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Research progress of micro-nano-bubbles in environmental remediation field

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Introduction: MNBs (MNBs), relying on its special chemical and physical properties, such as high surface potential, long stability and free radical generation capacity, have shown broad application prospects in environmental remediation.

Methods: Based on 508 related papers in the Web of Science database, this paper conducts a scientific knowledge mapping analysis using VOSviewer and CiteSpace software to reveal the research situation and trends. Researches show that MNB technology demonstrates remarkable effects in water pollution control (industrial wastewater, surface water, and groundwater) and soil pollution remediation.

Results and Discussion: For instance, ozone MNBs can increase the removal rate of plastic pollutants in industrial wastewater to 94.18% and enhance the degradation efficiency of polycyclic aromatic hydrocarbons through interfacial reactions. In soil remediation, their synergistic effect with surfactants can improve the petroleum pollutants' removal efficiency. From the perspective of research hotspots, the coupling of MNBs with advanced oxidation technologies (such as Fenton, plasma, and photocatalysis) has become the mainstream direction, significantly enhancing the degradation efficiency of pollutants through interfacial effects and radical generation mechanisms. The author collaboration network indicates that Chinese scholars have made outstanding contributions. The team led by Hu Liming from Tsinghua University has achieved fruitful results in groundwater remediation using ozone MNBs. However, the international cooperation network still needs to be strengthened. In terms of institutional collaboration, the Chinese Academy of Sciences (CAS) leads in both the volume of publications and academic influence, with its research covering multiple application areas such as semiconductor cleaning and membrane treatment. Keyword co-occurrence analysis divides the research topics into three major categories: degradation mechanisms, ozone MNB technology, and multi-technology coupling applications. Among them, "free radicals", "mass transfer", and "photocatalysis" are the core keywords. Although MNB technology has achieved phased progress, its long-term stability in complex environments, large-scale application costs, and cross-disciplinary collaborative mechanisms still need in-depth exploration.

KEYWORDS

MNBs, environmental remediation, ozone oxidation, photocatalysis, free radicals, multi-technology coupling

1 Introduction

With the acceleration of global urbanization and industrialization, environmental pollution issue is becoming increasingly severe, posing a serious threat to ecosystems and human health (Hoang et al., 2022; Wei et al., 2021). Among various pollution issues, water and soil pollution stand out prominently, making the search for efficient pollution control technologies an urgent matter. MNB technology, with its unique chemical and physical characteristics, has shown great environmental remediation potential and has become a research hotspot in recent years (Xiao et al., 2025; Haris et al., 2020; Xia et al., 2018; Xiao et al., 2019).

MNBs are bubbles with diameters at the micrometer and nanometer ranges. Compared with traditional macroscopic bubbles, they possess numerous superior characteristics, such as a high internal pressure, a large specific surface area, a longer residence time in liquids, and a high surface Zeta potential (Azuma et al., 2019; John et al., 2022; Loh et al., 2021; Temesgen et al., 2017). The large specific surface area of MNBs significantly increases the gas-liquid interface area, greatly enhancing various mass transfer efficiencies and rates (Xiao et al., 2022). Additionally, the surface of MNBs carries a charge, forming a double electric layer structure with a high interface potential. This property enables them to adsorb pollutants and promote their oxidative decomposition. Moreover, MNBs exhibit excellent stability in solutions and can persist for long periods due to their slow rising speed and charged surface. Some studies have shown that the existence time of oxygen MNBs (180–350 nm) can exceed 5 days, with the longest reaching 60 days (Zhou et al., 2021a), nitrogen MNBs (200–300 nm) can remain stable for a month (Ulatowski et al., 2019), and the existence time of air nano bubbles exceeds 3 months (Michailidi et al., 2020). When MNBs dissolve under pressure, they generate free radicals with strong oxidation capabilities, effectively degrading many refractory organic pollutants and enhancing the removal effect of pollutants (Li et al., 2009).

In the field of environmental remediation, MNB technology demonstrates broad application potential. In water pollution control, whether it is industrial wastewater, surface water, or groundwater pollution, this technology can play a significant role. For industrial wastewater, MNB ozonation can significantly increase the oxidation rate of ozone and effectively degrade organic pollutants (Kim et al., 2022; Zhang et al., 2018), with a removal rate of plastic reaching 94.18% (Masry et al., 2021). In surface water purification, MNBs can perform multiple functions such as aeration mass transfer, air flotation, advanced oxidation, and sterilization and disinfection, effectively removing suspended degrading organic and solids pollutants from water (Wang et al., 2024a). For groundwater pollution, MNBs can carry oxidants into the aquifer to achieve *in-situ* remediation (Chen and Chang, 2022; Shen et al., 2024).

In soil pollution remediation, MNBs also have significant application value. They can serve as carriers to transport oxygen and nutrients into the soil, enhancing the degradation ability of microorganisms towards organic pollutants (Kwon et al., 2020; Pa et al., 2009). Additionally, MNBs can improve the treatment effect on petroleum-contaminated soil and oil sludge by synergistically acting with surfactants, increasing the removal efficiency of petroleum pollutants (Chen et al., 2018; Ji et al., 2018; Sun et al., 2020a).

In summary, MNB technology holds broad application prospects in environmental remediation, but further in-depth research and improvement are still needed. This study utilized software like CiteSpace and VOSviewer to conduct a comprehensive analysis of relevant literature and create a scientific knowledge graph, including source journals, keywords, hotspots, publication trends, research frontiers, author contributions and collaborations, *etc.* The analysis identified and tracked the research frontiers and hotspots in this field, identified scientific hotspots, research topics and their dynamic evolution, and paid attention to existing and emerging research topics and trends. By understanding the current research hotspots and challenges in the technology, it is expected to promote its large-scale practical application and provide effective technical support for solving global environmental pollution problems.

2 Data sources and research methods

2.1 Data source

Web of Science is a globally renowned comprehensive academic information resource database, covering numerous disciplines. The literature it includes has high academic influence and wide representativeness, effectively reflecting the cutting-edge trends and development directions of international academic research. This article conducts a bibliometric analysis using Web of Science as the data source. In the advanced search interface of Web of Science, the search conditions are set as: the subject contains “Micro nano bubble”, “nano bubble”, and “micro bubble”, and on the basis of the above search results, further search for literature with the full text containing “degradation”. The search mode is set to exact match, and the search time range is from the establishment of the database to 1 April 2025. After the search, a total of 509 articles related to the management of hazardous waste in small and micro enterprises were obtained. After duplicate removal using Note Express software, 508 articles were finally obtained for subsequent in-depth analysis. The search scope is set as “subject” (TS): TS = [“Micro nano bubble” or “nano bubble” or “micro bubble” AND TS = (“degradation”)]. The specific screening items are shown in Table 1, excluding irrelevant research topics and directions such as “endocrinology and metabolism” and “agriculture”, while Table 1 presents the final data results.

2.2 Research methods

Compared with traditional bibliometric methods, visualization methods can more intuitively present citation information of literature and its inherent hierarchical structure, facilitating in-depth exploration of interaction relationships in complex networks. This paper, by means of the scientific knowledge mapping method, uses CiteSpace and VOSviewer software to conduct trend analysis of publications, research institutions, scholars, and keyword co-occurrence analysis based on the obtained 508 related literature data, and draw corresponding knowledge maps, thereby comprehensively and intuitively presenting the research situation in this field.

TABLE 1 Article selection situation and outputs.

Filter condition		Language	Document types	Time interval	
		English	Article and review	No requirement—2025.04.01	
Result	Papers	Countries	Institutions	Journals	Author
	508	211	5012	442	9213

TABLE 2 Top 20 authors in the field of MNBs.

Authors	Volume of publications	Citations	Country
Hu Liming	10	245	China
Fan Wei	8	214	China
Ma Xing	7	297	China
Wang Yong	5	279	China
Li Jia	5	87	China
Zheng Chan	5	86	China
Pumera Martin	4	362	Czech Republic
Wang Joseph	4	347	The United States
Sun Hongqi	4	183	China
Wang Shaobin	4	183	China
Moholkar Vijyanand s	4	176	The United States
Huo Mingxin	4	158	China
Zuo Min	4	46	China
Wang Sheng	4	32	China
Duan Yalong	4	28	China
Yu Jiang	4	28	China
Lan Ziwei	4	17	China
Xu Dandan	3	208	China
Villa Katherine	3	208	Czech Republic
Yuan Hao	3	167	China

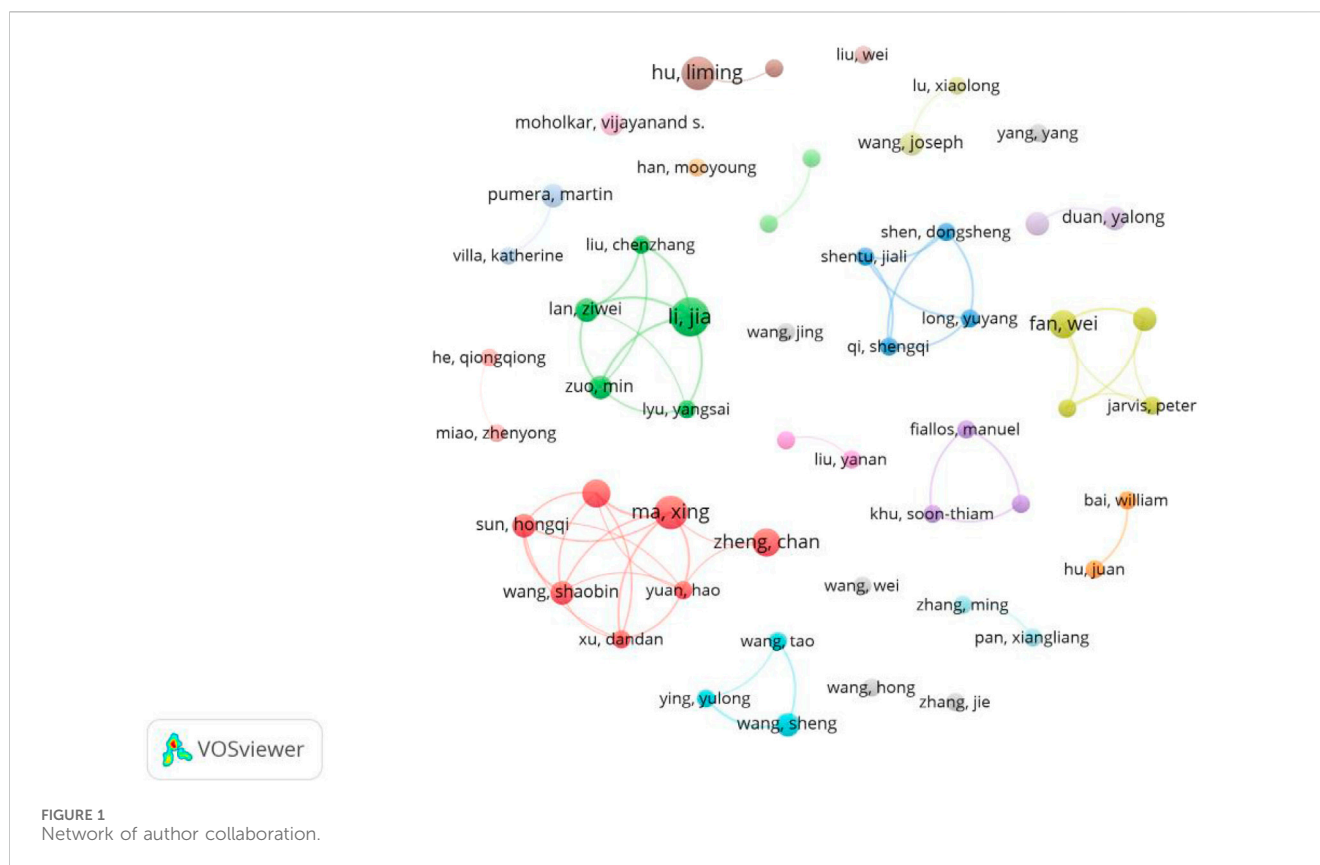
The bolded parts of the numbers indicate the authors with the highest number of published articles or the highest number of citations for their articles.

3 Basic article information architecture

3.1 Author information

Authors and their collaborations within a certain research field are key factors in promoting academic progress and spreading knowledge. Bibliometric analysis can identify authors who have contributed to a specific research field and their collaboration patterns. Table 2 shows the top 20 authors who have published the most papers in photocatalytic oxidation of volatile organic compounds (VOCs). There are 16 authors from China, demonstrating China’s outstanding contributions to this field. Hu Liming from Tsinghua University has published the most papers, with a total of 10. His most influential paper studied the characteristics of ozone MNBs, including their bubble number, size distribution, and zeta potential. The

experiment investigated the ozone MNBs’ mass transfer rate. They used ozone MNBs to deal with water contaminated with organic matter, which showed significant purification efficiency. They also conducted the column tests to research the efficiency of ozone MNBs in the remediation of groundwater contaminated with organic matter. Field monitoring was carried out on a site contaminated with trichloroethylene (TCE). The results indicated that ozone MNBs could significantly enhance the remediation efficiency and are an innovative *in-situ* remediation technology of groundwater contaminated with organic matter (Hu and Xia, 2018). His team mainly focuses on the ozone MNB technology application in groundwater pollution treatment, confirming the groundwater pH influence and salinity on the treatment capacity of the technology (Xia and Hu, 2019; Li et al., 2013). They believe that ozone MNBs have great oxidation capacity and low secondary



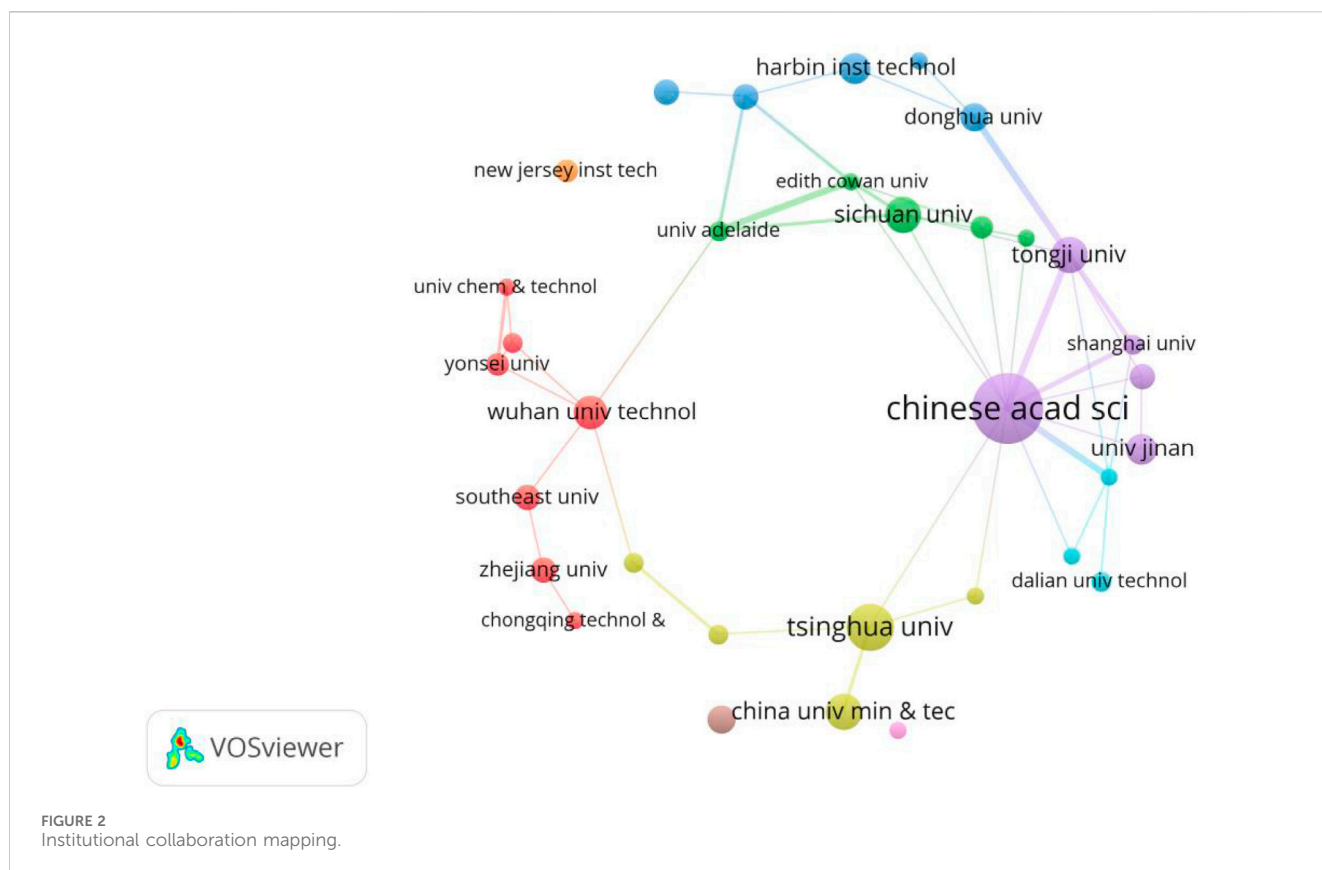
pollution (Cao et al., 2023), and possess the ability to transport and dissolve in porous media (Li et al., 2014), making it a promising *in-situ* remediation technology of groundwater contaminated with organic matter. Fan Wei from Jiangnan University ranks second with eight papers. The representative research direction of this author with the second-highest influence integrates MNB and photocatalytic technology. They found that the MNBs' interfacial photoelectric effect was also proved to be beneficial for pollutant degradation. MNBs guided strong light scattering, increasing 54.8% of the light path length in the photocatalytic medium at 700 nm and strengthening the photocatalyst light adsorption (Fan et al., 2021; Fan et al., 2019).

The author collaboration distribution map can well reflect the cooperation and joint research in environmental industrial pollution treatment using MNB technology (Figure 1). Each node's size in the figure represents the paper number published by the author (the larger node means that the author has published more papers), while the connecting lines represent the authors' collaboration. Figure 1 shows the degree of author collaboration, with several closely collaborating author groups emerging, including the teams of Ma Xing and Zheng Chan, as well as Li Jia and Lan Ziwei. Unlike the author with the highest volume of publications, their main research direction is nanomotors (Ma et al., 2016; Ye et al., 2021; Yang et al., 2023a). The closeness of the connections between different authors is shown in the figure, meaning that the international cooperation intensity in this field still needs to be strengthened. Analyzing the collaboration level among researchers is important because such collaboration not only helps to collect expertise from different disciplines, promoting innovation and progress, but also improves the reliability, quality and efficiency of research

through peer review, knowledge transfer and resource sharing, etc. Moreover, collaboration can promote the scientific research internationalization, help solve complicated interdisciplinary problems, and accelerate the transformation of research outcomes into practical applications, especially in the fields of pollution control and environmental protection.

3.2 Information graphic of the issuing institution

Research institution analysis provides information on the most influential and productive research institutions in a certain research field, which could make scholars well understand the current situation and field trends, and guide how to solve important problems and promote innovation. Figure 2 shows the knowledge domain of collaborative organizations using the software VOSviewer. Every circular node represents an organization and the circle size indicates the published paper number. Inter-institutional collaboration is represented by a line between two nodes, with the thickness of the line indicating the degree of collaboration. The CAS occupies the highest ranking and has published the most papers in Table 3, which has a critical academic influence. In its latest research, it reviewed the benefits of MNB in the cleaning process, then analyzed in depth the factors affecting its cleaning effect and the possible mechanisms involved. Additionally, it summarized the production and application of MNB in various cleaning scenarios and elaborated on its applications in semiconductor cleaning (Takahashi et al., 2015), membrane cleaning (Lee et al., 2015) and metal cleaning (Ulatowski



et al., 2024). In its latest research, it was found that the MNB technology enhanced the vacuum ultraviolet degradation rate by improving the mixing and mass transfer within the solution, optimizing the light performance in the solution, and increasing the dissolved oxygen level (El Aswar et al., 2025). Moreover, as shown in Figure 2, the CAS, Shanghai University, and Tongji University have relatively close cooperative relationships. Their works mainly focus on the application of MNB technology in treating polycyclic aromatic hydrocarbon pollution in groundwater, where the technology can enhance the surfactants transfer and thus improving the degradation capacity (Dai et al., 2023; Han et al., 2025).

3.3 Journal information

Journals in a research field help researchers understand the main academic resources and knowledge dissemination channels. The h-index is a hybrid quantitative indicator which could be used to evaluate the academic output quantity and quality. It was proposed by George Hirsch, a physicist at the University of California, San Diego, in 2005. As it can be seen in Table 4, the analysis of the journals has identified the top ten publications with the highest citation counts in the field of MNB technology for environmental pollution degradation. Chemical Engineering Journal is the journal with the highest number of articles published in this field, with 21 articles, and it is also the publication with the highest citation count, indicating its importance in the field. Next are Separation and Purification Technology and Ultrasonics Sonochemistry, which have published 18 and 13 articles respectively. Additionally,

although ACS Nano has only published seven research papers on MNBs, its citation count ranks second, suggesting that this publication is highly trusted by readers in the field and the articles published in it have significant influence within the field.

The different colored areas in the Figure 3 represent the different research preferences of various publications on the article's research direction. The publications in the red area led by Ultrasonics Sonochemistry mainly focus on the generation mechanism and methods of MNBs. Ultrasonics Sonochemistry mainly uses ultrasound to generate MNBs for water pollution treatment, with two main approaches: activating intermediate substances [such as quantum dots (Entezari and Ghows, 2011), nanomaterials (Bao et al., 2023), etc.] to enhance their oxidation capacity and enhancing the generation of free radicals through sonochemistry (Pétrier et al., 2010), to strengthen the effect of wastewater treatment. The publications in the yellow area led by Separation and purification technology mainly focus on the technology of using MNBs to clean dirt. This journal mainly studies the use of MNB technology to clean filter membranes, solve the problem of membrane fouling, thereby improving the stability of the membrane and enhancing the degradation capacity of water treatment (Duan et al., 2025; Duan et al., 2022; Mo et al., 2024). The publications in the green area led by Acs nano mainly focus on the R&D of water treatment materials and equipment. This journal mainly studies the nanoscale micro-motors application in water pollution treatment (Villa et al., 2018; Zhang et al., 2024; Soler et al., 2013). The publications in the blue area led by Chemical engineering journal have a relatively comprehensive research direction, covering various aspects of MNB technology.

TABLE 3 Top 20 organizations in the field of MNBs.

Organization	Volume of publications	Citations	Country
Chinese Acad Sci	19	649	China
Tsinghua Univ	14	328	China
China Univ Min and Technol	12	195	China
Sichuan Univ	11	132	China
Wuhan Univ Technol	9	305	China
Harbin Inst Technol	9	262	China
UnivJinan	9	121	China
Seoul Natl Univ	9	187	Republic of Korea
Harbin Inst Technol Shenzhen	7	309	China
Tianjin Univ	7	66	China
Zhejiang Univ	7	285	China
Beijing Univ Chem Technol	7	192	China
Univ Adelaide	6	402	Australia
Chongqing Technol and Business Univ	6	72	China
Xi'an Jiao Tong Univ	5	221	China
Univ Calif San Diego	5	390	The United States
Northeast Normal Univ	5	214	China
Edith Cowan Univ	4	183	Australia
Jiangsu Univ	4	116	China
Nanjing Tech Univ	4	162	China

TABLE 4 Top 10 most co-cited papers in the field of MNBs.

Source journal	Volume of publications	Citations	IF ^①	CPP ^②
Chemical Engineering Journal	21	896	13.4	43
ACS Nano	7	834	15.8	120
Ultrasonics Sonochemistry	13	585	8.7	45
Separation and Purification Technology	18	516	8.1	29
Journal of Hazardous Materials	9	476	12.2	53
Water Research	12	311	11.4	26
ACS Applied Materials and Interfaces	6	278	8.3	47
Nano Energy	4	269	16.8	68
Chemosphere	7	264	8.8	38
Small	4	250	13.3	63

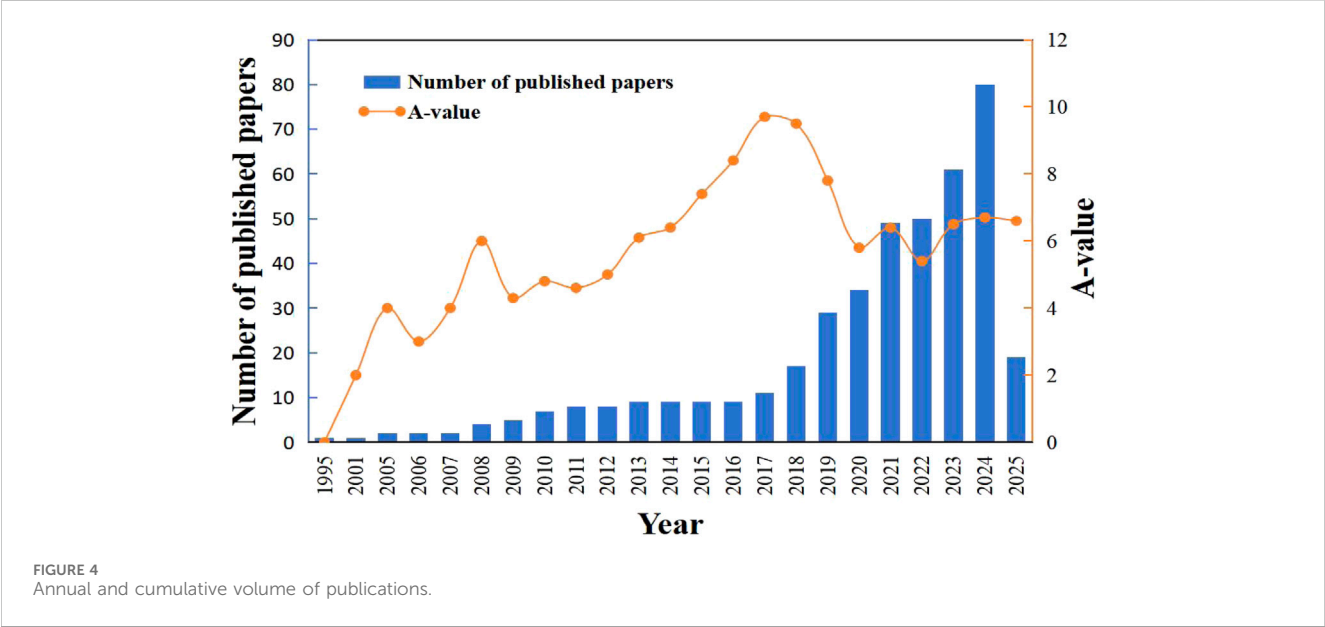
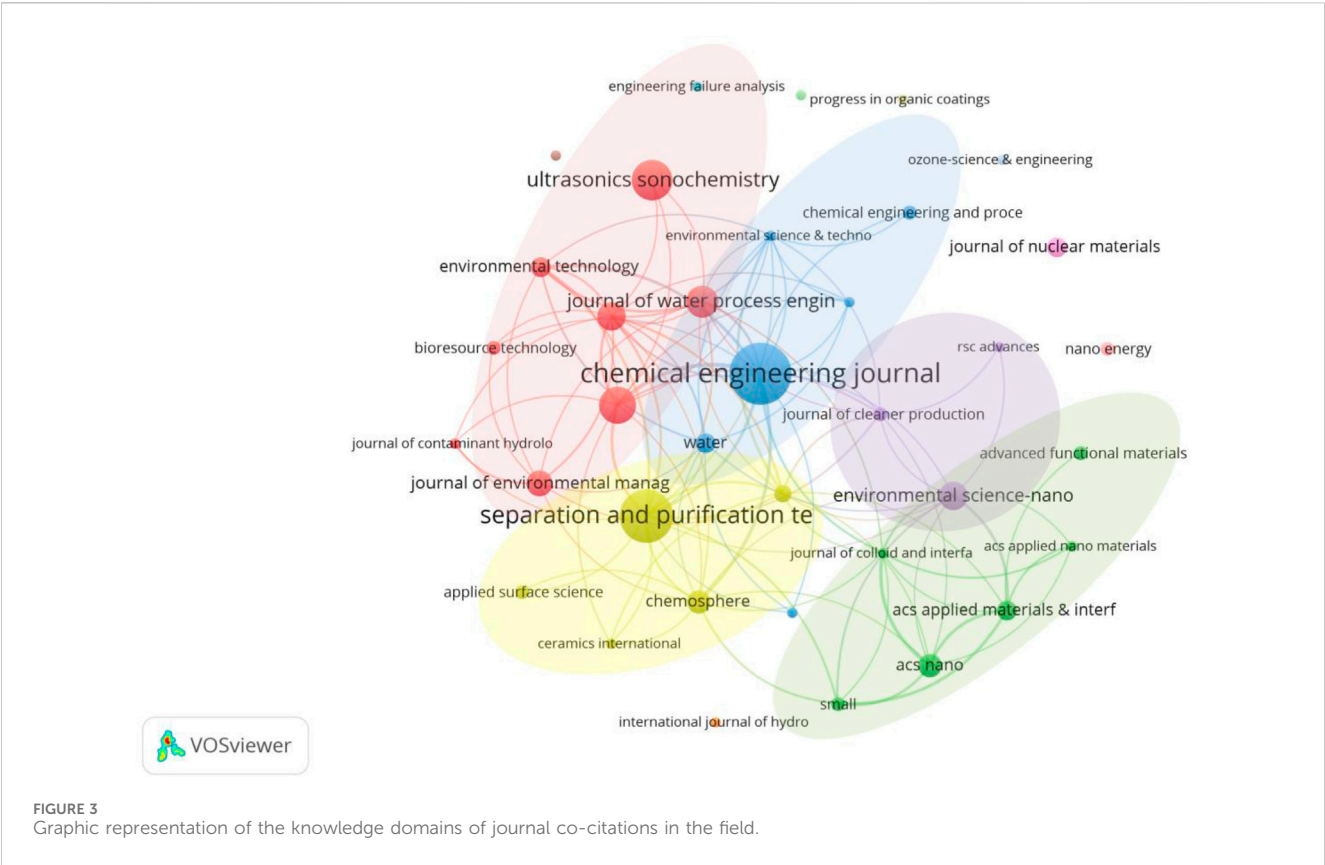
① 2024 impact factor; ② Citations per paper (the number of citations per paper on average).

4 The development of MNB technology

4.1 Trend of annual publications

By conducting a statistical analysis of the published paper number from 1995 to 2025, the status, maturity and development

trend of MNB technology research achievements can be clearly shown. Figure 4 presents the research result distribution on MNB technology in environmental treatment based on the time series. From 1995 to 2007, less than five articles on MNB technology were published each year. From 2008 to 2017, this field showed a overall slow growth trend, and the annual publication volume in this field



exceeded 10 for the first time in 2017. After that, research related to MNB technology gradually became a hot topic, which is inseparable from the pollution control and environmental protection policies of many countries as well as major technological breakthroughs. From 2017 to 2024, the published paper number increased significantly, with an annual publication volume of over 50 for five consecutive

years, and the publication volume reached 80 in 2024. As of 2025, 508 papers have been published in VOCs photocatalytic oxidation research. The continuous increase in the number of papers in this field indicates that researchers have paid more attention to the application of MNB technology in environmental pollution degradation.



From 2009 to 2018, it was the development period of MNB technology. Tasaki et al. studied the degradation effect of MNBs under ultraviolet (UV) irradiation on methyl orange, exploring the water treatment technology of light-MNB synergy (Utaka et al., 2009). In 2011, the first review on the application of MNB technology in water treatment was conducted, systematically summarizing the application achievements and prospects of this technology in water treatment at that time. In 2016, Agarwal et al. reviewed the history of MNBs, retrospectively summarizing its development trajectory from a more macroscopic perspective (Agarwal et al., 2016).

after 2018, due to its excellent mass transfer ability and the ability to produce active oxidative species, MNB technology was coupled with different environmental pollution degradation technologies and applied in multiple fields. There were studies on the degradation of aniline using non-thermal plasma/MNBs, further enriching the technical means of MNBs in the treatment of refractory organic pollutants. In 2019, Fenton/MNBs were used for dye separation and microplasma bubbles for inactivating microorganisms, exploring new directions for the combination of MNBs with other technologies. MNBs were used to enhance the degradation of oxytetracycline under visible light, broadening the application scope of MNBs in the field of photocatalytic degradation. In 2021, it was found that MNBs could promote the photocatalytic disinfection of microbial spores, and the stability of oxygen-containing MNBs in fresh water was confirmed, providing new evidence for their application in the disinfection field. In 2022, the exploration of ultraviolet C (UV-C)/hydrogen peroxide (H_2O_2)/MNBs as a new disinfection technology further explored the potential of MNBs in disinfection technology innovation.

From 2023 to 2025, the development of MNB technology has been rapid, and research has delved deeper. The focus of research on the applicability of MNB technology has mainly been on exploring the coupling effect of MNBs with other technologies. In previous studies, it was found that MNBs can effectively enhance gas mass transfer and the production of active species. Scholars have thus focused on the coupling effect between MNBs and various oxidants, using the strong oxidation effect of MNBs to activate different oxidants (such as persulfate, ferrous ions, and nano zero-valent iron) and treat complex pollutants in different media, continuously expanding the application scope of MNB technology. Jing et al. utilized MNBs to enhance the immobilized *Chlorella* technology. Thanks to the excellent mass

TABLE 5 Research on MNB technology in various application scenarios over the past 2 years.

Types of MNBs	Coupling technology	Target pollutants	Treatment effect	The main active species	References
Air	Advanced oxidation; Thermal-activated persulfate	Rhodamine B	Removal rate: 94.53%	$\cdot\text{OH}$, $\text{SO}_4^{\cdot-}$	Yang et al. (2023b)
Air	Advanced oxidation; Fe(II) and persulfate	Atrazine and its membrane fouling	Effectively reduce by 72%	$\cdot\text{OH}$, $\text{SO}_4^{\cdot-}$, $^1\text{O}_2$	Zhang et al. (2025)
Air	Advanced oxidation; Ferrous oxalate complex	4,4'-Sulfonyldiphenol (BPS)	The removal efficiency of BPS is increased by approximately 35%		Li et al. (2025a)
Air	Advanced oxidation; Persulfate	Printing and dyeing wastewater	The water quality meets the discharge standards		Yang et al. (2023c)
Air	Advanced oxidation; Sodium hypochlorite	Norfloxacin	The water quality meets the discharge standards		Li et al. (2024)
Air	Advanced oxidation; Cobalt-iron catalyst and persulfate	Tetracycline	The degradation efficiency is 95.63%	$\cdot\text{OH}$, $\text{SO}_4^{\cdot-}$, $^1\text{O}_2$	Ye et al. (2025)
Air	Vacuum ultraviolet photocatalysis	Sulfamethazine	The degradation rate increased by two times after the addition of MNBs	$\cdot\text{OH}$	El Aswar et al. (2025)
Air	photocatalysis; AC/TiO2	Indigo carmine, reactive black 5 and methylene blue	The degradation rates were 69.09%, 60.06% and 55.19% respectively		Boonwan et al. (2024)
Ozone	Advanced oxidation	Sulfadiazine	The reaction rate constant is 5.5 times that of conventional oxidation technology	$\cdot\text{OH}$, $\cdot\text{O}_2^{\cdot-}$	Liu et al. (2025)
Ozone	Advanced oxidation; H_2O_2	Ibuprofen	Except for an efficiency of 94.75%	$\cdot\text{OH}$	Li et al. (2025b)
Ozone	Advanced oxidation	2-Methylisoborneol and geosmin	Within 15 min, 94.38% of 2-MIB and 95.45% of GSM were removed	$\cdot\text{O}_2^{\cdot-}$	Ren et al. (2025)
Ozone	Advanced oxidation	Tetracycline	Degradation efficiency: 85%	Reactive oxygen species (ROS)	Zhao et al. (2024b)
Ozone	Micro-nano cavitation technology	Gaseous acetate ester	155.544 mg/m ³ degraded within 21.961 min	High temperature and high pressure caused by cavitation collapse	Wang et al. (2024b)

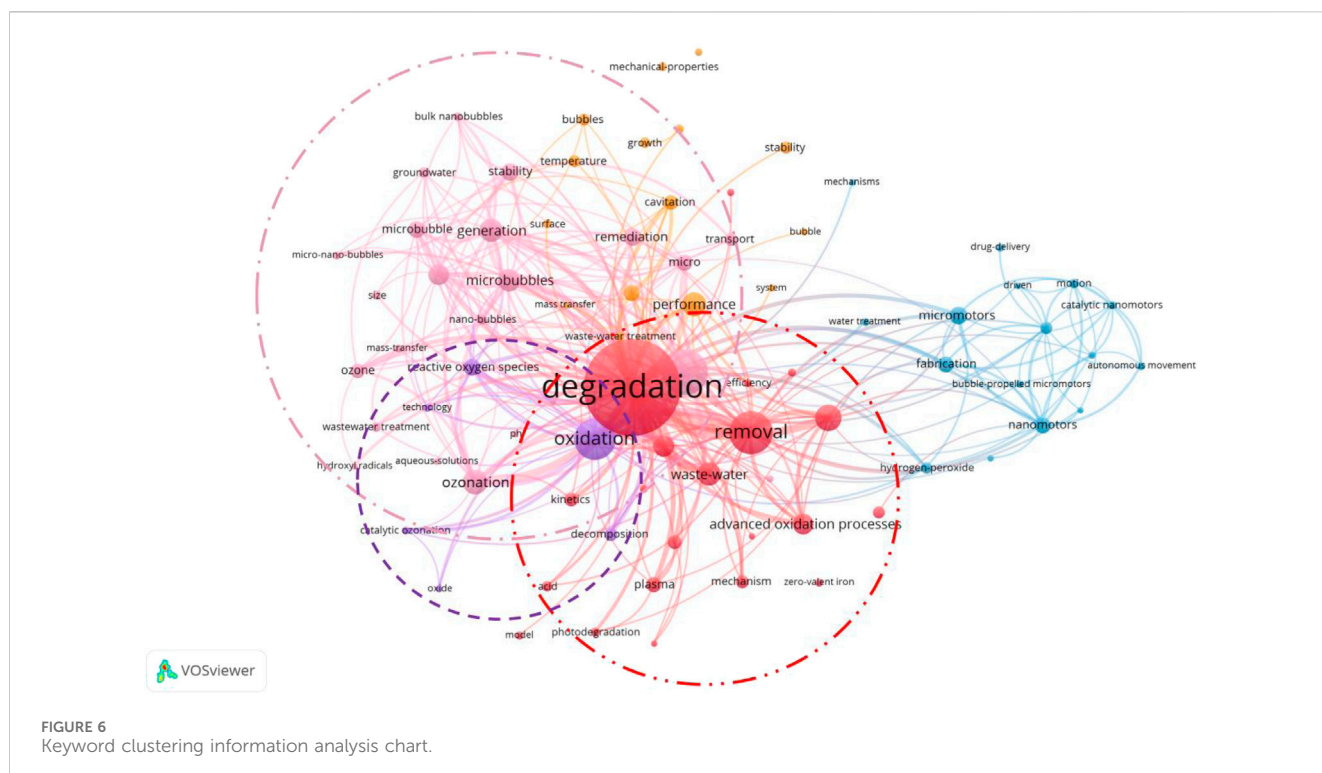
transfer capacity of MNBs, the biomass of *Chlorella* increased by 2.48 times, significantly improving the removal efficiency of ofloxacin (Jing et al., 2025). Chi et al. studied the degradation of tetracycline, a commonly used antibiotic in wastewater, using a system based on zero-valent nano-iron assisted by MNBs. MNBs can serve as an ideal carrier for zero-valent nano-iron. When they burst, they generate shock waves and highly reactive substances (such as $\bullet\text{OH}$), which can significantly enhance the degradation efficiency (Chi et al., 2024). Table 5 presents a portion of the relevant research on MNB technology in various application scenarios over the past 2 years.

Meanwhile, due to the mature development of ozone MNB technology, in recent studies, scholars no longer confine their research to the laboratory and have conducted many practical application studies, mainly exploring the influence of factors such as air intake rate, air intake volume, and pollutant concentration (Hu et al., 2023; Zhao et al., 2024a). Ponce-Robles et al. actively promoted the practical application of MNB technology. By adjusting the size of ozone MNBs, the air intake volume, and the air intake rate, they conducted experiments in large-scale pharmaceutical wastewater. They replaced the traditional tertiary sewage treatment equipment with ozone MNB technology, which enhanced the treatment capacity and reduced costs (Ponce-Robles et al., 2023).

5 Analysis of hotspots in MNB technology

5.1 Keyword clustering analysis

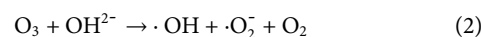
In the keyword spectrum diagram, VOSviewer has classified the keywords. Co-occurrence analysis of keywords helps to understand the basic themes and concepts in the literature or dataset. It assists researchers in positioning their research, decision-making, and collaboration to achieve a more comprehensive understanding of the challenges and opportunities in a specific field or topic. As shown in Figure 6, the keywords in the MNB field are divided into five categories. The three main categories are the red area led by “degradation”, which mainly focuses on the application of MNB technology to assist other different treatment technologies, such as non-thermal plasma bubbles, advanced oxidation, photocatalysis, etc., and ultimately focuses on the degradation effect of pollutants. The second category is the pink area, mainly summarizing the development of ozone MNB technology. The combination of ozone and MNB technology is the most developed technology. Between these two areas is the purple area, mainly summarizing the core keywords of MNB technology, “oxides” and “reactive oxygen species”. Next, we will further analyze the three key categories.



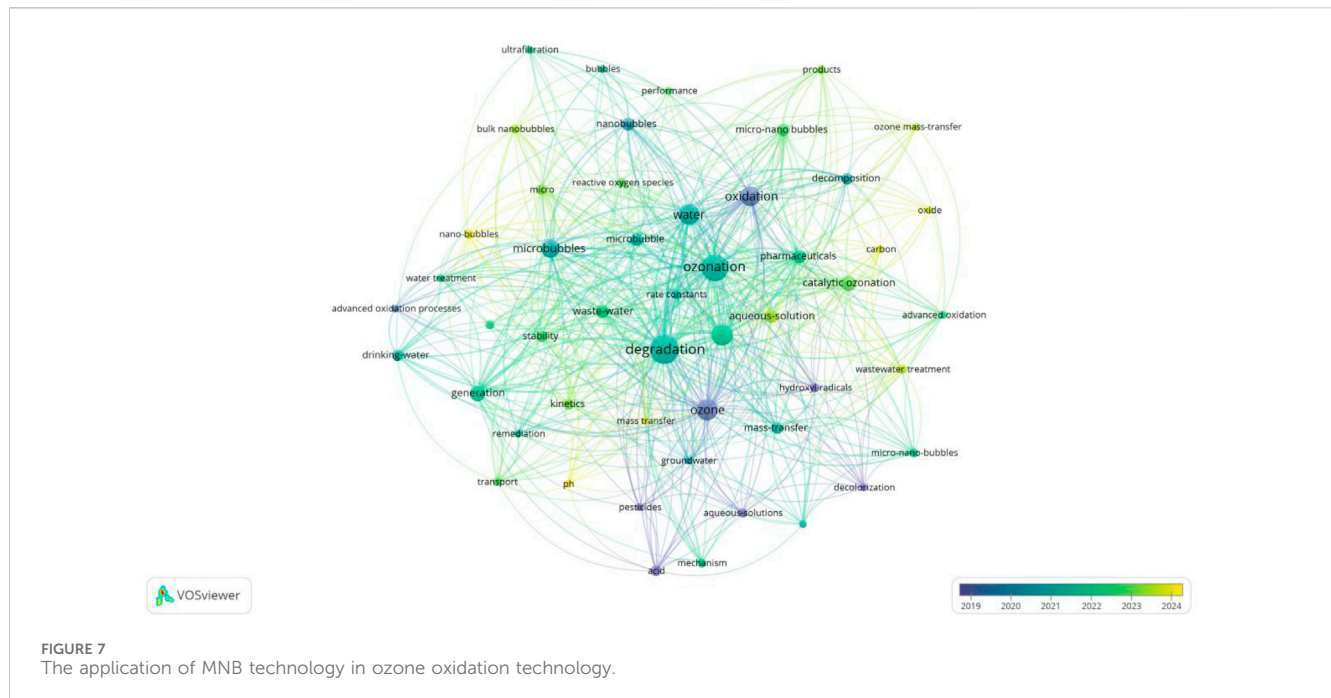
5.2 The principle of MNB technology

First, let's discuss the purple area section (Figure 6), which outlines the core principle of MNB technology. Now, two representative views explain the generation of reactive oxygen species (ROS) during MNB oxidation: one is the view of interface ion accumulation during the MNB contraction process (Takahashi et al., 2007a; Yang et al., 2023d). As MNBs contract, the surface Zeta potential increases with the increase in the contraction rate, which is inversely proportional to the bubble size. This indicates that the surface charge migration rate is insufficient to counteract the increase in the MNB contraction rate, leading to the accumulation of charges at the gas-liquid interface and the formation of a high chemical potential (Takahashi et al., 2015). According to this theory, under a wide range of pH conditions, MNBs carry a negative charge. Therefore, during the bubble contraction process, OH^- is more easily adsorbed onto the bubble surface than H^+ , resulting in an interface environment with high ion concentration and a double-layer structure (Takahashi et al., 2007b). When ozone gas diffuses and dissolves into the liquid phase within MNBs, the high concentration of OH^- at the interface triggers the ozone self-decomposition chain reaction, leading to the generation of $\cdot\text{OH}$ (Cheng et al., 2018; Khuntia et al., 2012; Cheng et al., 2019). This theory is applicable to ozone MNBs. Since ozone itself is a highly reactive oxidizing species, when ozone gas diffuses and dissolves into the liquid phase within MBs, the high concentration of OH^- at the interface triggers the ozone self-decomposition chain reaction, leading to the generation of $\cdot\text{OH}$ (Cheng et al., 2018; Khuntia et al., 2012; Cheng et al., 2019). During the accumulation of air and oxygen MNBs at the bubble interface, the reaction between oxygen and OH^- is slow and inefficient, and thus cannot generate a large amount of reactive oxygen free radicals.

Zhao et al. revealed the main free radicals produced and the pathways of ozone generating free radicals (Equations 1–4) when using ozone MNB technology to treat tetracycline wastewater, verifying the working mechanism of ozone MNBs (Zhao et al., 2024b).



The other view is the adiabatic compression during the MNB collapse process (Shi et al., 2021; Yasui et al., 2016; Zhou et al., 2020). As MNBs contract, the reduction in volume increases the internal gas pressure. Before reaching the critical collapse state, MNBs typically withstand an internal pressure of 0.83–1.65 MPa, which is over 50 times the atmospheric pressure (Yasui et al., 2019). At this point, ozone molecules remain in a dense state, colliding more frequently in a smaller space, resulting in a higher energy state. Simultaneously, the MNB wall contraction speed reaches 90 m/s, raising the critical temperature inside the bubble to 3,000 K and the temperature of the liquid near the bubble to 360 K. Although these extreme conditions of high temperature and pressure only last for approximately 19 picoseconds, a quasi-adiabatic compression effect is formed at the MNB interface, which is sufficient to trigger the thermal decomposition of gas molecules, thereby leading to the generation of free radicals. The applicability of this theory is not only limited to ozone MNBs, but also applies to MNBs composed of oxygen and air. Although the free radical yield of oxygen is far less than that of ozone, with the support of adiabatic compression theory, it can be coupled with different types of other technologies (such as advanced oxidation, photocatalysis, etc.) to



enhance the oxidation capacity and assist other water treatment technologies. Considering the cost, oxygen MNBs are cheaper than ozone MNBs and more suitable for coupling with other technologies. Li et al. found in the experiment of using divalent iron to catalyze the treatment of 4,4'-sulfonyl diphenol (BPS) that the degradation efficiency of pollutants increased by 35% after the addition of MNBs for co-treatment (Li et al., 2025a). El Aswad et al. utilized MNBs to assist in the ultraviolet photocatalytic degradation of sulfamethazine in water, doubling the degradation efficiency (El Aswad et al., 2025). During the treatment process, the presence of hydroxyl radicals was detected using pCBA, CCl_4 , and MDE probe compounds to identify $\bullet\text{OH}$, $\bullet\text{O}_2^-$, and $^1\text{O}_2$ respectively. The discovery of hydroxyl radicals indicates that the energy and free radicals generated during the collapse of MNBs are conducive to the oxidative degradation of water pollution. This inexpensive and simple bubble technology is expected to become an auxiliary means to enhance existing environmental pollution treatment technologies and engineering.

5.3 Ozone MNB technology

5.3.1 The principle of ozone MNB technology

The pink area (Figure 6) mainly focuses on the research of ozone MNB technology. By adding ozone as a search term and connecting it with “and” in the search formula, the keyword distribution map as shown in Figure 7 is obtained. The appearance of “Oxide” in the figure indicates that ozone is a strong oxidant with a high oxidation-reduction potential of 2.07 V, which can rapidly oxidize various organic and inorganic pollutants and convert them into harmless or low-harm substances. However, in traditional ozone water treatment technology, due to the low solubility of ozone in water and its easy decomposition, its utilization rate is not high ($\leq 10 \text{ mg L}^{-1}$).

5.3.2 Control factors of ozone MNB technology

The characteristics of ozone microbubbles (MBs), such as small size and long residence time, can promote the decomposition of ozone and gas-liquid mass transfer, thereby enhancing the removal effect of refractory organic compounds. Therefore, any parameters that affect the characteristics of MBs, such as bubble size, stability, mass transfer efficiency, and interfacial environment, will indirectly affect the treatment efficiency.

First, within a certain temperature range, the influence of temperature on the removal rate of pollutants is not significant. In the experiments of phenol and TOC removal, the temperature change has a negligible effect on the degradation rate, as the positive

and negative effects cancel each other out (Cheng et al., 2021; Mohite and Garg, 2017). Rising temperature will reduce the solubility of ozone in water, accelerate the escape of ozone, and lower the gas-liquid mass transfer rate. At the same time, it will decrease the mechanical strength of the bubble walls of MBs, making them more prone to rupture and accelerating the release of ozone. The temperature increase will significantly enhance the ozone oxidation rate (in line with the Van't Hoff equation, for every 10 °C increase in temperature, the reaction rate approximately doubles). Therefore, the optimal temperature should be determined based on the actual situation.

The influence of gas-liquid ratio on MNBs shows a phased pattern. Increasing the gas-liquid ratio enhances the air flow rate and the number of MBs, strengthens gas-liquid mass transfer, raises the dissolved ozone concentration, accelerates the oxidation process, and significantly boosts the degradation rate in the PhOH degradation experiment. When the gas flow rate exceeds the critical point, the increase in degradation rate and mass transfer efficiency slows down as the mass transfer flux has exceeded the reaction demand. Excessively high gas-liquid ratios may also lead to an increase in bubble size and a decrease in specific surface area, which in turn reduces mass transfer efficiency. The ozone MBs process can enhance mass transfer efficiency through small bubbles and long residence time at a low gas-liquid ratio. Therefore, in practical applications, the gas-liquid ratio and bubble size need to be optimized to maximize the effect.

Surface tension mainly affects the size and stability of MBs. The lower the surface tension of the solution, the easier it is to generate small-diameter MBs. The average diameter of MBs generated by sodium dodecyl sulfate (SDS) with a surface tension of 29.5 mN/m is 13.3 μm , which is significantly smaller than that in high surface tension systems, and small bubbles are usually beneficial for mass transfer (Melich et al., 2019). Surfactants can slow down the contraction, coalescence and rupture of bubbles, prolong the lifespan of MBs and enhance the stability of the interface, but they may reduce the mass transfer rate at the gas-liquid interface.

Finally, pH significantly alters the removal efficiency by influencing ozone decomposition, free radical generation, and the ionization state of organic compounds. A high pH promotes the self-decomposition of ozone and accelerates the generation of $\cdot\text{OH}$ radicals, thereby enhancing the degradation rate of refractory organic compounds. The degradation rate constant of PhOH at pH 11 is 2.7 times that at pH 3 (Lim et al., 2022).

5.3.3 The application of ozone MNB technology

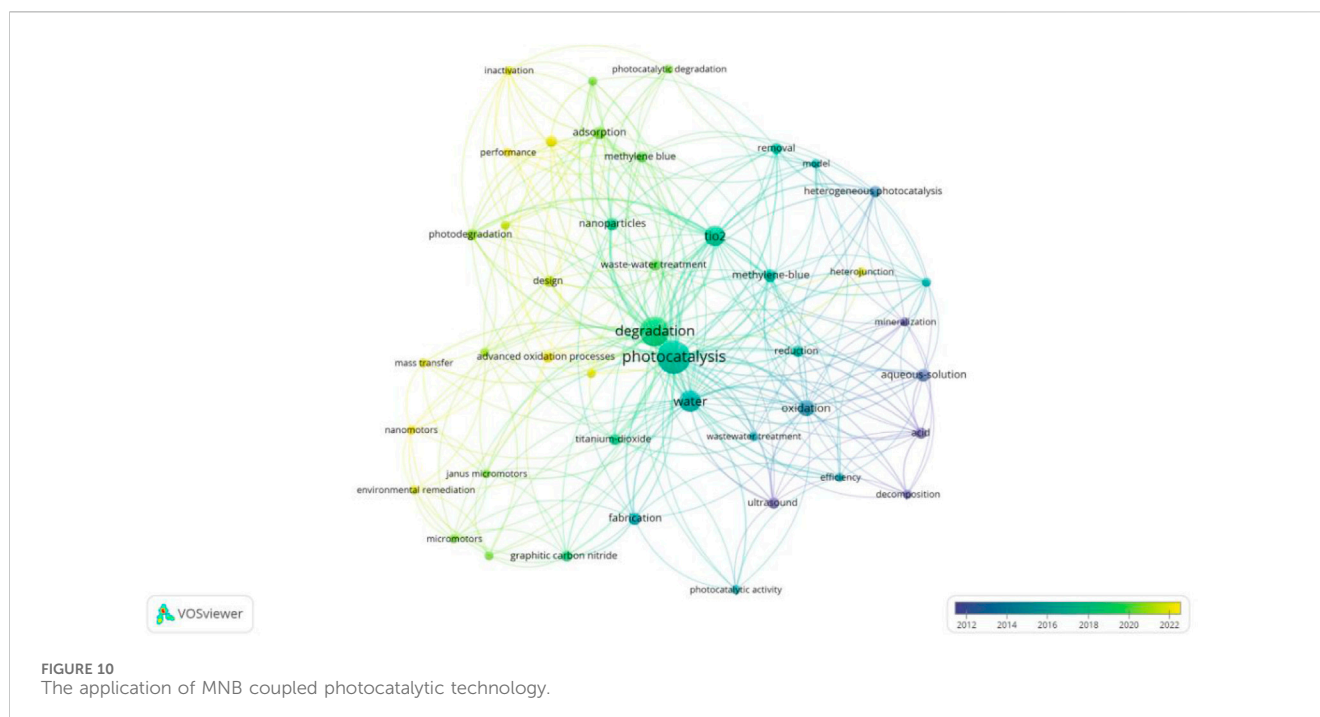
Ozone MNB technology has unique advantages in water treatment, being capable of removing organic pollutants in water and inhibiting the growth of microorganisms, ensuring the chemical and biological safety of drinking water. This technology oxidizes organic pollutants through the generation of $\cdot\text{OH}$, converting them into harmless substances, while also destroying the cell structure of microorganisms to achieve disinfection and sterilization. Compared with traditional drinking water treatment technologies, ozone MNB technology is green and clean, does not cause secondary pollution, and meets the strict requirements of drinking water treatment, providing a reliable technical means for ensuring drinking water safety. Studies have found that ozone MNB technology shows significant advantages in treating antibiotic wastewater. At an

ozone concentration of 8 mg/L, it can completely degrade 100 mg/L of tetracycline within 20 min (Koundle et al., 2024). The degradation process not only relies on the direct oxidation effect of ozone but also benefits from the large amount of hydroxyl radicals ($\cdot\text{OH}$) generated when MNBs burst. $\cdot\text{OH}$ has extremely strong oxidation ability and can rapidly oxidize tetracycline molecules, converting them into harmless substances. In the treatment of wastewater containing aromatic hydrocarbons, ozone MNB technology also performs well. According to research, compared with ordinary ozonated water, ozone MNB water increases the oxidation rate of aromatic hydrocarbons such as toluene, ethylbenzene, o-xylene, and p-xylene by 13.6%–22.6% (Shen et al., 2023). This is mainly because the interface effect of MNBs promotes the contact between aromatic hydrocarbons and $\cdot\text{OH}$, making the oxidation reaction easier to proceed. Studies have shown that ozone MNB technology can effectively penetrate low-permeability aquifers and oxidize and degrade organic pollutants in them (Shen et al., 2024). In the remediation of low-permeability aquifers contaminated by toluene, the removal rate of toluene is significantly improved by injecting encapsulated ozone MNB water (EOMBW).

Ozone MNB technology can also be applied to the treatment of organic petroleum pollution in soil. The micro-nano bubble oxidation process features short duration, low cost and high efficiency. It can enhance the effectiveness of surfactants and additives, providing a practical solution for the efficient remediation of petroleum pollution. MNBs can increase the negative zeta potential on the surface of soil particles, thereby enhancing the electrostatic repulsion between oil droplets and soil particles and weakening their adsorption, making it easier for oil droplets to detach from the soil surface. MNBs (such as 1 μm bubbles) can withstand extremely high pressure (about 390 kPa, four times the atmospheric pressure), and their collapse will generate intense pressure waves and micro-jets. This local impact force can directly act on the surface of soil particles such as sand grains, physically stripping off the adhered oil films or oil droplets. The small size characteristics of MNBs (large specific surface area and long residence time in the liquid phase) can significantly increase the collision probability with oil droplets and enhance the adhesion between particles and bubbles, enabling more oil droplets to be carried by bubbles and detached from the soil matrix. Finally, MNBs can capture dispersed oil stains and carry them to the soil surface or treatment system through buoyancy, facilitating subsequent separation and removal. Huang et al. utilized the saponin and cyclodextrin + MNBs enhanced system to degrade diesel in soil. The enhancement of MNBs increased the sand erosion diesel removal rate by more than 20% (Huang et al., 2021). Sun et al. utilized ozone MNB technology to degrade TPH in petroleum waste sludge, achieving a removal rate of 71.7%–79.5% (Sun et al., 2020b).

5.3.4 The application of ozone MNB technology

Ozone micro-nano bubble (MBs) technology has demonstrated high efficiency in oxidation and environmental friendliness in wastewater treatment, but it still has significant shortcomings. Technically, the generation devices of MBs are difficult to achieve uniform and controllable bubble sizes, making it hard to clearly distinguish the characteristics and degradation patterns of MBs of



gap energy, electrons are excited from the valence band to the conduction band, leaving holes in the valence band, thereby generating electron-hole pairs with strong oxidation capacity (Fu et al., 2019). These electron-hole pairs can react with substances such as water and oxygen adsorbed on the catalyst surface, generating ROS such as hydroxyl radicals ($\cdot\text{OH}$), superoxide anions, etc.) (Liu et al., 2020; Weng et al., 2019). These reactive oxygen species have extremely high redox potentials and can oxidize and decompose various organic pollutants into harmless small molecules such as CO_2 and H_2O , achieving the degradation and mineralization of pollutants. However, photocatalytic technology still faces some challenges in practical applications. For example, photogenerated carriers (electrons and holes) are prone to recombination, reducing their efficiency in participating in photocatalytic reactions; the adsorption capacity of photocatalysts for pollutants is limited, and their dispersion in the reaction system is poor, affecting the rate and effect of photocatalytic reactions (Hao et al., 2021).

Coupling photocatalytic technology with MNB technology can achieve complementary advantages. The key to the combined application of photocatalytic technology and micro-nano bubble technology is demonstrated in Figure 10. On the one hand, MNBs can provide abundant oxygen for photocatalytic reactions, promote the separation of photogenerated carriers, and reduce the recombination of electron-hole pairs, thereby improving the efficiency of photocatalytic reactions (Agarwal et al., 2011; Dong et al., 2022). On the other hand, the reactive species generated by photocatalysis can synergize with the reactive species produced by the rupture of MNBs to enhance the oxidation and degradation of pollutants. Additionally, the presence of MNBs can improve the dispersion of photocatalysts in the solution, increase the contact opportunities between photocatalysts and pollutants, and further enhance the degradation effect.

In water pollution control, this coupled technology has shown significant advantages. Studies have shown that this technology has high efficiency in degrading various organic pollutants, such as dyes, antibiotics, and pesticides. When treating wastewater containing methylene blue, the photocatalytic and MNB coupled system can achieve efficient decolorization and mineralization of methylene blue in a relatively short time (Yang et al., 2022). MNBs not only increase the dissolved oxygen content in the system, promoting the progress of photocatalytic reactions, but also directly participate in the degradation of pollutants through the reactive species produced by their own rupture. At the same time, the reactive oxygen species generated by photocatalysis can also synergize with MNBs to improve the degradation efficiency (Selihin and Tay, 2022). In the treatment of wastewater containing bacteria, this coupled technology has a good inactivation effect on microorganisms. By destroying the cell structure of bacteria through various reactive oxygen species, they lose their activity, thereby achieving disinfection and purification of water bodies (Fan et al., 2021).

In the field of air pollution control, the coupled technology of photocatalysis and MNBs also has potential application value. For the degradation of VOCs, MNBs can carry oxygen and other oxidants, increasing the contact opportunities between VOCs and oxidants. Under light conditions, photocatalytic reactions generate a large number of reactive species, oxidizing and decomposing VOCs into harmless substances.

5.4.4 The advantages and prospects of the combined application of MNB technology

At present, the combination of MBs with various environmental treatment technologies is the most suitable development direction for MNB technology. The standalone MNB technology cannot generate sufficient active free radicals to degrade most pollutants

in the environment. Although the ozone MNB technology is relatively mature, due to the uncertainty of control factors such as bubble existence form, stability, and size, as well as the lack of large-scale experimental data for complex polluted environments, the single MNB technology cannot be put into practical large-scale use yet. However, as an auxiliary technology coupled with other mature environmental treatment technologies, it benefits from its excellent free radical generation capacity and mass transfer efficiency, providing a better oxidation environment and enhancing the efficiency of other treatment technologies in degrading pollutants. It is a relatively practical auxiliary treatment technology. Especially, the combination of MBs with various advanced oxidation methods or photocatalytic methods has attracted increasing attention. This technology overcomes the limitations of ozone mass transfer utilization, effectively improving the oxidation efficiency of ozone. The presence of MBs keeps the catalyst particles in a dynamic dispersed state, effectively increasing the contact frequency between the catalyst and refractory organic compounds, significantly enhancing the mineralization efficiency of refractory organic compounds, and achieving efficient wastewater treatment.

6 Conclusion

MNB technology, with its unique physicochemical properties (such as large specific surface area, high surface Zeta potential, long stability and strong ability to generate oxidative free radicals), has demonstrated significant advantages in water pollution control (industrial wastewater, surface water, groundwater) and soil pollution remediation, and has become a research hotspot in the environmental field. By coupling with technologies such as ozone oxidation, photocatalysis, Fenton reaction and plasma technology, its pollutant degradation efficiency is significantly enhanced. For instance, the removal rate of plastic pollutants in industrial wastewater by ozone MNBs reaches 94.18%, and when combined with photocatalysis, it can increase the light absorption efficiency at a 700 nm light path by 54.8%.

China holds a dominant position in research in this field. Institutions such as Tsinghua University and the CAS have achieved remarkable results in applications such as groundwater remediation with ozone MNBs and semiconductor cleaning. However, the international cooperation network still needs to be strengthened. Keyword clustering analysis indicates that “degradation”, “ozone MNBs”, “free radicals”, and “photocatalysis” are the core research themes, and the coupling mechanism of technologies and interface reaction theory are the current exploration focuses.

However, the long-term stability of MNB technology in complex environments, the energy consumption and cost issues in large-scale applications, as well as the cross-disciplinary collaborative mechanisms (such as the interaction between microorganisms and bubbles) still require further research. In the future, efforts should be focused on technological optimization and adaptation to actual scenarios to promote its transformation from laboratory research to

industrial applications, providing efficient solutions for global environmental pollution control.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

QC: Formal Analysis, Writing – original draft, Conceptualization, Investigation, Data curation. XZ: Formal Analysis, Writing – original draft, Methodology, Data curation. YG: Project administration, Validation, Supervision, Writing – review and editing, Funding acquisition. QZ: Funding acquisition, Writing – review and editing, Project administration.

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Conflict of interest

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