78*, 103398. [CrossRef]
56. Jing, M.; Zhang, J.; Li, G.; Zhang, D.; Liu, F.; Yang, S. Micro-nano bubbles enhanced immobilized *Chlorella vulgaris* to remove ofloxacin from groundwater. *J. Contam. Hydrol.* **2025**, *268*, 104458. [CrossRef] [PubMed]
57. Zhou, Y.; Bastida, F.; Zhou, B.; Sun, Y.; Gu, T.; Li, S.; Li, Y. Soil fertility and crop production are fostered by micro-nano bubble irrigation with associated changes in soil bacterial community. *Soil Biol. Biochem.* **2020**, *141*, 107663. [CrossRef]

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