Vol. 18(5), pp. 110-120, May 2024
DOI: 10.5897/AJEST2024.3268
Article Number: C38407E72117
ISSN: 1996-0786

http://www.academicjournals.org/AJEST

ACADEMIC JOURNALS
expand your knowledge

African Journal of Environmental Science and Technology

Full Length Research Paper

Micro and nanobubbles aided membrane processes

Nachael Mwanga[1,2]*, Li Pan[1,2], Salum Kamota[2] and Chanuka Maheshani[3]

[1]State Key Laboratory of Pollution Control and Resource Reuse, College of Environmental Science and Engineering, Tongji University, Shanghai, 200092, PR China.
[2]College of Environmental Science and Engineering, Tongji University, Shanghai, 200092, PR China.
[3]UNEP-Institute of Environment and Sustainable Development (IESD), Tongji University, 1239 Siping Road, Shanghai, 200092, China.

Received 24 February, 2024 Accepted 17, April 2024

The efficacy of micro and nanobubbles (MNBs) in membrane processes, particularly in the realms of cleaning and foul control, has been previously established. However, a comprehensive review of the distinctive attributes and mechanisms that render MNBs effective in these tasks remains unclear, hindering their optimization for enhanced performance and widespread application across membrane types. This critical review seeks to bridge this gap by presenting a meticulous analysis of the traits and effects induced by micro and nanobubbles on membranes by synthesizing the latest research advancements in membrane processes during water treatment. We began by systematically outlining the relevant characteristics of MNBs in water treatment. Then, we delved into the mechanisms through which micro and nanobubbles contribute to foul control and cleaning processes. Finally, we identified future research directions and opportunities. This review anticipates that the fundamental insights provided will contribute to a deeper understanding of the mechanisms of MNBs in membrane processes. Additionally, it aims to offer critical guidance for the development of MNBs-based technologies for water treatment.

Key words: Filtration techniques, micro and nanobubbles, membrane cleaning, fouling control.

INTRODUCTION

In recent years, membrane separation technology has gained widespread popularity in the field of water treatment. Various membrane treatment techniques, such as Nanofiltration (NF), ultrafiltration (UF), microfiltration, and reverse osmosis (RO) play a vital role in water treatment, however fouling remains a significant challenge in all membrane filtration techniques (Yiantsios et al., 2005; Yuan, 2019). Fouling not only reduces filtration efficiency and escalates power consumption, but also results in enduring membrane damage necessitating frequent and costly replacements. To combat membrane fouling during water treatment, a comprehensive approach involves physical methods like backwashing and air scouring, chemical techniques involve using cleaning agents, antiscalants, and disinfectants, as well as membrane modifications such as surface coatings to improve hydrophobicity and adjustments to pore size (Park et al., 2019; Shan et al., 2020). Operational strategies like flux rate optimization, periodic back pulsing, and pre-treatment are also used in fouling prevention (Katsoufidou et al., 2005; Stoller, 2011). Traditional methods for controlling membrane fouling and

*Corresponding author. E-mail: nachaelimwanga@gmail.com. Tel: +255683139810.

cleaning fouled membranes face challenges such as reduced cleaning efficiency, longer process downtime, and environmental impact (Chen et al., 2003). These limitations have prompted the exploration of alternative approaches, sparking significant interest in micro and nanobubbles (MNBs) as a promising solution. MNBs are extremely small bubbles with diameters ranging from 100 µm to less than 100 nm. Their smaller size, increased ratio of surface area to volume, and high zeta potential give them peculiar characteristics that enable them to be used in various applications. They are currently used for medical purposes to aid in drug delivery during treatment (Luo et al., 2017; Ramaswamy et al., 2015). They are also used in agricultural activities to facilitate nutrient uptake (Ahmed et al., 2018; Marcelino et al., 2019), as well as water treatment to aid in oxidation processes (Sumikura et al., 2007), coagulation process (Tsai et al., 2007), and surface cleaning (Lee et al., 2015; Li et al., 2022). The trend in the use of MNBs in water treatment is well illustrated in Figure 1. The use of MNBs in membranes processes during water treatment have contributed to environmental conservation by reducing the generation of secondary pollutants while maintaining higher efficiencies. Substantial flux recovery was attained when membranes were cleaned with MNBs only as demonstrated in the studies by (Agarwal et al., 2013; Fazel and Chesters, 2014). Additionally, MNBs prove effective in mitigating fouling by preventing the formation of cake layers and pore blocking (Mohammad et al., 2012). They also play a pivotal role in addressing colloidal fouling concerns when treating salt water (Rezvani Mahmouee et al., 2023). Despite of many studies delving into the use of MNBs in membrane processes, a comprehensive summary that provides a detailed understanding of MNBs properties in terms of fouling prevention and membrane cleaning remains elusive. Moreover, the mechanisms of MNBs corresponding to mentioned processes have not been systematically summarized. Thus, this critical review aims to provide a comprehensive understanding of the behavior of MNBs in assisting membrane processes with particular emphasis on (1) a systematic summary of MNBs characteristics that perfectly match the enhancing demands of fouling control and membrane cleaning and (2) an in-depth analysis of the multiple roles played by MNBs. This review identifies the current gaps and future research needs for the use of MNBs in membrane processes during water treatment.

PROPERTIES AND BEHAVIORS OF MICRO AND NANOBUBBLES RELATED TO WATER TREATMENT

Definition

Micro and nanobubbles are extremely small gas bubbles, typically ranging in size from 1 to 100 µm for microbubbles (MBs) and nanobubbles (NBs) measuring less than 100 nm (Zhang et al., 2022). Nanobubbles, being much smaller in size with a higher surface area-to-volume ratio, experience stronger surface tension forces that help prevent their coalescence and promote their stability in liquid environments (Pan et al., 2021). This enhanced stability is further supported by the Laplace pressure, which increases as the bubble size decreases, leading to a resistance against dissolution or collapse (Oh and Kim, 2017; Sun et al., 2016). In contrast, microbubbles have a lower surface area-to-volume ratio, weaker surface tension forces, and lower Laplace pressure compared to nanobubbles, causing them to rise quickly due to buoyancy and coalesce more readily (Han et al., 2022). Additionally, microbubbles can be stabilized using surfactants or encapsulation techniques to prolong their lifespan and control their behavior in specific applications (Nguyen Hai Le et al., 2023). When introduced into water, MNBs can stay suspended for extended periods compared to macro bubbles and offer potential applications in various fields, including water treatment, agriculture, and medicine (Serizawa, 2017; Temesgen et al., 2017).

Preparation methods for MNBs in water treatment

Various methods are employed in the generation of micro and nanobubbles, each with its unique advantages and limitations (Jia et al., 2023). The selection of a specific method depends on factors such as bubble size requirements and the specific characteristics of the target liquid. In the realm of micro and nanobubble generation for water treatment, hydrodynamic cavitation stands out as a highly efficient and versatile method (Prakash et al., 2023) (Figure 1). Its superiority lies in its ability to induce microbubble formation through rapid changes in fluid flow, facilitated by devices such as nozzles or orifices. This technique harnesses-controlled flow conditions to create localized pressure changes, allowing for the precise generation of microbubbles even at low pressures (Wang et al., 2021). Hydrodynamic cavitation presents clear advantages over alternative methods due to its straightforward implementation and minimal energy requirements. Furthermore, it demonstrates remarkable effectiveness across diverse liquid properties and flow conditions, making it adaptable to a multitude of industrial and environmental applications (Wang et al., 2021). Sonic cavitation utilizes ultrasonic waves to create alternating regions of low and high pressure in a liquid, resulting in the formation of microbubbles, but compared to the former, it is somewhat more complex (Zimmerman et al., 2011). Several factors influence cavitation, including liquid properties and hydrodynamic characteristics. Liquid properties encompass density, saturated vapor pressure, temperature, viscosity, and surface tension. Hydrodynamic characteristics involve turbidity, the pressure gradient in the flow field, heat conduction, and the gas diffusion effect (Onishi et al.,

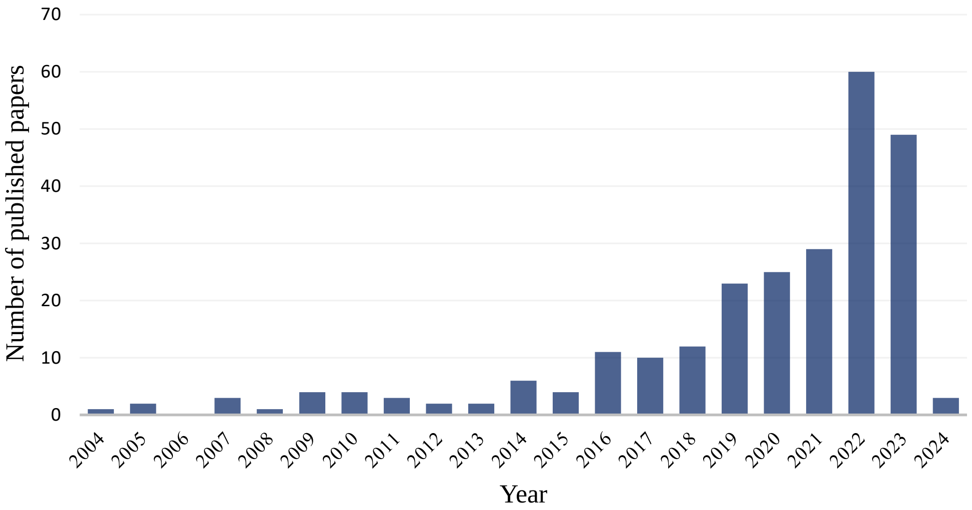

Figure 1. Illustrates the trend in the number of published papers focusing on the application of micro and nanobubbles in water treatment.
Source: The data was accessed from the Web of Science on February 9, 2024, using a topic search specifically targeting the application of micro and nanobubbles in water treatment.

2023).

High stability in water

The buoyancy force and drag force acting on the bubble normally define the rising velocity of bubbles in a fluid. MNBs violate the traditional bubbles theory of fast-rising. Instead, they have a far slower rising velocity compared to larger bubbles (Ushikubo et al., 2010). The slow-rising velocity phenomena in microbubbles have been extensively examined and linked to several reasons. One of them is a small size that decreases the buoyance effects and ability to coalesce and form bigger bubbles (Pagureva et al., 2016). The size of the bubble in a solution is influenced by factors such as the pressure and temperature of the surrounding liquid. As the pressure rises, so does the size of the bubble. At lower pressure, the shift in bubble size is visible however when the pressure exceeds a specific threshold there are no discernible differences (Rodrigues and Rubio, 2003; Wang et al., 2020). Different behavior is expressed with temperature. As the temperature rises, the average bubble radius decreases first, then slightly increases. Because thermal shrinkage is reversible, they revert to their original state when cooled (Tsujimoto and Horibe, 2021). Bubble growth accelerates when gas supersaturation in solution increases, and nucleation occurs earlier. As a result of higher supersaturations, the average bubble size becomes bigger (Sahu et al., 2014).

The higher surface-to-volume ratio of a bubble affects the surface tension, which is the force that tries to reduce the surface area of a liquid. For bubbles, this tension creates a thin layer of liquid around them called the liquid-gas interface. At very small scales, such as micro and nanoscales, this layer becomes more noticeable, resulting in greater stability and less merging of bubbles. Studies have shown that when the surface tension of liquids near a solid surface is reduced, the individual bubbles become less stable and collapse sooner (Wu et al., 2021). Microbubbles' stability not only has diverse applications in the field of water treatment but also in medicine as contrast agents and drug carriers. Their deliberate velocity enhances imaging precision and drug delivery efficiency, aiding medical diagnostics and therapeutics. In environmental engineering applications, particularly in wastewater treatment and pollutant remediation, bubble stability plays a crucial role in prolonging the contact period between bubbles and pollutants, and facilitating the removal of contaminants from water by encouraging the formation of larger flocks (Suwartha et al., 2020).

Generation of free radicals

The buildup of charge density within the electric double layer increases significantly throughout the process of decreasing micro and Nanobubbles. When the bubbles burst, a large number of ions accumulated at the interface of the electric double layer are rapidly expelled, releasing their chemical energy (Atkinson et al., 2019). This release generates a large number of reactive oxygen species, including hydroxyl radicals (OH), singlet oxygen, and superoxide anion radicals (Lyu et al., 2019). Hydroxyls are strong oxidants that react with many pollutants in water (Takahashi, 2007). The young-Laplace equation states that the interior pressure of a bubble with a diameter of 1 nm AT 298 K is around 390 Kpa or nearly four times the atmospheric pressure (Takahashi, 2007). Before the collapse of a bubble, a high-pressure zone develops in the final stage of bubble collapse. This phenomenon arises from the inverse correlation between the rate of internal pressure increase and the size of the object. Due to adiabatic compression, the temperature inside collapsing bubbles may significantly rise. If the collapsing speed of MNBs is faster than the speed of sound in water, the temperature rise can be noticed. At the gas-liquid interface, shock waves and the OH radical might be produced as a result of the pyrolytic breakdown that occurs within the collapsing bubbles (Serizawa, 2017). Several factors exert influence on the production of free radicals during the process of micro and nano bubble collapse. These factors encompass a range of parameters, such as the pH of the solution where high pH facilitated the production of radicals (Agarwal et al., 2011). The presence of catalysts, the type of gas involved whereby it was found that oxygen produced more OH radicals compared to nitrogen (Li et al., 2009). Due to their high reactivity, hydroxyl radicals facilitate the oxidation and decomposition of foulants, helping to restore the membrane's original performance.

High zeta potential

Zeta potential is the electric potential at the shear plane surrounding a charged particle or bubble in a liquid. MNBs with charged surfaces generate an electric field that draws ions with opposing charges from the surrounding fluid (Bueno-Tokunaga et al., 2015). As a result of the effect, a diffuse double layer emerges between the bubbles' surface charge and the oppositely charged ions (Meegoda et al., 2019). The layer formed is the Stern layer which is the innermost area next to the bubble surface where ions are tightly attached to the bubble. Beyond the Stern layer is an illustrious boundary known as the Slipping plane which separates ions that move with the bubble from those that do not. The level of stability of the particle dispersion system is also represented by the absolute zeta potential value. Since the van der Waals force can lead to particle aggregation, coagulation, and flocculation, a low absolute zeta value indicates that the nanoparticle dispersion is not stable (Zhang et al., 2022). It was found that the zeta potential value of oxygen MNBs and air MNBs in water ranged from -45 to -34 mV and -20 to -17 mV (Ushikubo et al., 2010). The electric charge of the MNBs surface tended to reject one another at higher ZP values which prevented MNBs from aggregating and helped the liquid systems bubble to become stable (Calgaroto et al., 2014; Sun et al., 2016). The solution's pH level, the composition of the gas, and the size of the bubble have also an influence on the Zeta potential value of MNBs (Wu et al., 2015). High zeta potential facilitates the long existence time of MNBs that increase the interaction time of bubbles and foulant.

APPLICATION OF MNBS IN MEMBRANE CLEANING

Membrane cleaning mechanisms

Membrane cleaning involves the removal of fouling materials from the membrane surface to restore its permeability and filtration capabilities (Trägårdh, 1989). Physical cleaning and chemical cleaning are the two main approaches used for cleaning fouled membranes. The physical approach modifies fluid dynamics through turbulence causing foulants to detach via kinetic forces (Shorrock and Bird, 1998). Forces that can be used include hydraulic, mechanical, or electrical. Hydraulic and mechanical forces change how water rubs against the membrane surface to get rid of the foulants. It can also be done by reversing the flow (backwashing) (Tian et al., 2010). Chemical cleaning utilizes agents to alter the solution's chemistry during membrane cleaning. The main categories of commonly used cleaning agents are acids, alkalis, oxidants, and surfactants (Strugholtz et al., 2005; Trägårdh, 1989). Alteration of solution chemistry caused by chemicals favors electrostatic repulsion between foulants and the membrane material or causes foulants to rapidly react and decompose into the liquid stream (Li and Elimelech, 2004). In practical applications, a combination of physical and chemical methods is often employed to enhance the effectiveness of cleaning (Lateef et al., 2013; Muthukumaran et al., 2004). The efficient filtration of a membrane relies on both physical and chemical cleaning techniques, yet their use may entail potential negative side effects. Physical cleaning methods such as scrubbing can lead to mechanical damage and incomplete removal of foulants that are stuck inside the membrane pores potentially diminishing the membrane's lifespan and filtration efficacy (Muthukumaran et al., 2005). Standard and generic cleaning chemicals are ineffective in removing certain pollutants such as clay deposits from RO membranes. Plasticity character, the presence of different structural cations, and the impermeability of clay to water make it hard to attain good cleaning results (Armstrong et al., 2009). Modern techniques such as the use of electric fields and ultrasound are currently under study but they also have some challenges. It was observed that polyethersulphone (PES) flat-sheet membranes showed damage signs when subjected to a 47 kHz ultrasound stream for just 5 min (Li et al., 2011). Additionally, these techniques often consume more energy contributing to higher operational costs (Chen et al., 2003; Liang et al., 2008).

Employing MNBs in membrane cleaning

The unique attributes of micro and nanobubbles have significantly impacted their application, especially in the domain of cleaning fouled membranes. Their influence on the membrane-foulant interaction has been proven to efficiently restore membrane performance across diverse filtration techniques. The following are among the effects.

Scoring effect

The scoring effect refers to the process by which micro and nanobubbles physically dislodge and remove fouling substances from a surface, such as a membrane by gently rubbing it creating abrasion or scratching effects on the membrane surface (Patel et al., 2021). The scouring effect exerted by micro and nanobubbles plays a vital role in membrane cleaning, as it offers unique advantages that optimize the removal of fouling substances (Hilares et al., 2022). Their small size of MNBs enables them to penetrate confined spaces within complex membrane structures, ensuring a thorough cleaning process that traditional methods may struggle to achieve. Additionally, they provide gentle cleaning with minimal impact on the membrane. Due to their high surface area relative to volume, these bubbles enhance interaction with contaminants, leading to efficient adsorption and detachment of particles. However, while the physical dislodging action of the bubbles is especially effective against stubborn deposits, addressing irregularities on the membrane surface and preventing recontamination by eliminating potential fouling sites, further research is needed to fully understand the long-term effects and durability of membranes subjected to frequent micro and nanobubble cleaning processes. This includes investigating potential structural changes in the membrane material over time and assessing any impacts on membrane performance and lifespan. Moreover, the efficiency of the scouring effect can fluctuate based on factors like bubble size and concentration, and cleaning duration. Optimizing these parameters for different membrane types and fouling scenarios could enhance the overall cleaning efficiency and contribute to more sustainable membrane operations.

Oxidation and redox reactions

Microbubbles and nanobubbles play a significant role in membrane cleaning by generating reactive oxygen species, particularly hydroxyl radicals upon their collapse (Wang et al., 2024). The production of OH radicals through microbubble collapse in water, increases with the flow rate, pH, and oxygen concentration of the water (Wang et al., 2018). When directed at organic foulants on the membrane surface, hydroxyl radicals initiate oxidation reactions, breaking chemical bonds and fragmenting the foulant into smaller, more water-soluble byproducts (Ghadimkhani et al., 2016). This oxidative process significantly weakens the structural integrity of the foulant, making it more susceptible to physical removal mechanisms such as shear forces and fluid dynamics during the cleaning process. Nanobubbles have shown the ability to prevent virus and bacterial growth, thus preventing bio-fouling of the membrane, as they can persist in water for an extended period. Hydroxyl radicals (OH) can break down pollutants that are resistant to decomposition under typical conditions, such as organic phenol (Fang et al., 2019). In a bench-scale experiment, the ceramic membrane exhibited a 99% flux recovery rate when nanobubbles were used for cleaning, whereas the fouling rate reached 53% after only 2 h of operation in the absence of nanobubbles, as demonstrated in Table 1. These outcomes were linked to the influence of radicals produced in the presence of nanobubbles. Reactive oxygen species generated using other methods also showed promising results in membrane cleaning. For instance, a combination of H_2O_2 and MnO_2 achieved over 95% restoration of permeate flux and complete removal of foulants when used to clean polyvinylidene fluoride (PVDF) and PES membranes (He et al., 2019). Although the free radicals generated by MNBs are helpful in cleaning but also, they also have many uncertainties that need to be studied more. It is suspected that Free radicals may unintentionally target the membrane material itself, causing degradation and a subsequent decline in performance over time. Also, reactive oxygen species produced by MNBs do not have a long life span that will make sure they stay active enough to break down foulant completely during the cleaning process. It's crucial to keep them active and powerful for a longer time without losing their efficiency to make the process feasible. This action necessitates continuous bubbling water with MNBs adding to more power consumption (Aliasghar Ghadimkhani et al., 2016).

Enhanced mass transfer

Microbubbles demonstrate heightened transfer efficiency owing to their smaller size, with the resulting shrinkage leading to increased interior gas pressure. This heightened internal pressure accelerates the diffusion of entrapped gases, causing the bubbles to shrink further and ultimately collapse, contributing to enhanced mass transfer (Li et al., 2014). Studies have demonstrated that the inclusion of MNBs during membrane cleaning significantly enhances the rates of foulant removal. This is achieved by the accelerated chemical reactions of foulants due to MNBs, which create weaker bonds, facilitating their easier removal from surfaces (Xiao and Xu, 2020). MNBs increased the mass transfer coefficient by 4.7 times, signifying a more efficient transfer of O_3 from the gas phase to the liquid phase, leading to higher reactivity and improved microplastic removal efficiency (Fan et al., 2021). In a wastewater treatment study, nanobubble aeration enhanced oxygen supply to biofilms, achieving 1.5 times higher transfer efficiency that accelerated growth, and improved removal, while saving

Table 1. Effects of MNBs on cleaning and fouling prevention of various membranes.

Membrane type	Results		Reference
	With MNBs	Without MNBS	
Monolithic ceramic membrane	Zeta potential 20	Zeta potential is 25-29	Hashimoto et al. (2022)
RO membranes	530 GPM	484 GPM	Fazel and Chesters (2014)
Flat sheet RO	113% flux increment	88% flux increment	Wilson and Jarrige (2013)
Monolith-type porous ceramic	97% TMP recovery	80% TMP recovery	Hashimoto et al. (2022)
Ceramic membrane	47% flux recovery	0 permeate after 6 h of operation	Ghadimkhani et al. (2016)
Polytetrafluoroethylene (PTFE)	70% removal of salt scaling Contact angle recovery 94%	-	Zhang et al. (2022)
Polyether sulfone membranes	51% improve with 0.5 bars TMP	-	Levitsky et al. (2021)

around 80% energy (Xiao and Xu, 2020). During drinking water treatment, ozone micro-nano-bubbles improved cleaning efficiency and achieved 100% flux recovery due to enhanced mass transfer that facilitated foulants removal (Mo et al., 2024).

While mass transfer can facilitate foulants removal and sustain membrane cleanness, optimization of the size and concentration of MNBs are crucial to attain the best results whenever MNBs are used. Reducing the bubble's size and raising its internal pressure will lead to heightened mass transfer rates for micro and nanobubbles into the nearby liquid (Li et al., 2014). Furthermore, the speed of gas diffusion from regions of higher pressure to lower pressure is directly linked to the pressure difference. Thus, utilizing smaller bubble sizes can improve gas transfer efficiency.

APPLICATION OF MICRO AND NANOBUBBLES IN FOULING PREVENTION

Fouling and its occurrence

Fouling occurs when particles, microorganisms, or substances accumulate on a membrane's surface and diminish its performance. It is mainly categorized as reversible or irreversible fouling depending on how strongly contaminants adhere (Kimura et al., 2004; Tu et al., 2005). The foulants can be broken down into four groups which are organic, inorganic scaling, colloidal, and biofouling (Lee et al., 2015). Reversible fouling is easily removed through methods like backwashing, aeration, and relaxation while irreversible fouling is hard to remove because of the strong bond that poses a challenge to eliminate by physical means. It is more associated with smaller particles that experience lower shear stress and adhere more firmly to the membrane than larger ones (Bourgeous et al., 2001). Not only do small particles act as nuclei for larger aggregates but also trap additional foulants, leading to a more substantial fouling layer on the membrane (Wen-Qiong et al., 2019).

Methods used to prevent fouling

Multiple techniques and strategies are employed to address membrane fouling in water treatment processes. One essential technique among these is pretreatment, which holds a central role in controlling impurities in raw water right from the initial stage. Screening and filtration techniques utilize pre-filters or screens to eliminate larger particles and coarse contaminants before they reach the membrane (Nnanna et al., 2015). Coagulation and flocculation promote the aggregation of smaller particles, facilitating their removal through filtration (Bratby, 2016). These methods serve as initial defenses, reducing particulate matter and enhancing membrane performance. Physical methods such as backwashing involve reversing water flow through the membrane, dislodging, and eliminating adhered particles. These steps are crucial for maintaining clear membranes free from foulants. Surface modification is another approach that enhances resistance to fouling by applying hydrophilic coatings that minimize foulant adhesion (Rana and Matsuura, 2010). Furthermore, optimizing operating conditions involves controlling parameters like pH, temperature, and flow rates to minimize particle residence time and decrease fouling rates (Gönder et al., 2011). The challenges associated with conventional fouling prevention methods highlight the necessity to explore innovative approaches, particularly in terms of cleaning efficiency. These methods often require increased chemical usage for operational maintenance, leading to the generation of sludge as a secondary pollutant (Zhang et al., 2019). Additionally, processes like backwashing require system shutdowns, causing disruptions in production. Research indicates that extending backwashing by just 5 s could result in production losses ranging from 3.5 to 8.8%. Significantly, it was discovered that the duration of backwashing is more crucial than the filtration phase itself. Any delays in the backwashing process can significantly impact permeate production, emphasizing the crucial importance of timely backwashing (Jepsen et al., 2019).

Mechanism of MNBs facilitating fouling prevention

Turbulence action

Turbulence is the controlled disturbance or agitation of fluid flowing across the membrane or on its surface (Pourbozorg et al., 2016). Numerous studies have delved into the effectiveness of turbulence promoters to enhance fluid dynamics and mitigate fouling issues (Kertész et al., 2023; Lin et al., 2023). When the liquid inside a membrane system swirls around, it facilitates the movement of substances through the system, preventing them from adhering to the membrane (Celmer et al., 2008; Pourbozorg et al., 2016). The strategic use of turbulence as a means to control fouling has been explored in various studies. For instance, in a study by Guigui et al. (2003), turbulence was harnessed through air-enhanced flushing, leading to a remarkable improvement in colloidal particle removal rates by 30 to 130% under diverse hydrodynamic conditions. Notably, the energy consumption during this process remained comparable to standard backwashing practices, making this finding particularly noteworthy (Guigui et al., 2003). Additionally, corrugated membranes have been utilized to promote turbulence. The corrugations present in these membranes create a scouring action that disrupts and improves the mixing of the boundary layer, leading to an increased permeate flux while maintaining a remarkable 100% rejection of the water phase (Scott et al., 2000). Another effective technique that achieves similar outcomes is the use of Micro/Nano Bubbles (MNBs). The hydrodynamic effects of MNBs in fouling prevention are primarily driven by their churning action, which results from their interaction with the surrounding liquid. MNBs effectively reduce membrane fouling by sweeping over and scouring the membrane surface. Their small size allows for a more uniform distribution of turbulence across the membrane surface, ensuring consistent fouling prevention and reducing the likelihood of localized fouling hotspots (Jankhah and Berube, 2013). In a study that examined the impact of MNBs on gypsum scaling in a brackish water reverse osmosis (RO) membrane, the results demonstrated that MNBs significantly reduced scaling and enhanced membrane performance by disrupting concentration polarization, particularly in central and outlet areas, leading to an 83% increase in permeate flux and a 98% improvement in salt rejection (Dayarathne et al., 2017). The power transferred onto membranes, which characterizes these effects, is directly related to turbulence parameters such as shear stress, induced vorticity, and bubble rise velocity. In the context of fouling control, turbulence generated by pulse bubble sparging proved more efficient than coarse bubble sparging, leading to higher power transfer efficiency and better control over membrane fouling (Jankhah and Berube, 2013). The strategic use of MNBs to induce turbulence shows great promise for controlling membrane fouling. MNBs churning action effectively reduces fouling by sweeping and scouring the membrane surface, leading to improved permeate flux and salt rejection.

Electrostatic repulsion

One of the mechanisms demonstrated by MNBs in membrane fouling control is electrostatic repulsion. Often, membranes and foulants possess, unlike charges which attract foulants on the membrane as unlike charges attract each other and like charges repel (Jia et al., 2013). MNBs are more negatively charged on their outer surface, introducing them in water increases the repulsive or attraction force between membrane and foulant as they attach with the positively charged foulants. Research has revealed that microbubbles retain a negative charge across a broad pH range, which increases the likelihood of preventing fouling under diverse conditions (Takahashi, 2005). The effectiveness of microbubbles in adhering to suspended particles is enhanced by the elevated zeta potentials that prevent the collision of bubbles to form bigger bubbles that can rise faster, prolonging the contact time between the bubble and suspended particles (Fang et al., 2019). Contrary to repulsion, electrostatic attraction is strategically harnessed to facilitate the removal of foulants from the membrane surface. By manipulating the charge interactions, the negatively charged bubbles attract positively charged particles forming agglomerates that are easier to remove from the system. This attractive force aids in the prevention of foulant build-up on the membrane, ensuring sustained efficiency over prolonged water treatment operations (Farid et al., 2021). Optimizing operational conditions is crucial to fully harness the potential of the electrostatic repulsion effect as the surface charge density or zeta potential of nanobubbles depends on factors like viscosity, bulk solution density, electrolyte concentration, chemical surfactants, pH, and temperature (Meegoda et al., 2018).

Gass bridge effect

The gas bridge effect refers to a phenomenon observed in water treatment where nanobubbles act as a barrier between foulants and the membrane surface preventing direct contact and adhesion of foulants to the membrane (Figure 2). Foulants such as suspended solids, organic compounds, and biological contaminants are less likely to attach to the membrane because they encounter the gas

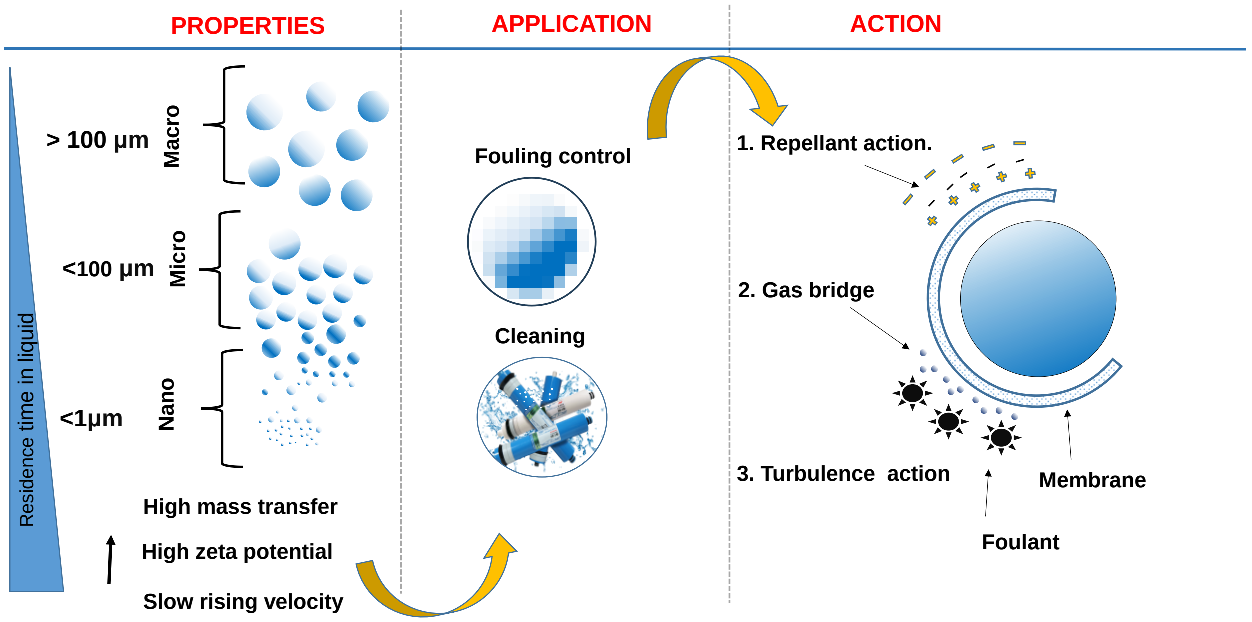

Figure 2. Characteristics of micro and nanobubbles in membrane processes and their impact on the membrane.

phase first, which has different properties compared to the liquid phase. MNBs are negatively charged increasing their chances of attaching to positively charged pollutants such as calcium (Zhang et al., 2020). In the study using ceramic membranes, MNBs significantly enhanced membrane permeability, rejection performance, and antifouling ability by serving as a gas bridge to prevent pollutant adhesion, leading to a 165.9% improvement in antifouling performance (Fan et al., 2022). In addition to preventing fouling, the gas bridge effect also enhances the effectiveness of cleaning procedures. When fouling occurred despite the gas bridge, the loosely attached foulants were easily removed during cleaning cycles because they were less firmly bound to the membrane surface (Wu et al., 2008).

CONCLUSION

This comprehensive assessment explored the efficacy of MNBs in membrane processes for water treatment, particularly focusing on their role in cleaning and controlling fouling. The review systematically outlined the distinctive properties of MNBs, including their high stability in water, generation of free radicals, and high zeta potential, shedding light on their effectiveness in cleaning fouled membranes. MNBs employ various mechanisms such as turbulence, repulsion, gas bridge effects, and scoring effects, among others, which collectively contribute to significant flux recovery, prevent cake layers and pore blocking, and address colloidal fouling concerns in saltwater applications. The attributes and mechanisms of MNBs mainly depend on bubble size and concentration. Optimizing these factors as well as refining operating conditions can enhance the global application of this technology. Further research is needed to assess how the effects of MNBs on membranes change over time and to understand the specific contributions of each mechanism to fouling prevention. Exploring ways to control bubble size effectively is crucial to ensure the use of the most impactful bubble size for optimal results.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

Agarwal A, Ng W J,Liu Y (2013). Cleaning of biologically fouled membranes with self-collapsing microbubbles. Biofouling 29(1):69-76.

Agarwal A, Ng WJ, Liu Y (2011). Principle and applications of microbubble and nanobubble technology for water treatment. Chemosphere 84(9):1175-1180.

Ahmed AK A, Shi X, Hua L, Manzueta L, Qing W, Marhaba T, Zhang W (2018). Influences of Air, Oxygen, Nitrogen, and Carbon Dioxide Nanobubbles on Seed Germination and Plant Growth. Journal of Agricultural and Food Chemistry 66(20):5117-5124.

Armstrong MW, Gallego S, Chesters S (2009). Cleaning clay from fouled membranes. Desalination and Water Treatment 10(1-3):108-114.

Atkinson AJ, Apul OG, Schneider O, Garcia-Segura S, Westerhoff P (2019). Nanobubble Technologies Offer Opportunities To Improve Water Treatment. Accounts of Chemical Research 52(5):1196-1205.

Bourgeous KN, Darby JL, Tchobanoglous G (2001). Ultrafiltration of wastewater: effects of particles, mode of operation, and backwash effectiveness. Water Research 35(1):77-90.

Bratby J (2016). Coagulation and flocculation in water and wastewater treatment. IWA publishing.

Bueno-Tokunaga A, Pérez-Garibay R, Martínez-Carrillo D (2015). Zeta potential of air bubbles conditioned with typical froth flotation reagents. International Journal of Mineral Processing 140:50-57.

Calgaroto S, Wilberg KQ, Rubio J (2014). On the nanobubbles interfacial properties and future applications in flotation. Minerals Engineering 60:33-40.

Celmer D, Oleszkiewicz JA, Cicek N (2008). Impact of shear force on the biofilm structure and performance of a membrane biofilm reactor for tertiary hydrogen-driven denitrification of municipal wastewater. Water Research 42(12):3057-3065.

Chen JP, Kim SL, Ting YP (2003). Optimization of membrane physical and chemical cleaning by a statistically designed approach. Journal of Membrane Science 219(1):27-45.

Dayarathne HNP, Choi J, Jang A (2017). Enhancement of cleaning-in-place (CIP) of a reverse osmosis desalination process with air micro-nano bubbles. Desalination 422:1-4.

Fan K, Huang Z, Lin H, Shen L, Gao C, Zhou G, Hu J, Yang H, Xu F (2022). Effects of micro-/nanobubble on membrane antifouling performance and the mechanism insights. Journal of Cleaner Production 376:134331

Fan W, An W, Huo M, Xiao D, Lyu T, Cui J (2021). An integrated approach using ozone nanobubble and cyclodextrin inclusion complexation to enhance the removal of micropollutants. Water Research 196:11-7039.

Fang T Y, Liu C, Tang Y, Khaletski V (2019). Application research of micro and nanobubbles in water pollution control. E3S Web of Conferences (Vol. 136, p. 06028).

Farid MU, Kharraz JA, Lee CH, Fang JK, St-Hilaire S, An AK (2021). Nanobubble-assisted scaling inhibition in membrane distillation for the treatment of high-salinity brine. Water Research 209:117954.

Fazel M, Chesters S (2014). RO membrane cleaning using microbubbles at 6,800 m 3 /d wastewater RO plant in UAE. Desalination and Water Treatment 55:1-9.

Ghadimkhani A, Zhang W, Marhaba T (2016). Ceramic membrane defouling (cleaning) by air Nano Bubbles. Chemosphere 146:379-384.

Gönder ZB, Arayici S,Barlas H (2011). Advanced treatment of pulp and paper mill wastewater by nanofiltration process: Effects of operating conditions on membrane fouling. Separation and Purification Technology 76(3):292-302.

Guigui C, Mougenot M, Cabassud C (2003). Air sparging backwash in ultrafiltration hollow fibres for drinking water production. Water Supply 3(5-6):415-422.

Han G, Chen S, Su S, Huang Y, Liu B, Sun H (2022). A review and perspective on micro and nanobubbles: What They Are and Why They Matter. Minerals Engineering 189:107906.

Hashimoto K, Onzuka A, Nishijima W, Yamazaki M, Aoki M, Sao T (2022). Effect of fine bubbles for washing of monolith type porous ceramic membranes treating oil-in-water emulsions. Chemosphere 305:135487.

He X, Li B, Wang P, Ma J (2019). Novel H2O2–MnO2 system for efficient physico-chemical cleaning of fouled ultrafiltration membranes by simultaneous generation of reactive free radicals and oxygen. Water Research 167:115111.

Hilares RT, Singh I, Meza KT, Andrade GJC,Tanaka DAP (2022). Alternative methods for cleaning membranes in water and wastewater treatment. Water Environment Research 94(4).

Jankhah S, Berube PR (2013). Power induced by bubbles of different sizes and frequencies on to hollow fibers in submerged membrane systems. Water Research 47(17):6516-6526.

Jepsen KL Bram MV, Hansen L, Yang Z, Lauridsen SM (2019). Online Backwash Optimization of Membrane Filtration for Produced Water Treatment. Membranes 9(6):68.

Jia J, Zhu Z, Chen H, Pan H, Jiang L, Su WH, Chen Q, Tang Y, Pan J, Yu K (2023). Full life circle of micro-nano bubbles: Generation, characterization and applications. Chemical Engineering Journal 471.

Jia W, Ren S, Hu B (2013). Effect of Water Chemistry on Zeta Potential of Air Bubbles. International Journal of Electrochemical Science 8(4):5828-5837.

Katsoufidou K, Yiantsios S, Karabelas A (2005). A study of ultrafiltration membrane fouling by humic acids and flux recovery by backwashing: Experiments and modeling. Journal of Membrane Science 266(1-2):40-50.

Kertész S, Gulyás NS, Al-Tayawi AN, Huszár G, Lennert JR, Csanádi J, Beszédes S, Hodúr C, Szabó T, László Z (2023). Modeling of Organic Fouling in an Ultrafiltration Cell Using Different Three-Dimensional Printed Turbulence Promoters. Membranes (Basel) 13(3).

Kimura K, Hane Y, Watanabe Y, Amy G, Ohkuma N (2004). Irreversible membrane fouling during ultrafilration of surface water. Water Research 38(14):3431-3441.

Lateef SK, Soh BZ, Kimura K (2013). Direct membrane filtration of municipal wastewater with chemically enhanced backwash for recovery of organic matter. Bioresource Technology 150:149-155.

Lee EJ, Kim YH, Kim HS, Jang A (2015). Influence of microbubble in physical cleaning of MF membrane process for wastewater reuse. Environmental Science and Pollution Research International 22(11):8451-8459.

Levitsky I, Tavor D, Gitis V (2021). Microbubbles and organic fouling in flat sheet ultrafiltration membranes. Separation and Purification Technology 268.

Li H, Hu L, Song D, Al-Tabbaa A (2014). Subsurface Transport Behavior of Micro-Nano Bubbles and Potential Applications for Groundwater Remediation. International Journal of Environmental Research and Public Health 11(1):473-486.

Li H, Hu L, Song D, Lin F (2014). Characteristics of micro-nano bubbles and potential application in groundwater bioremediation. Water Environment Research 86(9):844-851.

Li P, Takahashi M, Chiba K (2009). Enhanced free-radical generation by shrinking microbubbles using a copper catalyst. Chemosphere 77(8):1157-1160.

Li P, Wang J, Liao Z, Ueda Y, Yoshikawa K, Zhang G (2022). Microbubbles for Effective Cleaning of Metal Surfaces Without Chemical Agents. Langmuir 38(2):769-776.

Li Q, Elimelech M (2004). Organic Fouling and Chemical Cleaning of Nanofiltration Membranes: Measurements and Mechanisms. Environmental Science and Technology 38(17):4683-4693.

Li X, Yu J, Nnanna A (2011). Fouling mitigation for hollow-fiber UF membrane by sonication. Desalination 281:23-29.

Liang H, Gong W, Chen J, Li G (2008). Cleaning of fouled ultrafiltration (UF) membrane by algae during reservoir water treatment. Desalination 220(1):267-272.

Lin B, Matinpour H, Malmali M (2023). Evaluation of spacer-induced hydrodynamic mixing using particle image velocimetry: Impact on membrane distillation performance. Desalination 564:116758.

Luo MH, Yeh K, Situ B, Yu JS, Li BC, Chen ZY (2017). Microbubbles: A Novel Strategy for Chemotherapy. Current Pharmaceutical Design 23(23):3383-3390.

Lyu T, Wu S, Mortimer RJG, Pan G (2019). Nanobubble Technology in Environmental Engineering: Revolutionization Potential and Challenges. Environmental Science and Technology 53(13):7175-7176.

Marcelino KR, Ling L, Wongkiew S, Nhan HT, Surendra KC, Shitanaka T, Lu H, Khanal SK (2019). Nanobubble technology applications in environmental and agricultural systems: Opportunities and challenges. Critical Reviews in Environmental Science and Technology 53(14):1378-1403.

Meegoda JN, Aluthgun HS, Batagoda JH (2018). Stability of Nanobubbles. Environmental Engineering Science 35(11):1216-1227.

Meegoda JN, Hewage SA, Batagoda JH (2019). Application of the Diffused Double Layer Theory to Nanobubbles. Langmuir 35(37):12100-12112.

Mo J, Lin T, Liu W, Zhang Z, Yan Y (2024). Cleaning efficiency and mechanism of ozone micro-nano-bubbles on ceramic membrane fouling. Separation and Purification Technology 331:125698.

Mohammad AW, Ng CY, Lim YP, Ng GH (2012). Ultrafiltration in Food Processing Industry: Review on Application, Membrane Fouling, and Fouling Control. Food and Bioprocess Technology 5(4):1143-1156.

Muthukumaran S, Kentish S, Lalchandani S, Ashokkumar M, Mawson R, Stevens GW, Grieser F (2005). The optimisation of ultrasonic cleaning procedures for dairy fouled ultrafiltration membranes. Ultrasonics Sonochemistry 12(1): 29-35.

Muthukumaran S, Yang K, Seuren A, Kentish S, Ashokkumar M, Steven GW, Grieser F (2004). The use of ultrasonic cleaning for ultrafiltration membranes in the dairy industry. Separation and Purification Technology 39(1):99-107.

Nguyen H, Le N, Sugai Y, Nguele R, Sreu T (2023). Bubble size distribution and stability of CO2 microbubbles for enhanced oil recovery: effect of polymer, surfactant and salt concentrations. Journal of Dispersion Science and Technology 44(5):795-805.

Nnanna AA, Sheng C, Conrad K, Crowley G (2015). Performance Assessment of Pre-Filtration Strainer of an Ultrafiltration Membrane System by Particle Size Analysis. ASME International Mechanical Engineering Congress and Exposition. (Vol. 57465, p. V07AT09A015). American Society of Mechanical Engineers.

Oh SH, Kim JM (2017). Generation and stability of bulk nanobubbles. Langmuir 33(15):3818-3823.

Onishi T, Peng Y, Ji H, Peng G (2023). Numerical simulations of cavitating water jet by an improved cavitation model of compressible mixture flow with an emphasis on phase change effects. Physics of Fluids 35(7).

Pagureva N, Tcholakova S, Rusanova K, Denkov N, Dimitrova T (2016). Factors affecting the coalescence stability of microbubbles. Colloids and Surfaces A: Physicochemical and Engineering Aspects 508:21-29.

Pan Y, He B, Wen B (2021). Effects of surface tension on the stability of surface nanobubbles. Frontiers in Physics 9:731804.

Park HM, Yoo J, Lee YT (2019). Improved fouling resistance for RO membranes by a surface modification method. Journal of Industrial and Engineering Chemistry 76:344-354.

Patel AK, Singhania RR, Chen CW, Tseng YS, Kuo CH, Wu CH, Di Dong C (2021). Advances in micro-and nano bubbles technology for application in biochemical processes. Environmental Technology Innovation 23:101729.

Pourbozorg M, Li T, Law AWK (2016). Effect of turbulence on fouling control of submerged hollow fibre membrane filtration. Water Research 99:101-111.

Prakash R, Lee J, Moon Y, Pradhan D, Kim SH, Lee HY, Lee J (2023). Experimental Investigation of Cavitation Bulk Nanobubbles Characteristics: Effects of pH and Surface-Active Agents. Langmuir 39(5):1968-1986.

Ramaswamy K, Marx V, Laser D, Kenny T, Chi T, Bailey M, Sorensen MD, Grubbs RH, Stoller ML (2015). Targeted microbubbles: a novel application for the treatment of kidney stones. BJU International 116(1):9-16.

Rana D, Matsuura T (2010). Surface modifications for antifouling membranes. Chemical reviews 110(4):2448-2471.

Rezvani Mahmouee A, Saghravani SF, Dahrazma B (2023). Evaluation of the Anti-Fouling Effects of Micro-Nano Bubbles on the Performance of Reverse Osmosis Membrane. Journal of Environmental Engineering 149(4).

Rodrigues RT, Rubio J (2003). New basis for measuring the size distribution of bubbles. Minerals Engineering 16(8):757-765.

Sahu SN, Gokhale AA, Mehra A (2014). Modeling nucleation and growth of bubbles during foaming of molten aluminum with high initial gas supersaturation. Journal of Materials Processing Technology 214(1):1-12.

Scott K, Mahmood AJ, Jachuck RJ, Hu B (2000). Intensified membrane filtration with corrugated membranes. Journal of Membrane Science 173(1):1-16.

Serizawa A (2017). MicroNano-Bubbles-Fundamentals-and-Applications. Available at: https://www.studocu.com/id/document/universitas-agung-podomoro/fisika/2017-0106155252-97638-sifat-nanobubble/64728007

Shan X, Li SL, Fu W, Hu Y, Gong G, Hu Y (2020). Preparation of high performance TFC RO membranes by surface grafting of small-molecule zwitterions. Journal of Membrane Science 608:118209.

Shorrock CJ, Bird MR (1998). Membrane Cleaning: Chemically Enhanced Removal of Deposits Formed During Yeast Cell Harvesting. Food and Bioproducts Processing 76(1):30-38.

Stoller M (2011). Effective fouling inhibition by critical flux based optimization methods on a NF membrane module for olive mill wastewater treatment. Chemical Engineering Journal 168(3):1140-1148.

Strugholtz S, Sundaramoorthy K, Panglisch S, Lerch A, Brügger A, Gimbel R (2005). Evaluation of the performance of different chemicals for cleaning capillary membranes. Desalination 179(1):191-202.

Sumikura M, Hidaka M, Murakami H, Nobutomo Y, Murakami T (2007). Ozone micro-bubble disinfection method for wastewater reuse system. Water Science and Technology 56(5):53-61.

Sun Y, Xie G, Peng Y, Xia W, Sha J (2016). Stability theories of nanobubbles at solid–liquid interface: A review. Colloids and Surfaces A: Physicochemical and Engineering Aspects 495:176-186.

Suwartha N, Syamzida D, Priadi CR, Moersidik SS, Ali F (2020). Effect of size variation on microbubble mass transfer coefficient in flotation and aeration processes. Heliyon 6(4):03748.

Takahashi M (2005). ζ Potential of Microbubbles in Aqueous Solutions: Electrical Properties of the Gas−Water Interface. The Journal of Physical Chemistry B 109(46):21858-21864.

Takahashi M, Chiba K, Li P (2007). Formation of Hydroxyl Radicals by Collapsing Ozone Microbubbles under Strongly Acidic Conditions. The Journal of Physical Chemistry B 111(39):11443-11446.

Temesgen T, Bui TT, Han M, Kim TI, Park H (2017). Micro and nanobubble technologies as a new horizon for water-treatment techniques: A review. Advances in Colloid and Interface Science 246:40-51.

Tian Jy, Xu Yp, Chen Zl, Nan J, Li Gb (2010). Air bubbling for alleviating membrane fouling of immersed hollow-fiber membrane for ultrafiltration of river water. Desalination 260(1-3):225-230.

Trägårdh G (1989). Membrane cleaning. Desalination 71(3):325-335.

Tsai J, Kumar M, Chen S, Lin J (2007). Nano-bubble flotation technology with coagulation process for the cost-effective treatment of chemical mechanical polishing wastewater. Separation and Purification Technology 58(1):61-67.

Tsujimoto K, Horibe H (2021). Effect of pH on Decomposition of Organic Compounds Using Ozone Microbubble Water. Journal of Photopolymer Science and Technology 34(5):485-489.

Tu SC, Ravindran V, Pirbazari M (2005). A pore diffusion transport model for forecasting the performance of membrane processes. Journal of Membrane Science 265(1):29-50.

Ushikubo FY, Furukawa T, Nakagawa R, Enari M, Makino Y, Kawagoe Y, Shiina T, Oshita S (2010). Evidence of the existence and the stability of nano-bubbles in water. Colloids and Surfaces A: Physicochemical and Engineering Aspects 361(1-3):31-37.

Wang B, Su H, Zhang B (2021). Hydrodynamic cavitation as a promising route for wastewater treatment–A review. Chemical Engineering Journal 412:128685.

Wang H, Yang W, Yan X, Wang L, Wang Y, Zhang H (2020). Regulation of bubble size in flotation: A review. Journal of Environmental Chemical Engineering 8(5):104070.

Wang T, Yang C, Sun P, Wang M, Lin F, Fiallos M, Soon-Thiam K (2024). Generation Mechanism of Hydroxyl Radical in Micro Nano Bubbles Water and Its Prospect in Drinking Water.

Wang W, Fan W, Huo M, Zhao H, Lu Y (2018). Hydroxyl radical generation and contaminant removal from water by the collapse of microbubbles under different hydrochemical conditions. Water, Air and Soil Pollution 229:1-11.

Wen-Qiong W, Yun-Chao W, Xiao-Feng Z, Rui-Xia G, Mao-Lin L (2019). Whey protein membrane processing methods and membrane fouling mechanism analysis. Food Chemistry 289:468-481.

Wilson MF, Jarrige S (2013). Air Bubbles Enhance Membrane Cleaning:A Future Perspective. The International Desalination Association World Congress on Desalination and Water Reuse.

Wu C, Wang L, Harbottle D, Masliyah J, Xu, Z (2015). Studying bubble-particle interactions by zeta potential distribution analysis. Journal of Colloid and Interface Science 449:399-408.

Wu H, Zheng H, Li Y, Ohl C-D, Yu H, Li, D (2021). Effects of surface tension on the dynamics of a single micro bubble near a rigid wall in an ultrasonic field. Ultrasonics Sonochemistry 78:105735.

Wu Z, Chen H, Dong Y, Mao H, Sun J, Chen S, Craig V S J, Hu J (2008). Cleaning using nanobubbles: Defouling by electrochemical generation of bubbles. Journal of Colloid and Interface Science

328(1):10-14.

Xiao W, Xu G (2020). Mass transfer of nanobubble aeration and its effect on biofilm growth: Microbial activity and structural properties. Science of the Total Environment 703:134976.

Yiantsios SG, Sioutopoulos D, Karabelas AJ (2005). Colloidal fouling of RO membranes: an overview of key issues and efforts to develop improved prediction techniques. Desalination 183(1):257-272.

Yuan C (2019). Experimental Study on UF-NF Filtration Purification of Pipe Drinking Water.Journal of Physics Conference Series 1176(6):062021. IOP Publishing.

Zhang H, Sun M, Song L, Guo J, Zhang L (2019). Fate of NaClO and membrane foulants during in-situ cleaning of membrane bioreactors: Combined effect on thermodynamic properties of sludge. Biochemical Engineering Journal 147:146-152.

Zhang M, Qiu L, Liu G (2020). Basic characteristics and application of micro-nano bubbles in water treatment. IOP Conference Series, Earth and Environmental Science 510(4):042050.

Zhang W, Yu S, Zhao H, Ji X, Ning R (2022). Vacuum membrane distillation for seawater concentrate treatment coupled with microbubble aeration cleaning to alleviate membrane fouling. Separation and Purification Technology 290 p.

Zhang ZH, Wang S, Cheng L, Ma H, Gao X, Brennan CS, Yan JK (2022). Micro-nano-bubble technology and its applications in food industry: A critical review. Food Reviews International pp. 1-23.

Zimmerman WB, Tesař V, Bandulasena H (2011). Towards energy efficient nanobubble generation with fluidic oscillation. Current Opinion in Colloid and Interface Science 16(4):350-356.