

A critical review of electromagnetic fields, ultrasound, and nanobubbles for membrane fouling control and cleaning: Mechanisms, applications, challenges and opportunities

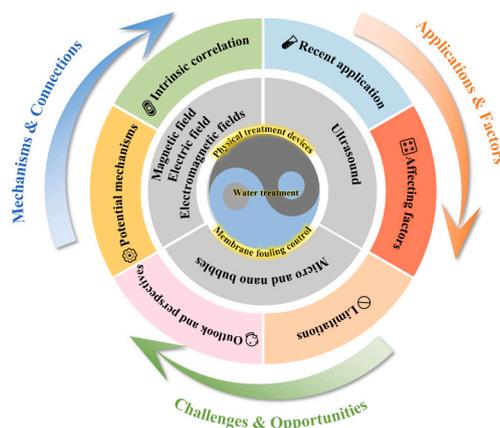
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HIGHLIGHTS

- PTDs are sustainable, chemical-free strategies for membrane fouling control.
- Interconnected mechanisms of EMFs, US, and MNBs in fouling mitigation are elucidated.
- Synergistic effects from combined PTD applications are highlighted.
- Future directions are proposed to support scalable PTD integration.

GRAPHICAL ABSTRACT



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ABSTRACT

Membrane technologies are increasingly pivotal in advancing the circular economy by enabling efficient water recovery and supporting stricter environmental regulations through the reduction of emerging pollutant emissions. However, membrane fouling remains a critical barrier to optimal performance, long-term durability, and sustainability. To overcome this challenge, physical treatment devices (PTDs) including magnetic fields (MFs), electric fields (EFs), electromagnetic fields (EMFs), ultrasound (US), and micro/nanobubbles (MNBs) have emerged as environmentally friendly and sustainable alternatives to conventional chemical cleaning. This review critically examines the current state of research on these physical treatments, particularly focusing on their distinct and shared fouling control mechanisms, integration into membrane system configurations, and practical applications. Based on mechanistic analysis, this review highlights the potential synergistic effects of combining two different PTDs to enhance cleaning efficacy, reduce chemical dependence, and lower energy demand. Notably, combinations such as EFs with MNBs or EFs with US have demonstrated substantial improvements in fouling control, however, other combined configurations such as EMFs or US with MNBs remain underexplored and need further investigation. Furthermore, this review outlines the current research limitations and identifies

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key directions for future investigation, particularly regarding biofouling, its interactions with other fouling types, fouling control mechanisms, system-level optimization, synergistic effects from combined PTDs and engineering applications. Addressing these knowledge gaps is essential to fully unlock the potential of physical treatment and advancing more efficient, sustainable, and cost-effective membrane-based water treatment solutions.

1. Introduction

Membrane-based separation technologies are playing an increasingly critical role in addressing global water challenges, driven by their efficiency, selectivity, scalability, and adaptability to diverse effluent quality requirements [1]. These technologies encompass a broad spectrum of processes, including pressure-driven methods like microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO); thermally-driven processes such as membrane distillation (MD); and osmosis-driven systems like forward osmosis (FO). Their versatility enables widespread application in areas such as desalination, wastewater treatment, process intensification, and resource recovery. As freshwater scarcity intensifies and global population rises, the need for effective water reuse and reclamation strategies becomes increasingly urgent. Membrane systems are especially vital for removing emerging contaminants and ensuring compliance with stringent standards for reclaimed water. In addition, the rapid expansion of global desalination capacity with an average annual growth rate of approximately 7% was observed between 2010 and 2019 [2]. Together, these trends underscore the expanding importance of membrane-based separation in securing sustainable water resources.

Despite the wide-ranging applications of membrane filtration, membrane fouling remains a major obstacle to its long-term performance and cost-effectiveness. Regular cleaning is necessary to restore membrane performance, with chemical cleaning often employed when hydraulic flushing alone is insufficient. However, chemical cleaning leads to chemical usage, operational downtime, and environmental impacts. According to the *Membrane Chemicals Market Analysis & Forecast*, the global membrane chemicals market is projected to grow from \$2.49 billion in 2025 to \$3.98 billion by 2032 [3]. The increasing reliance on cleaning chemicals not only incurs operational costs but also contributes to greenhouse gas emissions from chemical production, transportation, and disposal, thereby undermining the environmental sustainability of membrane processes [4,5]. To advance sustainable

water treatment and move toward net-zero carbon emissions, it is imperative to reduce both chemical and energy demands associated with membrane fouling control and cleaning [6].

To address the limitations of conventional chemical-based methods for membrane fouling control and cleaning, a variety of advanced and emerging strategies have been explored over the past decade. For example, the development of novel membrane materials with intrinsic antifouling or self-cleaning functionalities is a growing area of research. While such innovations offer long-term promise, most remain in the research. In contrast, physical cleaning devices and field-assisted technologies are currently more viable for rapid deployment in existing membrane systems. These include the use of magnetic fields (MFs), electric fields (EFs), electromagnetic fields (EMFs), ultrasound (US), and micro/nanobubbles (MNBs) [7–9]. Despite growing interest and review papers on the use of individual MFs/EFs/EMFs [10], US [11], and MNBs [12] on membrane cleaning, there remains a lack of comprehensive reviews, focusing specifically on the underlying mechanisms, integration, and potential benefits of these emerging technologies, particularly in the context of their combined applications. Research investigating the synergistic effects of integrating these techniques for membrane fouling control is still limited and fragmented despite their promising potential.

Given the potential of such integrated approaches to enable chemical-reduced and energy-efficient membrane cleaning, a systematic evaluation is both timely and necessary. This review addresses that gap by critically examining the mechanisms, applications, challenges and opportunities associated with MFs, EFs, EMFs, US, and MNBs, with a special emphasis on their combined use for sustainable fouling mitigation and some commonalities. The structure of this review is as follows: (1) introduces membrane fouling types and conventional mitigation and cleaning approaches; (2) reviews configurations employing different methods for membrane fouling control, analysing both distinct and overlapping mechanisms; (3) discusses practical applications, key operational parameters, synergistic integration, and economic considerations; and (4) outlines current limitations and future research

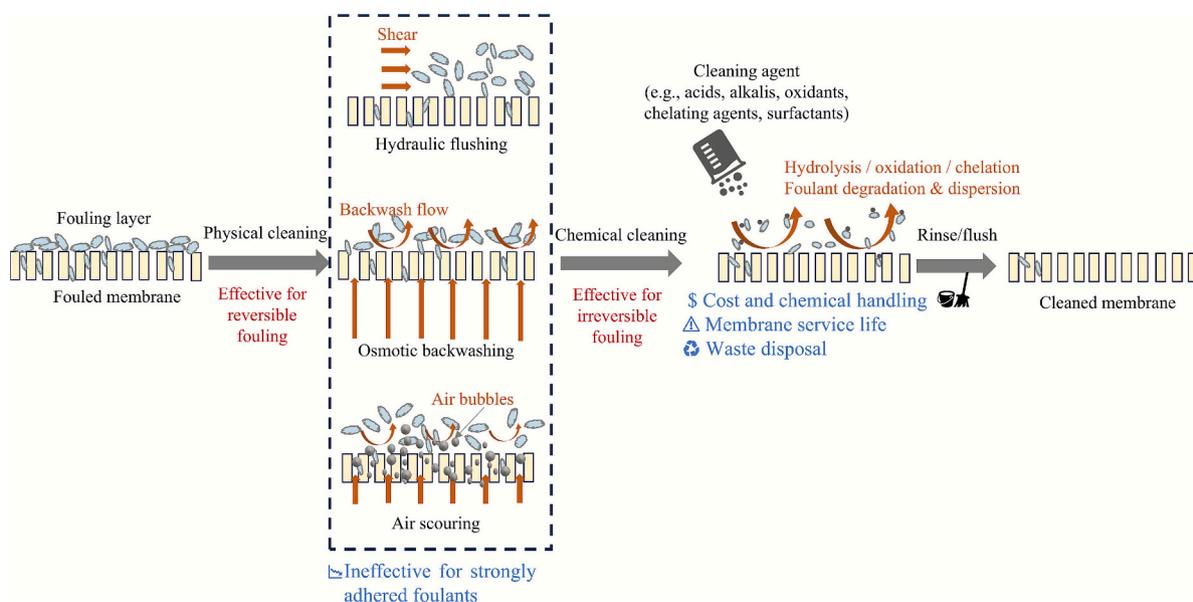


Fig. 1. Schematic illustration of conventional physical and chemical cleaning strategies for membrane fouling control, including their primary mechanisms and operational limitations.

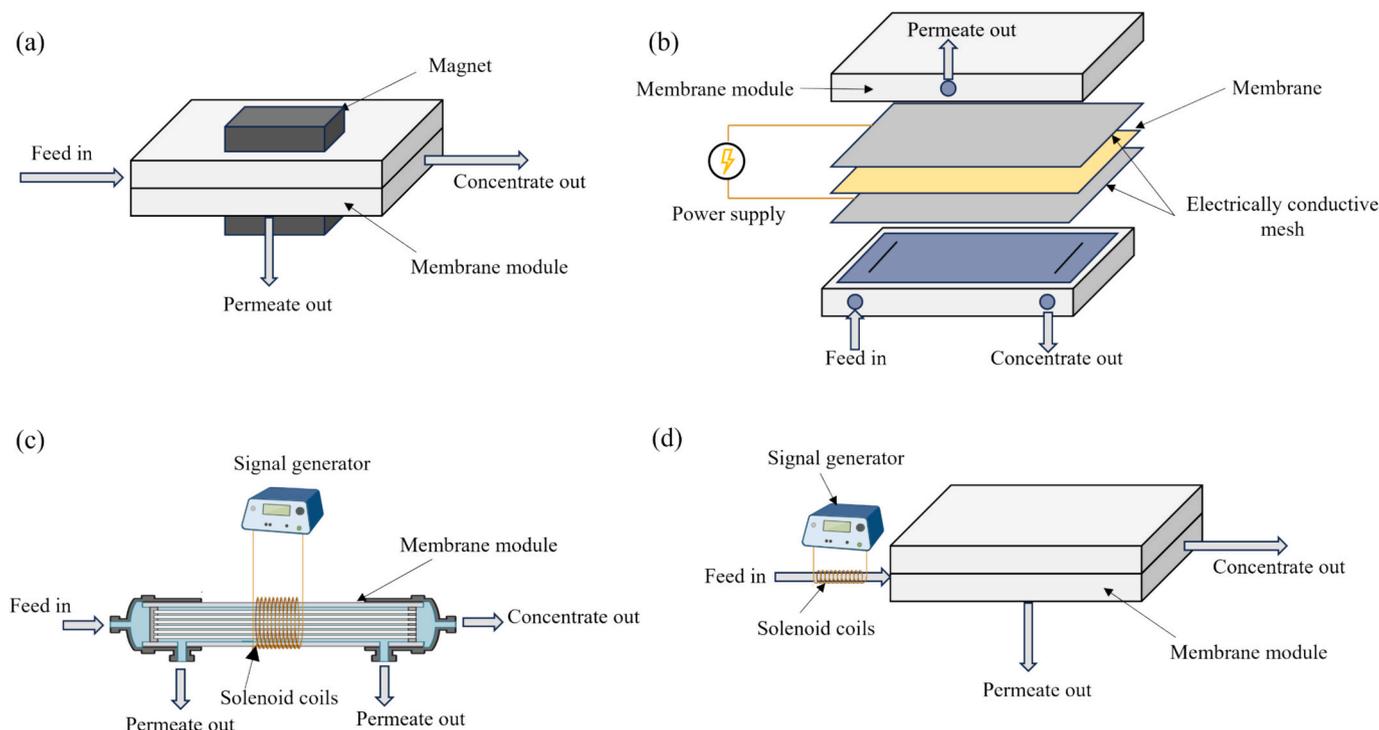


Fig. 2. MF-, EF-, and EMF-assisted membrane system configurations: (a) Permanent magnets mounted on the membrane module; (b) Metal electrodes positioned inside the membrane module, generating EFs via applied current; (c) A copper solenoid connected to a signal generator produces an EMF along the membrane surface; (d) A copper solenoid, connected to a signal generator, was installed in the feed pipe upstream of the membrane module.

directions. By comparing, contrasting, and integrating these emerging strategies, the review aims to guide future research and support the development and optimization of hybrid membrane cleaning technologies across a range of membrane systems and fouling scenarios. Together, these complementary strategies represent a shift toward more sustainable and low-impact membrane operation.

2. Membrane fouling and its mitigation and cleaning approaches

2.1. Types of membrane fouling

Membrane fouling can result from a variety of sources, including inorganic scaling, organic compounds, particulates/colloids, and biofilm formation on the membrane surface. Inorganic scaling occurs when solvent permeation increases the concentration of ions near the membrane surface beyond their solubility limits, leading to salt precipitation [13]. The fouling potential is further exacerbated by the tendency of these ions to form complexes with other molecules [14]. Organic fouling arises through multiple mechanisms and is influenced by the size and chemical nature of the organic foulant molecules. It typically involves the adsorption or deposition of dissolved or colloidal organic matter onto the membrane surface. Particulate and colloidal fouling results from the deposition of fine suspended and colloidal particles such as silt, clay, silica and organic matter, which can block membrane pores or form a surface cake layer. Biofouling results from the adhesion and colonization of microorganisms on the membrane surface, leading to the gradual formation of a biofilm that impairs membrane performance over time [15]. Collectively, these fouling mechanisms lead to the formation of a fouling layer that diminishes membrane permeability, selectivity, and lifespan [16]. Therefore, to ensure the long-term, stable operation of membrane filtration systems, it is essential to implement strategies that either control fouling formation or effectively clean fouled membranes.

2.2. Conventional methods for membrane fouling mitigation and cleaning

Membrane fouling can be mitigated and removed using a range of strategies, broadly classified into physical and chemical cleaning methods. As shown in Fig. 1, physical methods such as hydraulic flushing, osmotic backwashing, and air scouring are commonly employed to dislodge loosely bound foulants from the membrane surface and, in some cases, from internal membrane pores [17]. These techniques rely on hydrodynamic forces to detach accumulated foulants and transport them away from the membrane surface. Physical cleaning is particularly effective against reversible fouling, such as that caused by particulate matter or some organic contaminants. However, they are often insufficient for addressing irreversible fouling or biofouling, where chemical interactions or microbial activity have led to more persistent deposits.

In such cases, chemical cleaning becomes essential to restore membrane performance. Chemical methods can be applied either preventively (e.g., pretreatment with acids or antiscalants) or correctively after fouling occurs. While acid and antiscalant dosing can control inorganic scaling, they offer limited protection against biofouling and organic fouling, which often require complementary strategies. For membranes cleaning, chemical agents such as acids, alkalis, oxidants, chelating agents, and surfactants are routinely used [18] (Fig. 1). These reagents disrupt foulant–membrane interactions through mechanisms such as hydrolysis, chelation, oxidation, disinfection, and dispersion [19]. While chemical cleaning has been widely adopted in full-scale membrane operations, it poses several challenges. These include optimizing chemical dosage, managing cleaning frequency, and minimising environmental impact through appropriate waste disposal. Additionally, chemical cleaning could alter the composition of treated water, generate toxic by-products, and may have limited long-term effectiveness in controlling microbial adhesion due to the complex and adaptable nature of microbial surface structures [20,21]. Frequent cleaning may also degrade membrane materials over time, shortening membrane lifespan and increasing the risk of environmentally hazardous waste generation.

Therefore, optimizing fouling control and cleaning strategies is essential, not only for maintaining long-term membrane performance, but also for minimising operational costs and environmental impacts.

2.3. Emerging physical treatment devices (PTDs) for membrane fouling control and cleaning

Conventional physical and chemical cleaning methods act as corrective solutions that remove foulants after deposition, whereas emerging physical treatment devices (PTDs) aim to proactively suppress fouling formation during membrane operation. These technologies, including MFs, EFs, EMFs, US, and MNBs, interact with foulants at the molecular, interfacial, or microscale levels, altering their transport, aggregation, and adhesion behaviours. Their antifouling actions may involve altering surface charge and crystallization pathways (under exposure to MFs, EFs, EMFs), enhancing localized shear forces and transient cavitation effects near the membrane surface (US), or forming weakly adhesive interfacial barriers that hinder foulant deposition (MNBs). A key advantage of PTDs is that they can be applied in situ without interrupting ongoing filtration, enabling continuous fouling mitigation and reduced reliance on chemical cleaning. These technologies are also highly versatile, adaptable to a wide range of membranes and foulant types, and easily controlled through adjustable operating parameters. While MFs, EFs, and EMFs have been studied for decades, particularly for preventing scale formation in water treatment systems such as heat exchangers [10,21–23], their application to membrane fouling control and cleaning has only recently emerged as a research focus. Similarly, US [24] and MNBs [25] have shown strong potential for fouling mitigation by leveraging hydrodynamic shear, radical generation, and enhanced mass transfer at the membrane surface. More importantly, several studies have reported both capital and operational cost reductions associated with these techniques [26]. Despite these advantages, PTDs show variable performance across different system configurations and operational conditions, reflecting the complexity of their underlying mechanisms, which remain not fully understood. Further investigations are required to evaluate their adaptability to diverse membrane systems and to address remaining technical and operational challenges before widespread implementation can be achieved.

3. Overview and mechanistic basis of PTD-assisted membrane fouling control and cleaning

3.1. Magnetic, electric and electromagnetic fields in membrane fouling control and cleaning

3.1.1. MF/EF/EMF-assisted membrane system configurations

Although water magnetic treatment dates back to 1803 [27], the first study applying MFs to membrane system was conducted by Al-Qahtani in 1996 [23]. In this study, the application of constant MFs in seawater desalination using RO was found to enhance membrane performance by increasing salt rejection. MFs are commonly generated using fixed permanent magnets placed on the membrane module, without incurring additional energy consumption as shown in Fig. 2a.

The application of EFs in membrane filtration began in the 1980s, with electrodialysis representing the earliest successful demonstration of electric potential in reducing membrane fouling. However, EF-assisted fouling control in pressure- and osmosis-driven membrane processes has gained significant research attention only since the early 2000s, driven by the growing demand for advanced antifouling strategies. EFs are commonly generated by applying direct current (DC) to metal electrodes (Fig. 2b) placed within the membrane module, in direct contact with the treated water. In flat-sheet membrane systems, this setup creates an EF perpendicular to the membrane surface, promoting fouling mitigation through mechanisms such as electrostatic repulsion and electrophoresis. More recently, electrically conductive (or

electroactive) membranes have been developed by incorporating conductive materials such as metals or carbon-based additives into the membrane structure. In these systems, the membrane itself can function as an electrode, providing localized and energy-efficient control of foulant accumulation. Despite their effectiveness, both internal electrode integration and conductive membrane design present engineering challenges, including achieving uniform field distribution, minimising additional electrical resistance, and preventing long-term deterioration of membrane integrity.

Inspired by the external application of MFs using permanent magnets, several studies have investigated the external application of EMFs around hollow fibre membranes [28] or as a pretreatment step [29], with observed fouling mitigation effects. In EMF-assisted membrane filtration systems, the EMF is applied indirectly, meaning the treated solution does not come into direct contact with the electrodes or coils. Instead, coils or EMF devices are strategically positioned around the membrane module (Fig. 2c) or along the feed pipe as pretreatment (Fig. 2d), allowing for non-invasive field application. From configuration perspective, EMFs are very similar to MFs as non-invasive devices, and EMF-assisted membrane technologies are highly adaptable and promising for a range of water treatment applications, offering performance enhancements without compromising system integrity.

3.1.2. Potential fouling control mechanisms

In recent years, significant progress has been made in the study of MF, EF, and EMF antifouling techniques and their underlying mechanisms [21]. MFs can mitigate fouling primarily through magnetohydrodynamic effects, changes in ionic hydration, and alterations in crystallization or scaling behaviour, thereby reducing inorganic deposition on membrane surfaces. EFs exert influence by generating electrostatic repulsion, enhancing electrophoretic mobility of charged foulants, and promoting electrochemical reactions that suppress biofilm formation. EMFs combine these effects and further act through electrodynamic interactions, polarization phenomena, and biological responses such as microbial inhibition. Collectively, these mechanisms contribute to fouling mitigation, improved water flux, and enhanced overall membrane performance.

3.1.2.1. Hydration and magnetohydrodynamic effects. MFs and EMFs share several physicochemical effects that can influence scaling and fouling behaviour. Both fields have been reported to disrupt the structure of water by weakening hydrogen bonding and reducing intermolecular attractive forces, which increases molecular mobility, lowers surface tension, and enhances the hydration of ions [10]. Such field-induced modifications to the hydration shells of CO_3^{2-} , HCO_3^- , Ca^{2+} , and H^+ , can directly affect ion-ion interactions and the formation of prenucleation clusters, which in turn governs the early stages of mineral scaling [30]. By restructuring hydration layers and modulating ionic interactions, these effects can shift CaCO_3 nucleation pathways toward less adherent polymorphs such as aragonite or vaterite, while suppressing the formation of dense, strongly attached calcite layers [31,32]. These changes also influence crystal morphology and aggregation behaviour, producing deposits that are more porous and loosely bound, and therefore more easily removed during hydraulic or chemical cleaning.

In addition to these overlapping mechanisms, MFs and EMFs also exhibit distinct effects. Under static MFs, any magnetohydrodynamic influence is generally weak and arises only when flowing ionic species interact with the magnetic field, leading to minor modifications in ion transport and spatial distribution. By contrast, EMFs generate alternating magnetic and electric fields that induce micro-currents in the solution, producing substantially stronger Lorentz-force-driven magnetohydrodynamic effects. These EMF-induced forces enhance micro-mixing near membrane surfaces, disrupt concentration polarization, and can interfere with microbial activity and EPS production, providing

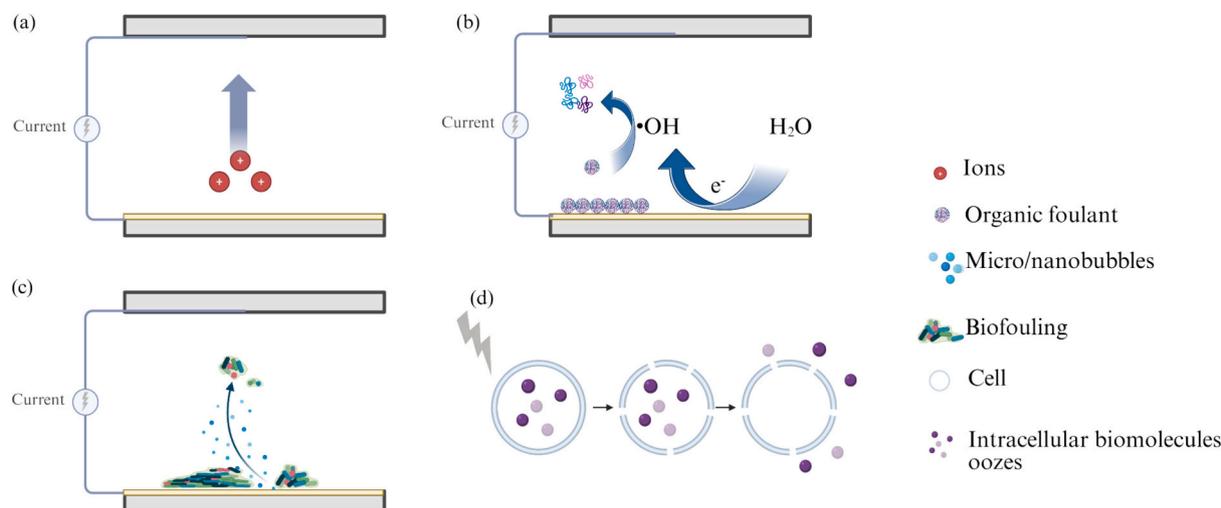


Fig. 3. EFs fouling control mechanisms: (a) Charged particles migrate away from the membrane surface via electrophoresis; (b) Hydroxyl radicals generated by electrochemical oxidation and reduction; (c) Bio-foulants dislodged by Micro and nano bubbles generated by electrolysis, and (d) Electroporation occurs when cells exposed to electric fields above a critical threshold.

additional control over organic and biofouling. However, under conditions of strong CaCO_3 supersaturation, both MF- and EMF-induced transport effects may promote homogeneous precipitation by enhancing bulk nucleation and accelerating crystallization in the solution phase [32].

Additionally, recent studies have highlighted the role of alternating magnetic fields (AMFs) in destabilizing dissolved gases in water. The continuous oscillation of the MFs can induce Lorentz forces, disrupt molecular interactions, and destabilize dissolved gases, contributing to nanobubble formation [33]. Quach et al. [34] revealed that AMFs facilitate nanobubble formation and enhance clustering interactions with CaCO_3 nanoparticles, as evidenced by light scattering and zeta potential measurements. These findings suggest that AMFs could play a significant role in membrane fouling control, potentially through nanobubble-mediated mechanisms that alter particle interactions, aggregation behaviour, and surface adhesion.

3.1.2.2. Electrodynamics. In membrane filtration systems, the application of EFs can influence fluids and particles within the system. The primary electrokinetic processes involved are electrophoresis, electroosmosis, and dielectrophoresis. Electrophoresis describes the motion of charged particles, such as ions and colloids, in response to an applied uniform EF. In membrane filtration, applying an external field can reduce fouling by driving positively charged foulants away from the negatively charged membrane surface, preventing their accumulation due to electrostatic attraction [35,36] as shown in Fig. 3a. In an alternating EF, fouling can be reduced by inducing oscillatory motion of charged particles near the membrane surface, which disrupts the formation of a fouling layer by preventing long-term adhesion, enhancing mixing, and weakening particle-membrane interactions. Electroosmosis refers to the movement of liquid through membrane pores, driven by the migration of counterions under an applied EF, which in turn enhances membrane flux [37,38]. While electrophoresis and electroosmosis act on charged species, dielectrophoresis is effective for manipulating neutral particles. When a particle is placed in a dielectric medium under a non-uniform EF, it becomes polarized, resulting in an asymmetric force distribution (stronger on one side), which drives the particle toward regions of higher field strength. This dielectrophoretic force is more strongly influenced by the EF gradient than by the applied voltage [39]. With properly designed EF strength and gradient, electrodynamic mechanisms can play a significant role in mitigating fouling in membrane systems.

3.1.2.3. Electrochemical effects. When an electric current is applied and the electrodes are in contact with water, electrolysis may occur, producing oxygen and hydrogen gas bubbles through redox reactions at the anode and cathode, respectively. In more complex feed water compositions, additional redox reactions can occur, leading to the generation of reactive oxygen species (ROS) such as hydroxyl radicals ($\bullet\text{OH}$) and hydrogen peroxide (H_2O_2) (Fig. 3b). These ROS are highly oxidative and effective in degrading organic foulants and cells. Highlighting the potential of EF-induced electrochemical effects for mitigating both organic fouling and biofouling.

In addition to chemical effects, gas bubbles generated during electrolysis can mechanically dislodge foulant layers from the membrane surface [40] (Fig. 3c). Bubbles formed on or near the membrane can also serve as physical barriers that limit foulant transport, weaken adhesion, and facilitate detachment, thereby promoting a self-cleaning effect on the membrane surface [41,42].

3.1.2.4. Biological effects. To date, various hypotheses have been proposed to explain the mechanisms by which MFs influence biofilm development, yet no definitive conclusions have been established. MFs are known to exert both stimulatory and inhibitory effects on cells, depending on their strength, frequency and duration of exposure. It was reported that MFs may alter transmembrane ion transport, disrupt bacterial cell signalling, reduce extracellular polymeric substances (EPS) production, and inhibit bacterial motility - factors that collectively reduce bacterial adhesion and hinder biofilm formation. Notably, biological responses to MFs do not follow a linear dose-response relationship [43]. In addition to these cellular-level effects, MFs may also modulate microbial physiology through interactions with radical pairs and ROS, which play essential roles in cellular redox processes. Although MFs do not create radicals directly, they can influence the spin states of radical pairs and thereby alter ROS production, potentially affecting microbial stress responses, viability, and biofilm development [44]. EMFs, which contain both electric and magnetic components oscillating in time, may exert additional biological effects that differ from those of static or low-frequency MFs. Low-frequency EMFs have been reported to influence cellular redox balance, mitochondrial activity, membrane-associated processes, and signalling pathways that regulate microbial growth and stress tolerance [45]. Although EMFs do not directly generate radicals or cause electrochemical reactions, they can still suppress or enhance biofilm formation by modulating cellular physiological processes. Despite increasing interest, the molecular and genetic mechanisms by which microorganisms respond to EMFs in

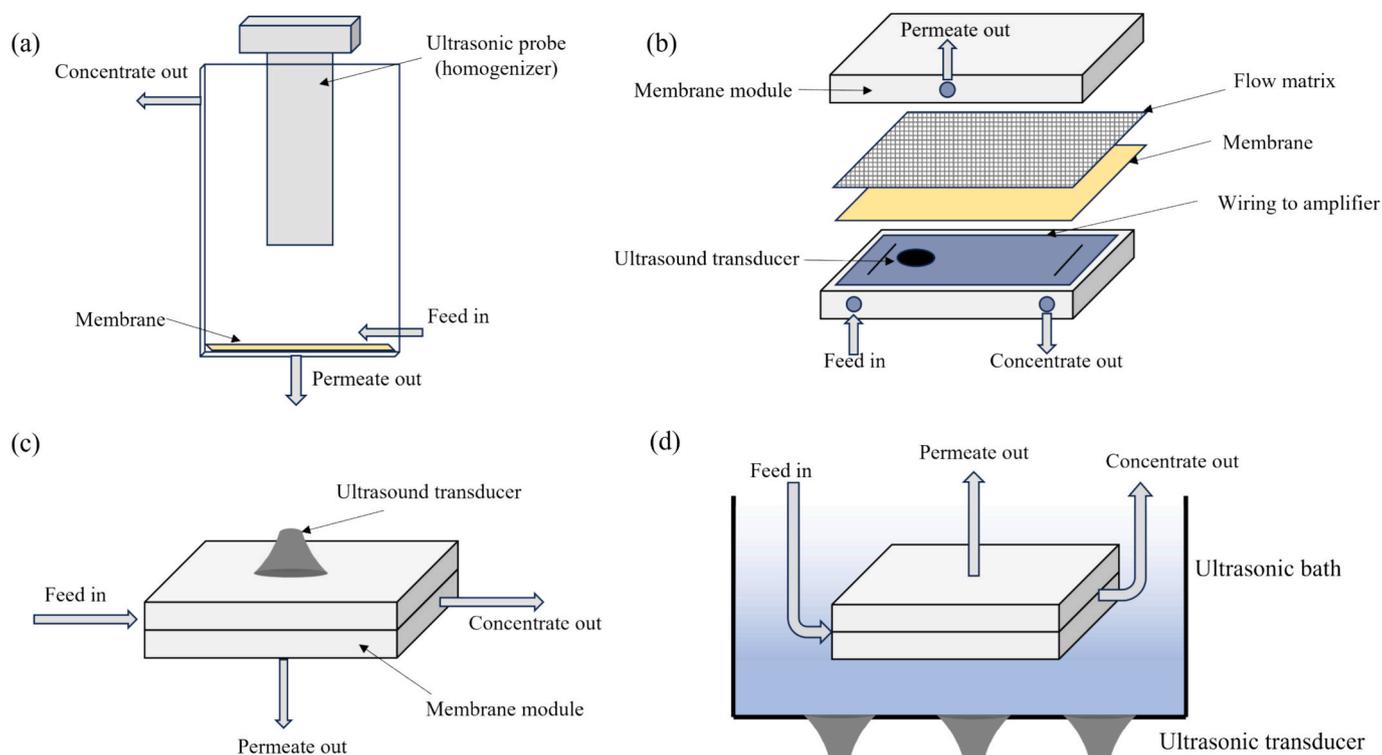


Fig. 4. Configuration diagrams of US-assisted membrane filtration systems for membrane fouling control and cleaning in research: (a) the US probe (homogenizer) is inserted into the surface of the membrane cell; (b) the US piezoelectric element is embedded into the membrane module; (c) the US transducer is placed directly on the top of membrane module; (d) US bath is used for membrane cleaning or the online fouling control.

membrane filtration systems remain poorly understood.

Electroporation is another proposed mechanism for how EF-based systems may prevent biofouling formation [21,46] (Fig. 3d). When the transmembrane voltage exceeds a critical threshold, typically around 1 V, pores are formed in the cell membrane, resulting in ion imbalance, metabolic disruption, and cellular stress [47], leading to irreversible microbial inactivation. The effectiveness of electroporation depends on multiple factors, including EF intensity, pulse width and frequency, treatment duration, temperature, microbial species and size, and the physicochemical properties of the substrate [21]. Although electroporation and electromagnetic modulation offer promising avenues for biofouling control, the biological responses of microorganisms to EFs, MFs, and EMFs remain insufficiently understood, highlighting the need for further mechanistic studies at molecular and genetic levels.

3.2. Ultrasound in membrane fouling control and cleaning

3.2.1. US-assisted membrane configurations

Compared with MFs, EFs and EMFs, US has been more widely studied, and its application for fouling control has advanced significantly since its initial introduction in the 1960s. Key timelines in its development, including recent integrations with other technologies for synergistic effects, are summarized in Fig. S1 of the Supplementary Material.

US can be applied for fouling control using either directly coupled or externally coupled configurations as illustrated in Fig. 4. In the directly coupled setup, the US source is inserted into the membrane cell as a probe (e.g., homogenizer) [48] (Fig. 4a) or integrated into the module as a thin piezoelectric element [49] (Fig. 4b). While these approaches allow efficient energy transfer at low power, their integration into standard hollow fibre or spiral-wound modules, the most common module formats in practice, remains challenging due to non-uniform energy distribution, structural incompatibility, and flow disruption [50,51]. In contrast, externally coupled configurations are more

practical for real-world applications. These include placing US transducers directly on the exterior of the membrane housing [52] (Fig. 4c) or submerging the entire module in a water bath [53] (Fig. 4d). Direct mounting on the housing shortens the propagation path of acoustic waves, reducing energy loss and improving efficiency compared with water bath setups [54]. Furthermore, externally mounted systems minimize the risk of membrane damage, which can occur in directly coupled designs due to localized high-intensity exposure [55]. Such features make external configurations particularly promising for large-scale processes. However, because US energy must still transmit through the housing and surrounding liquid, wave attenuation and dispersion can reduce the effective intensity at the membrane surface, especially in dense or multi-layered modules. Overall, directly coupled configurations tend to require lower input power and provide more uniform acoustic exposure near the membrane surface, while externally coupled systems offer greater compatibility with practical module designs. Therefore, careful optimization of transducer placement, operating frequency, and power input is essential to balance efficiency, scalability, and fouling mitigation performance in real-world applications.

3.2.2. Potential fouling control and cleaning mechanisms

3.2.2.1. Physical effects. As shown in Fig. 5, US mitigates membrane fouling through several cavitation-related and flow-induced physical effects. The fundamental process underlying these phenomena is acoustic cavitation, in which microbubbles nucleate, grow, and undergo cyclic expansion and contraction under the alternating compression and rarefaction phases of the acoustic field (Fig. 5a). When the acoustic pressure exceeds a critical threshold, some cavitation bubbles collapse, releasing localized energy in the form of microjets, shockwaves, and intense shear forces that dislodge foulants. These collapse-driven effects operate alongside non-collapse mechanisms such as microstreaming and acoustic streaming, which collectively form the basis of US-enhanced

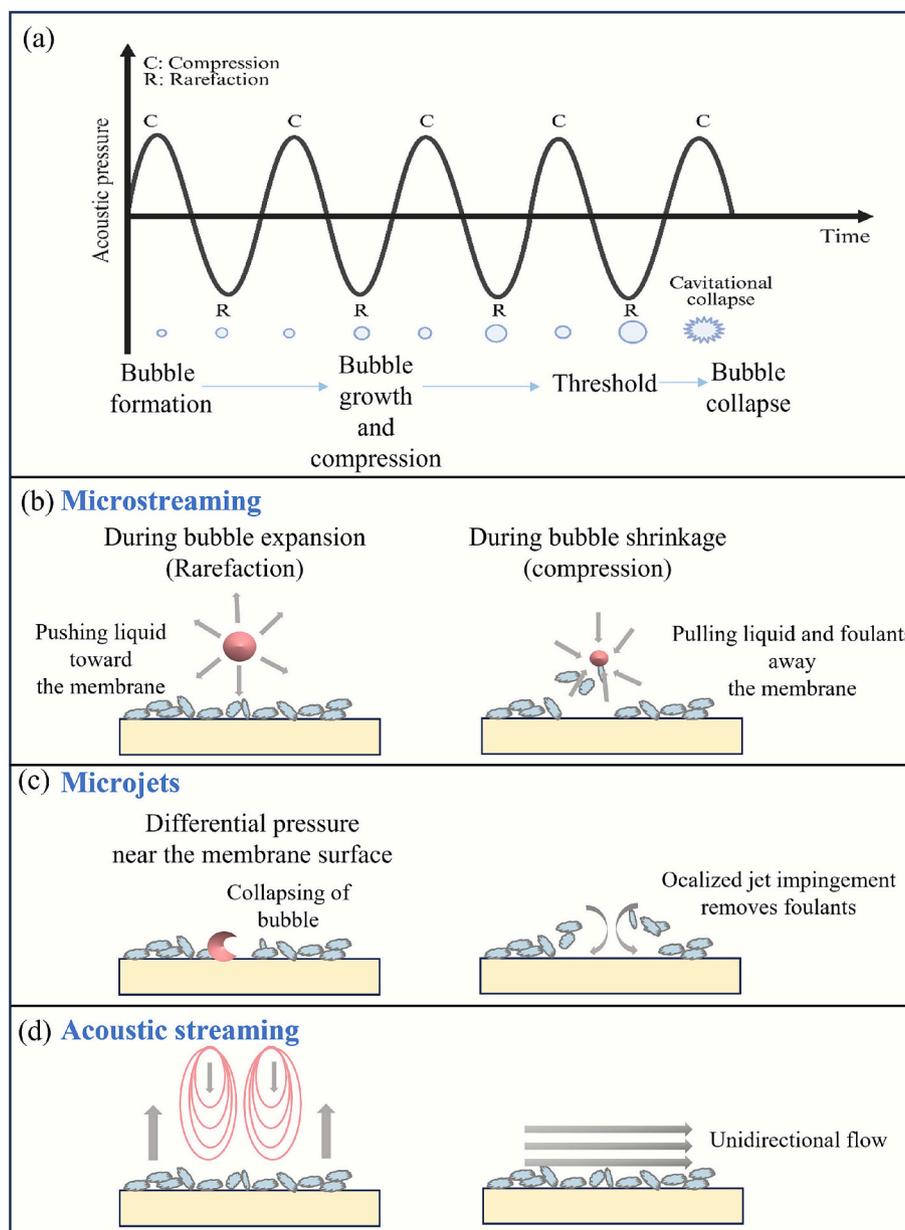


Fig. 5. Schematic illustration of the major US-induced physical mechanisms involved in membrane fouling mitigation. (a) Acoustic cavitation: bubble nucleation and oscillation under alternating compression and rarefaction. (b) Microstreaming: localized oscillatory flows generated around an oscillating bubble, producing shear fields that weaken foulant–surface adhesion. (c) Microjets: formation of high-velocity jets during asymmetric bubble collapse near the membrane, resulting in localized impingement and foulant removal. (d) Acoustic streaming: bulk unidirectional flow produced by ultrasound propagation and cavitation activity, generating shear currents parallel to the membrane and transporting detached particles away from the surface.

fouling mitigation.

At the microscale, microstreaming arises from the radial oscillation of cavitation bubbles during their non-inertial expansion and contraction. During rarefaction, bubble expansion drives liquid toward the membrane surface, whereas during compression, bubble shrinkage draws liquid away. These rapid oscillatory flows—acting over distances of approximately 1–100 μm —generate localized shear and drag forces that weaken foulant–membrane adhesion (Fig. 5b) [56]. The most mechanically aggressive effect is the formation of microjets, which requires asymmetric bubble collapse. When a cavitation bubble is positioned near a solid surface, reduced fluid mobility on the membrane side produces a pressure imbalance that distorts the bubble shape. Upon collapse, the bubble generates a high-velocity jet (typically 100–200 m/s) [57] directed toward the membrane, causing pitting and forceful removal of strongly adhered foulants (Fig. 5c). In FO systems, US

enhances transport within the porous support layer by inducing cavitation-driven oscillations [58]. These motions redistribute accumulated solutes, reduce internal concentration polarization (ICP), and strengthen the effective osmotic driving force. As a result, substantial flux improvement can be achieved—often approaching a two-fold increase—particularly when low-frequency US (~ 20 kHz) is applied to the support side of thin-film composite membranes.

At larger length scales, cavitation activity generates acoustic streaming, a steady bulk fluid motion. Streaming velocities increase with US frequency and power intensity. When this bulk flow encounters the membrane boundary layer, the perpendicular component of motion is restricted, causing the streamlines to be redirected into strong unidirectional currents parallel to the membrane surface. These shear-rich currents assist in sweeping away loosely attached foulants (Fig. 5d). These shear-rich currents help sweep away loosely attached particles.

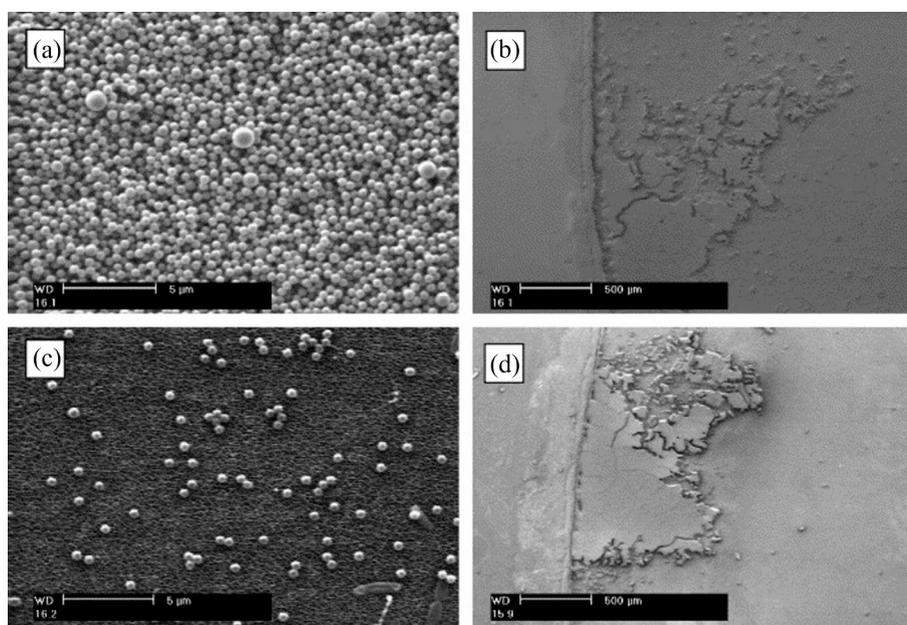


Fig. 6. Effect of membrane orientation on ultrasonic cleaning efficiency. SEM images (a) and (b) show the same membrane treated with US at 620 kHz, 0.21 W/cm² for 5 s with the fouled surface facing away from the transducer; (c) and (d) show the same membrane treated under identical conditions but with fouled surface facing the transducer. Adapted from [56].

Evidence from ultrasonic cleaning experiments further clarifies the contribution of acoustic streaming. Cleaning efficiency at low power intensities depended strongly on membrane orientation: the cleaned flux ratio increased from 0.78 to 0.94 when the fouled surface was oriented toward the transducer [56]. SEM images (Fig. 6) corroborate this orientation-dependent behaviour. However, this dependence diminished at higher power intensities (>1.05 W/cm²) and lower frequencies (<205 kHz), where collapse-driven cavitation dominant. Under these conditions, both orientation-dependent behaviour exhibit similar degrees of particle removal. The orientation effect at low power indicates that acoustic streaming, which is directional, mainly transports already-detached particles. At higher power and lower frequencies, the loss of orientation dependence shows that cavitation, which is non-directional, is responsible for detaching strongly adhered foulants.

Consistently, when 20 kHz US was applied to a silica-fouled ceramic membrane, the highest flux enhancement occurred when the membrane was positioned close to—but not within the cavitation zone, where cavitation activity and associated hydrodynamic effects are strongest [59]. Together, these physical processes weaken foulant–membrane interactions and enhance cleaning performance. Overall, cavitation mechanisms (e.g., microstreaming and microjets) are primarily responsible for foulant detachment, whereas acoustic streaming promotes post-detachment particle transport. In addition to mechanical effects, adiabatic heating during bubble collapse also generates transient high temperatures, which can promote eddy diffusion at the membrane and further improve mass transport.

3.2.2.2. Chemical and biological effects. Beyond its physical mechanisms, US also contributes to fouling control through chemical and biological effects. Cavitation-induced bubble collapse can generate reactive species such as •OH, •H, and H₂O₂ [60]. These species degrade organic foulants by breaking down complex macromolecules into smaller, more soluble compounds. In the context of biofouling, the reactive species generated by US can degrade EPS secreted by microbial cells, thereby weakening the biofilm matrix and facilitating the detachment of both bacterial cells and EPS [61]. Moreover, US has been reported to disrupt bacterial quorum sensing (QS) systems, a communication system that regulates biofilm formation by inhibiting signalling

molecules such as autoinducer-2. While these findings highlight the potential of US for biofouling mitigation, further research is needed to clarify its effects on EPS compositions and QS signalling pathways in complex, mixed-species systems, particularly within membrane filtration processes.

3.3. Micro/nanobubbles in membrane fouling control and cleaning

3.3.1. Micro/nanobubble generation and practical application

MNBs are microscopic gas bubbles classified as microbubbles with diameters of less than 100 μm and nanobubbles measuring under 1000 nm. The first direct observation of bulk nanobubbles (<1 μm) was reported in 1981 [62] followed by evidence of stable nanobubbles in the 40–300 nm range in 1982 [63]. Compared to macrobubbles, MNBs exhibit a much larger gas-liquid interfacial area, longer residence time, slower rising velocity, and elevated internal pressure. These characteristics result in enhanced gas-liquid mass transfer and improved gas solubility in water. As a result, MNBs have demonstrated promising potential across various applications, including drug delivery, microbial growth enhancement, mineral flotation, water and wastewater treatment [64].

Growing interest in MNBs has led to extensive research into scalable and energy-efficient generation methods. Common techniques include hydrodynamic cavitation, acoustic cavitation, electrolysis, solvent exchange, and nanoporous membrane method, each offering distinct advantages and limitations in terms of scalability, efficiency, and applicability. Hydrodynamic cavitation, widely used in commercial systems, induces bubble formation through rapid pressure drops in constricted geometries (e.g., Venturi tubes), triggering vapor nucleation and collapse. Electrolysis produces nanobubbles via gas evolution at the electrodes, leading to localized supersaturation. Acoustic cavitation utilizes US-induced pressure oscillations to form cavitation nuclei, which can evolve into stable nanobubbles; however, this approach remains difficult to scale [65]. The nanoporous membrane method introduces gas into nanoscale pores of membrane under pressure, facilitating bubble release into the liquid phase [66]. External electric/magnetic fields were also reported recently to be able to generate MNBs [34,67]. Several recent review articles provide detailed comparisons of

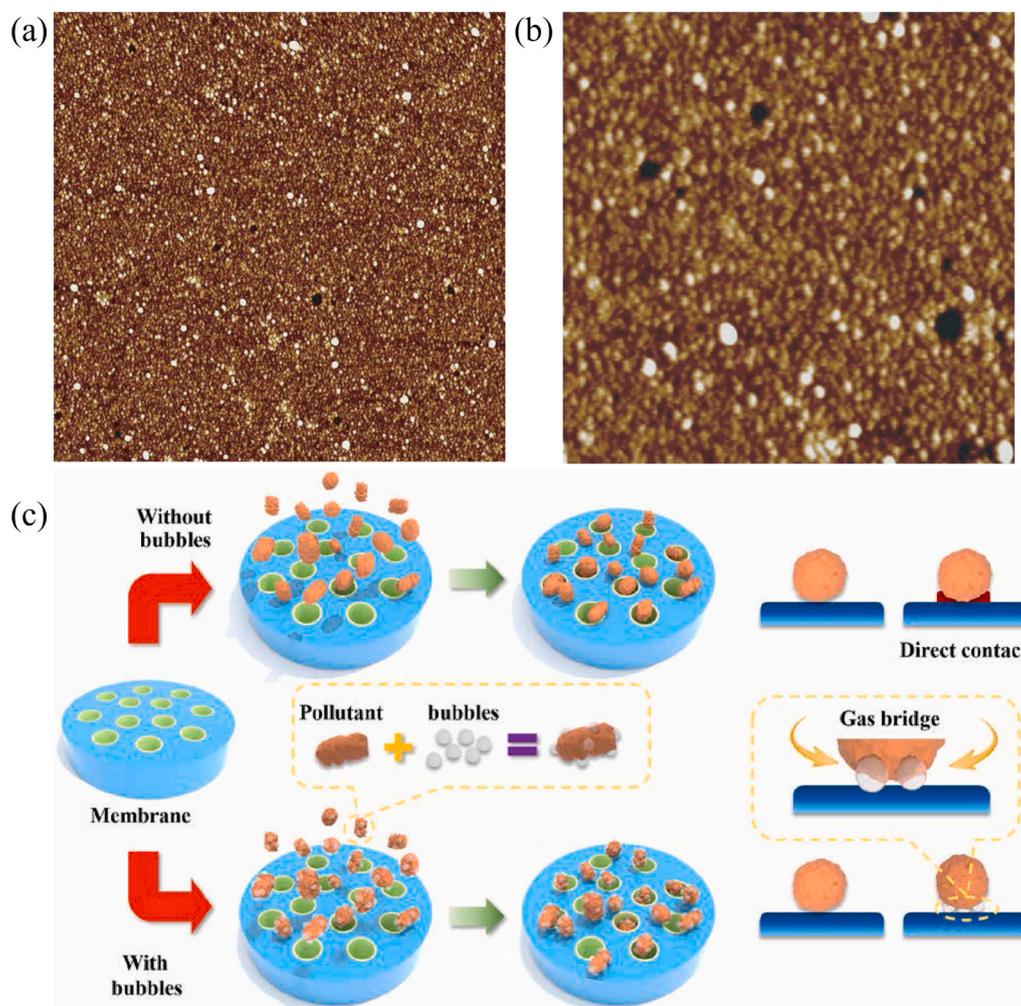


Fig. 7. (a, b) AFM images in air of a BSA film adsorbed on a mica surface showing the presence of interfacial nanobubbles (scan sizes: $3 \times 3 \mu\text{m}$ and $1 \times 1 \mu\text{m}$; z-range: 3 nm), adapted from [80]. (c) Schematic illustration of the gas-bridge effect and the resulting improved foulant removal on membrane surfaces, adapted from [82].

these MNB generation methods [65,68]. Each technique presents trade-offs. While hydrodynamic cavitation is highly scalable and commonly applied, acoustic and solvent exchange methods face limitations in large-scale implementation. Electrolysis is generally restricted to gases such as hydrogen and oxygen. Developing scalable, efficient, and cost-effective MNB generation technologies remain essential for enabling broader industrial applications.

Beyond generation, the practical application of MNBs is critical for effective membrane fouling control. MNBs can be introduced directly into the feed stream, where continuous or intermittent dosing provides hydrodynamic scouring, Brownian-motion-driven interactions, and interfacial charge effects that weaken foulant-membrane adhesion and suppress cake-layer formation. In addition to online dosing, MNBs can also be applied in a side-stream or pretreatment mode, in which an external generator injects bubbles into a recirculation or feed-conditioning loop before the solution enters the membrane system. This approach allows flexible integration without altering the primary flow conditions while improving the physicochemical characteristics of foulants prior to filtration. MNBs are further used for fouling removal through MNB-assisted backwashing or cleaning-in-place (CIP). Their nanoscale size allows them to penetrate dense fouling layers, and the collapse or shrinkage of bubbles generates localized shear forces that detach and mobilize accumulated foulants. As a result, MNB-assisted cleaning has demonstrated superior flux recovery compared with conventional physical or chemical cleaning [69,70], and MNB-enhanced

CIP has shown improved removal of organic, inorganic, and biological foulants from RO and UF membranes while reducing chemical consumption [71,72]. Overall, these application modes highlight the versatility of MNBs and their growing potential to improve fouling mitigation and cleaning efficiency in diverse membrane systems.

3.3.2. Potential fouling control and cleaning mechanisms

3.3.2.1. Hydrodynamic effects. The small size of MNBs results in elevated internal gas pressure, which accelerates gas diffusion and promotes bubble shrinkage and eventual collapse [73]. This dynamic process enhances gas-liquid mass transfer, thereby improving foulant removal and membrane cleaning efficiency [74]. In addition, the interaction of MNBs with surrounding fluid generates localized turbulence, disrupting concentration boundary layers and sweeping the membrane surface to inhibit foulant deposition. This contributes to sustained permeate flux and consistent salt rejection [75]. Beyond turbulence enhancement, MNBs exert a gentle scouring effect, physically dislodging foulants through abrasion at the membrane interface [76]. Their micro- and nano-scale dimensions enable them to penetrate narrow pores and surface irregularities, allowing for more thorough cleaning than conventional methods [77]. Furthermore, their high specific surface area facilitates contaminant adsorption and detachment.

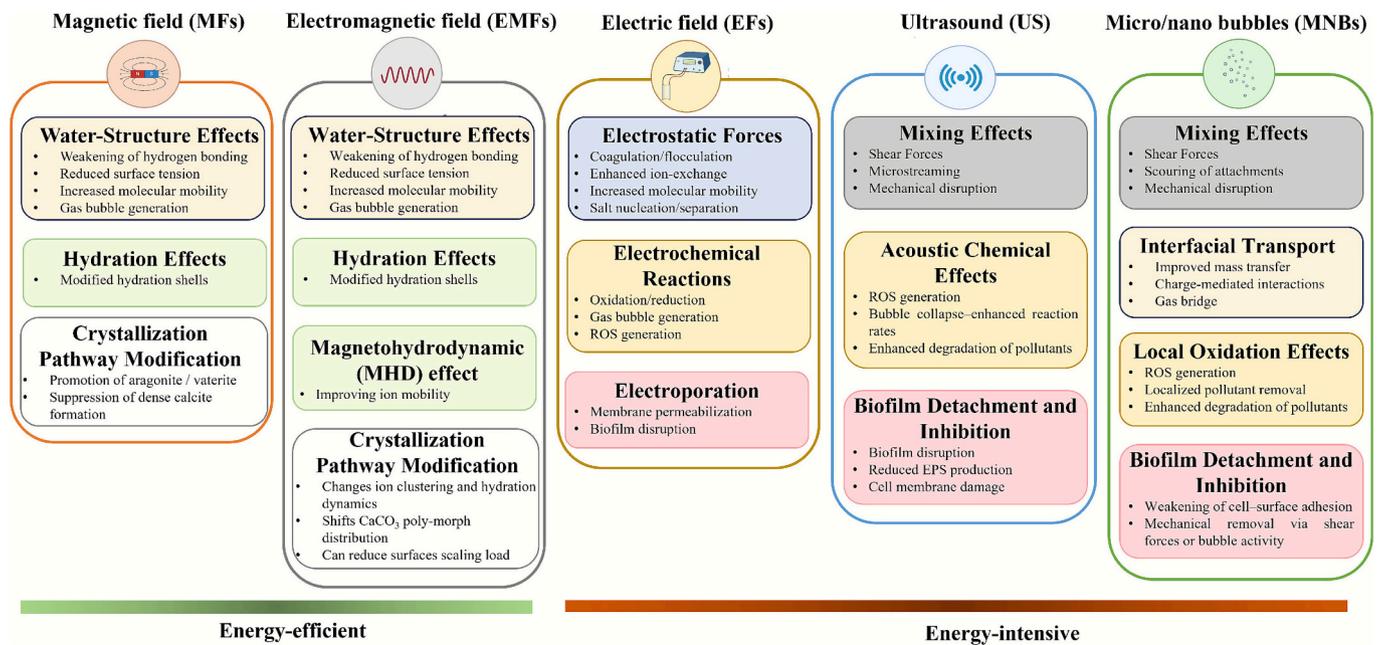


Fig. 8. Comparison of the mechanistic pathways through which MFs, EMFs, EFs, US, and MNBs act to mitigate membrane fouling.

3.3.2.2. *Gas bridge effects.* The gas bridge effect is a phenomenon observed in water treatment process where MNBs form a protective interfacial barrier between foulants and the membrane surface, preventing direct contact and adhesion [77]. This barrier reduces the deposition of contaminants such as suspended solids, organic compounds, and biofoulants by exposing them to a gas-liquid interface rather than the membrane material. Studies have shown that MNBs can facilitate the aggregation of dispersed pollutant particles, forming larger flocs that can be more easily separated from water. This behaviour is attributed to the gas coating effect, which enhances inter-particle bridging and aggregation [78].

Experimental evidence strongly supports this mechanism [79,80]. Atomic force microscopy (AFM) imaging of bovine serum albumin (BSA) films adsorbed on mica in Fig. 7a,b has shown that the regions covered by interfacial nanobubbles substantially reduced BSA adsorption compared with adjacent bubble-free areas, confirming that MNBs act as physical barriers that inhibit foulant-surface adhesion [80]. Additional force-spectroscopy studies have shown that nanobubbles can coalesce to form gaseous capillary bridges between approaching surfaces in aqueous environments, further validating MNB-mediated interfacial separation [81]. These findings demonstrate that MNB-modified interfaces weaken foulant attachment strength and alter surface interaction behaviour. Even when deposits form, the weakened foulant-membrane interactions allow contaminants to detach more easily during hydraulic or physical cleaning cycles, as illustrated in Fig. 7c [82]. Thus, the gas bridge effect provides a mechanistically and experimentally validated basis for the antifouling and self-cleaning advantages of MNBs in membrane systems.

3.3.2.3. *Electrostatic interactions and ion distribution.* MNBs can mitigate membrane fouling through electrostatic interactions that modify ion distribution and surface charge. Owing to their highly negative surface charge, MNBs attract cations such as Ca²⁺ and Mg²⁺ to their gas-liquid interfaces [25], decreasing the likelihood of cation-anion pairing and subsequent inorganic precipitation. These interactions also influence foulant adhesion behaviour. For example, negatively charged foulants can be repelled to prevent deposition, while weakly bound particles may be attracted and destabilized to facilitate removal. MNBs retain their negative charge over a wide pH range, contributing to enhanced colloidal stability and fouling prevention under varying operational conditions [83]. Their elevated zeta potential further prevents bubble

coalescence, prolongs contact time with suspended particles, and improves foulant detachment efficiency [84]. Collectively, these electrostatic effects support more stable and sustainable membrane performance during extended operation [85].

MNBs also affect inorganic scaling, particularly calcite formation, through ion regulation and surface charge-mediated interactions. At pH > 5, nanobubbles acquire negative surface charges due to OH⁻ adsorption, which facilitates the adsorption of Ca²⁺ ions onto their interfaces. This reduces the free Ca²⁺ concentration available to interact with CO₃²⁻, lowering the Ca²⁺/CO₃²⁻ ratio at the liquid-solid interface. As a result, the nucleation and growth of CaCO₃ crystals are suppressed [86]. Additionally, MNBs promote the conversion of CaCO₃ from calcite, the more stable and tightly bound crystalline form to aragonite, a less adherent and more easily removable polymorph, reducing the severity of membrane scaling [87].

3.3.2.4. *Radical effects.* The collapse of MNBs generates highly localized high pressures and temperatures, inducing cavitation and forming ROS such as •OH, O₂^{•-}, and singlet oxygen (¹O₂) [88]. Among these, •OH radicals have been identified as the dominant oxidative agents, particularly in systems using oxygen nanobubbles [89]. Similar to cavitation in US, the ROS generated induce oxidative degradation of organic molecules and microbial cells, thereby weakening foulant structures and enhancing their removal by shear forces. However, the short lifespan of ROS limits their capacity for complete foulant degradation and may pose risks of membrane material degradation over time. Extending ROS activity requires continuous MNBs generation, leading to higher energy consumption when using traditional hydrodynamic cavitation. Therefore, effective application of MNBs for fouling control requires a careful balance between cleaning efficiency, membrane integrity, and energy demand or a novel MNB generation method with low cost.

3.4. Interconnected mechanisms and synergistic interactions among MFs, EFs, EMFs, US and MNBs

Among the various technologies investigated for membrane fouling control such as MFs, EFs, EMFs, US and MNBs, there exist both distinct mechanisms and substantial mechanistic commonalities, particularly involving bubble dynamics, radical oxidation, and electrostatic interactions. While each operates through different physical principles,

their effects often converge on the disruption of foulant layers through localized shear, interfacial turbulence, chemical oxidation, and manipulation of charged species in the feedwater. Fig. 8 illustrates both unique and overlapping mechanisms of these technologies for membrane fouling mitigation.

MFs, EFs, and EMFs influence fouling primarily through modifications to the ionic and electrostatic environment. EFs induce electrophoretic motion, electrostatic repulsion, and electrochemical ROS generation, directly affecting the transport and attachment behaviour of charged colloids, proteins, and microorganisms. MFs and EMFs alter ionic mobility, ion clustering, and hydration structures, potentially weakening foulant adhesion or modifying interfacial forces at the membrane surface. Importantly, recent studies indicate that MFs, EFs, and EMFs may also contribute to bubble-related processes. AMFs have been shown to promote nanobubble clustering in CaCO₃-containing water [34], while external EFs were recently reported to generate metastable bulk nanobubbles for the first time [90]. EMFs may also alter ion distribution at bubble interfaces, potentially facilitating bubble formation or stabilization [67]. These findings demonstrate that bubble-mediated effects, traditionally attributed to US and MNBs, also play a role in field-based fouling control methods.

US and MNBs introduces complementary mechanical and interfacial mechanisms. Low-frequency US (20–40 kHz) generates cavitation bubbles that undergo rapid oscillation and collapse, producing hydrodynamic shear, localized turbulence, and cavitation-induced ROS formation. Increasing US power intensifies bubble generation and collapse, thereby enhancing foulant detachment and near-surface mixing [91]. MNBs contribute additional bubble-related mechanisms—including bubble generation, bubble dynamics, surface-charge-driven interactions, and O₂/O₃-derived ROS production—and can either collapse to release mechanical energy or persist to provide long-term interfacial scouring and oxidation.

Because many of these technologies share overlapping mechanisms, synergistic interactions often emerge. Bubble generation, common to all five technologies, provides a central foundation on which several mechanisms operate. These bubble-mediated phenomena can be initiated or intensified through different pathways—for example, acoustic cavitation under US, gas destabilization under MF or EMF exposure, and in situ nanobubble nucleation under applied EFs. Beyond bubble formation, several technologies also converge on radical oxidation mechanisms. Similarly, ROS pathways can originate from electrochemical reactions (EF), cavitation collapse (US), or bubble interfaces (MNBs), collectively intensifying oxidative cleaning. Although some biological studies have reported EMF-induced oxidative stress within microorganisms, these effects arise from intracellular metabolic responses rather than ROS generation in the bulk solution. Additional mechanistic overlap exists in electrostatic and ionic manipulation processes. EFs directly induce electrophoretic motion and electrostatic repulsion, whereas MFs and EMFs influence ionic mobility, hydration structures, and ion clustering. MNBs contribute further electrostatic effects through their inherently negative surface charge, which modulates particle interactions, fouling-layer permeability, and bubble–surface behaviour.

These interactions reveal a central unifying theme: detachment-dominant mechanisms (e.g., cavitation, shear, microjets) and transport- or oxidation-dominant mechanisms (e.g., ROS, electrophoresis, hydrodynamic flow) mutually reinforce one another. Surface-charge and electrostatic mechanisms (EFs, EMFs, MNBs) can enhance bubble dispersion, increase bubble–foulant interactions, and improve the access of mechanical or oxidative forces to the membrane surface. In addition, field-induced changes in ionic mobility and hydration structure (MFs, EFs, EMFs) may improve cavitation efficiency or bubble stability when combined with US or MNBs. From a practical perspective, EF- or US-induced bubbles can complement MNB-based cleaning by coupling gas–liquid interfacial interactions with mechanical scouring. Reactive MNBs combined with US may produce substantially enhanced cleaning through the coupled action of oxidative and mechanical forces,

surpassing the performance of either mechanism alone. MNBs may also act as highly effective cavitation nuclei, amplifying ultrasonic bubble activity and increasing the intensity of acoustic shear and collapse events. EMFs may enhance MNB stability and dispersion, increasing bubble–foulant contact time and improving antifouling performance. The negative surface charge of MNBs may further interact with external electric or magnetic fields, improving bubble distribution near the membrane surface and strengthening hybrid cleaning strategies.

The synergistic interaction between EFs and US observed in electroacoustic microfiltration provides direct evidence that combined physical fields can amplify bubble-, electrokinetic-, and hydrodynamic-based fouling mitigation mechanisms [92]. This enhancement was attributed to mutually reinforcing mechanisms, including weak but coordinated electrophoretic and dielectrophoretic mobility, cavitation-induced bubble oscillation and expansion, local acoustic radiation forces, and field-induced alterations to foulant agglomeration and deposition patterns. Neither EFs or US alone in this study produced meaningful foulant detachment, but together they generated sufficient combined mechanical and electrokinetic forces to disrupt particle deposition, reduce cake resistance, and improve foulant back-transport. The work also highlighted that synergy is strongly modulated by EF strength, acoustic frequency, foulant composition, and pH, emphasizing the sensitive interplay between ionic environment, bubble dynamics, and particle–membrane electrostatic interactions. These findings reinforce the broader conclusion that hybrid field-based processes—like those combining MFs, EFs, EMFs, US, and MNBs—benefit from convergence of complementary mechanisms that together exceed the performance of each technology individually.

Overall, although MFs, EFs, EMFs, US, and MNBs differ in their fundamental physics, they exhibit substantial mechanistic overlap and complementarity—as illustrated in the Venn diagram—including shared contributions from bubble generation and collapse, ROS-based oxidation, electrokinetic interactions, and hydrodynamic forces. These converging mechanisms highlight the potential of hybrid operation to amplify individual effects, reduce energy consumption, and improve long-term membrane performance. Continued investigation of foulant transport, bubble dynamics, and field-induced interfacial effects will be essential for fully understanding and optimizing the synergistic behaviour of these technologies.

4. Applications for membrane fouling control and cleaning and their economic considerations

4.1. Magnetic, electric and electromagnetic fields

4.1.1. Magnetic fields

MFs have demonstrated promising effectiveness in mitigating membrane fouling in both laboratory and pilot-scale systems, as summarized in Table S1 of the Supplementary Material. For example, Gao et al. [93] reported that applying 0.5–0.6 T MFs using neodymium iron boron (NdFeB) magnets altered CaCO₃ crystallization in RO systems, promoting the formation of looser aragonite structures that were more readily removed during cleaning. In UF treating BSA-containing water, application of a 0.7 T MF improved permeate flux by approximately 90% [94]. This enhancement was attributed to modifications in the electric double-layer conformation and the net charge of protein molecules, which increased colloidal stability and repulsive interactions among BSA aggregates, thereby reducing their deposition on the membrane surface and improving filtration performance. However, the influence of MFs on organic fouling is not universally beneficial. When a static 0.4 T MF was applied during BSA ultrafiltration, no improvement in fouling mitigation was observed, and flux recovery after cleaning was even lower than the control, indicating limited magnetic responsiveness of BSA molecules [95]. This highlights that MF performance is strongly dependent on foulant type, solution chemistry, and field application strategy.

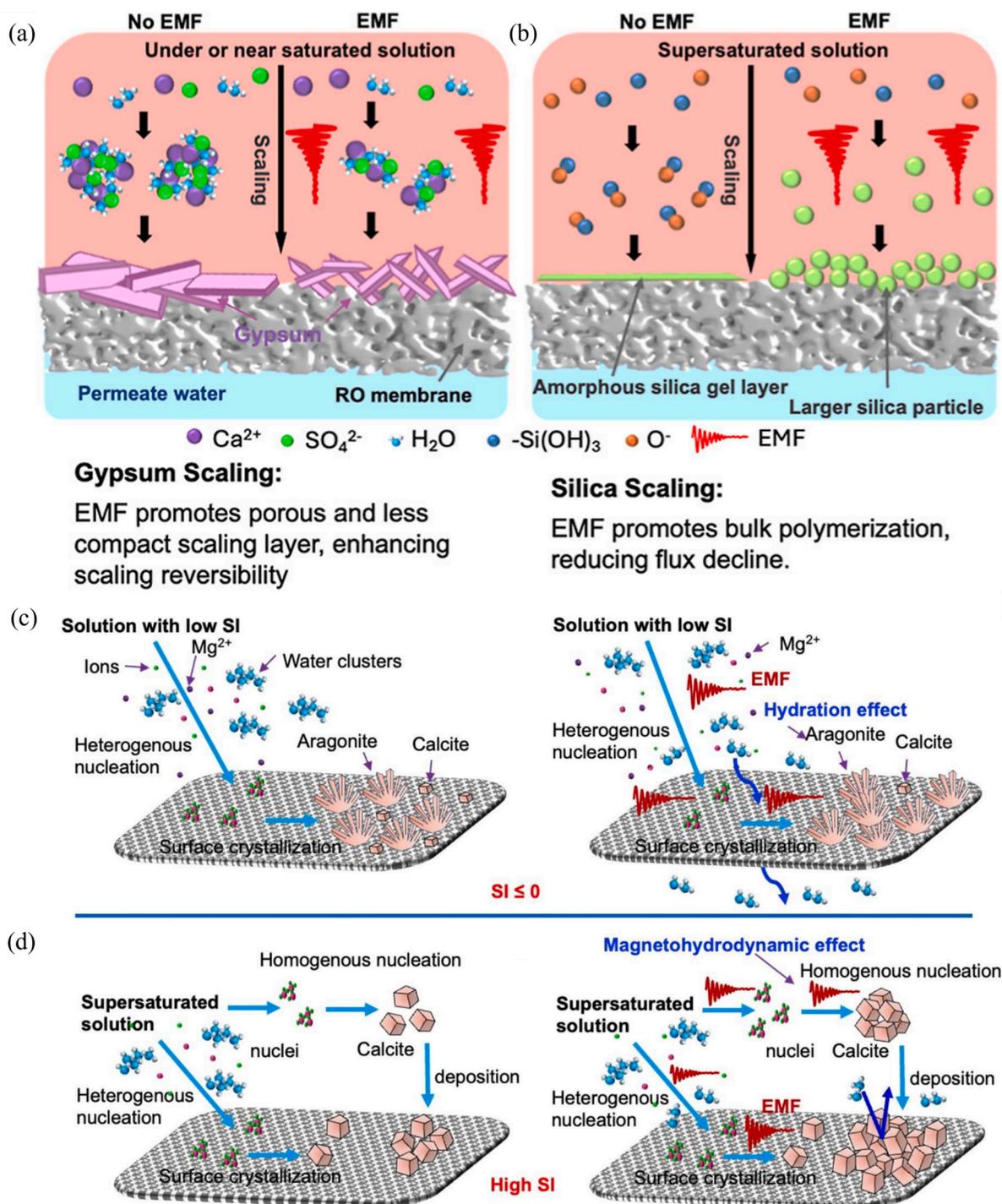


Fig. 9. Schematic illustration of the effects of EMFs on inorganic scaling in membrane systems: (a) gypsum and (b) silica, adapted from [106], and (c) CaCO_3 , adapted from [32].

The antifouling effectiveness of MFs also varies by membrane process and fouling types. NF and RO systems commonly experience severe inorganic scaling due to high operating pressures and concentration polarization at the membrane surface [96], and MFs have demonstrated strong antifouling effects in these processes by modifying crystallization pathways and reducing scale adhesion. In MD, MF exposure has been reported to enhance the reversibility of supersaturation-driven interfacial scaling. Overall, MF treatment is particularly advantageous in scaling-prone membrane systems, while applications in organic-fouling-dominated processes remain more limited and require further validation.

4.1.2. Electric fields

EFs have been widely investigated as an antifouling strategy across diverse membrane systems and water matrices, as summarized in Table S2 of the Supplementary Material. In UF and MBR operations, where charged organic and biological foulants predominate, EFs are particularly effective due to their ability to induce electrophoretic mobility and electrostatic repulsion. For example, Akamatsu et al. [97] demonstrated that applying a 6 V/cm EF in a submerged MBR significantly enhanced permeate flux by repelling activated-sludge flocs and reducing bio-cake accumulation. In UF treating humic-rich surface water, increased EF strength improved cake porosity and hydrophilicity,

resulting in 97.3 % retention of the initial flux at 20 A/m² [98]. These findings indicate that EF-assisted fouling mitigation is highly effective when foulants possess significant surface charge. EF applications have also demonstrated mineral-specific antifouling performance in RO and MD systems. Duan et al. [99] demonstrated that intermittent anodic polarization at 2.5 V in RO effectively removed CaCO₃ by locally acidifying and dissolving existing deposits, whereas continuous application of 1.5 V mainly suppressed CaSO₄ scaling by promoting bulk nucleation through counter-ion layer formation. For silica scaling in MD, alternating EFs (2 V, 1 Hz) extended the induction period for deposition from 0 to 100 min and reduced flux-decline rate by ~79 % by enhancing electrophoretic transport and shifting silicate polymerization into the bulk solution [100]. These findings confirm that the effectiveness of EF-based scaling mitigation depends strongly on the foulant mineral and the corresponding electrochemical mechanism involved. Despite these advantages, EF implementation can introduce operational challenges. Membrane materials may be vulnerable to electrochemical degradation, and additional energy demand can be substantial [101]. These trade-offs highlight the importance of carefully evaluating energy efficiency and material durability when considering the practical implementation of EF-assisted membrane systems.

4.1.3. Electromagnetic fields

The effectiveness of EMFs has been demonstrated in RO [28,32,102–104], NF [29,31] and MD [105] systems treating seawater, brackish groundwater and secondary effluent from wastewater treatment plants (WWTPs) (Table S3 in the Supplementary Material). For instance, in a pilot RO system treating brackish water, Jiang et al. [103] reported a 38.3 % increase in permeate flux over 150 h using EMFs (± 150 kHz, 1.2 W), indicating substantial antifouling benefits under practical operating conditions. The effects of EMFs on membrane scaling are strongly dependent on the foulant mineral and operating chemistry. As illustrated in Fig. 9, the antifouling performance of EMFs varies depending on the type of inorganic scaling. For gypsum scaling in RO, EMF application increased the water recovery ratio by 11 % and enhanced post-flushing flux recovery from 83 % to 100 % by promoting the formation of porous, weakly adherent crystal deposits (Fig. 9a) [106]. In silica-rich waters, EMFs shifted precipitation toward homogeneous bulk polymerization (Fig. 9b), improving cleaning outcomes by increasing post-flushing flux recovery from 95 % to 100 % and enhancing water recovery from 39.7 % to 45.8 % in the second cycle [106]. During desalination of brackish water with a low saturation index, EMFs promoted the formation of less-adherent polymorphs (e.g., aragonite instead of calcite) (Fig. 9c), which was easier to remove from the membrane during hydraulic flushing. Under strongly supersaturated conditions, bulk precipitation was enhanced due to magnetohydrodynamic effects (Fig. 9d), underscoring the importance of the saturation index and local hydrodynamics in determining EMF efficacy [32].

However, their performance may remain process-dependent. In NF and RO systems, where high pressures intensify concentration polarization and inorganic supersaturation near the membrane surface, EMFs are particularly effective at suppressing surface nucleation and enhancing the reversibility of scale layers. In MD, where crystallization at the vapor–liquid interface is a major operational challenge, emerging studies report improved scale removability under EMF exposure [105,107]. Multiple studies report improved permeate flux and reduced scaling under EMF exposure. Although EMFs have shown some potential for mitigating organic fouling [104], the available evidence remains limited, and further systematic investigation is needed to fully clarify their mechanisms and practical effectiveness for these fouling types.

The effectiveness of EMFs on membrane performance may vary depending on the specific waveform applied [92]. For instance, Piyadasa et al. [108] found that a device producing a less homogeneous waveform generated more CaCO₃ microcrystals, suggesting that waveform shape influences scaling behaviour. Similarly, biological responses to EMFs might be waveform dependent. For example, exposure to

pulsed-square wave EMFs reduced *Escherichia coli* viability, while sinusoidal waveforms enhanced it [109]. These findings suggest that EMFs may affect cellular metabolic activity and scaling dynamics differently, depending on the applied waveform. Therefore, further investigation is needed to clarify how specific EMF parameters such as frequency, intensity, and waveform impact membrane performance and fouling control.

Overall, EMFs demonstrate the greatest benefits in scaling-prone NF, RO, and MD operations, while their effectiveness in UF, MF and FO processes remains limited and requires further investigation. Continued research on parameter optimization, long-term stability, and membrane–device compatibility will be essential for translating EMFs into full-scale practice.

4.2. Ultrasound

Table S4 in the Supplementary Material summarizes the application of US across various membrane processes, including thermally driven, osmosis-driven, and pressure-driven membrane systems. US has been applied to mitigate a wide range of fouling types—including organic fouling, inorganic scaling, colloidal fouling, and biofouling—across these membrane technologies. For example, in a MD system, US at 260 W and 20 kHz refreshed the membrane interface, reducing humic acid deposition and increasing flux by over 30 % [110]. Choi et al. [24] found that 72 kHz US reduced calcium sulphate and silica fouling on cellulose acetate FO membranes. US has been widely used in pressure-driven processes, particularly UF and MF [111–116].

Key US parameters affecting fouling control include frequency, power intensity, and operation mode. Frequencies between 20 and 100 kHz and power levels from 50 to 700 W are typically used. Generally, lower frequencies and higher power enhance flux by promoting stronger cavitation and reducing concentration polarization [91,117,118]. For instance, Ehsani et al. [91] found that 20 kHz US improved mass transfer more than effectively than higher frequencies in a UF system. Increasing US power has been shown to generate more bubbles and intensify their collapse, producing strong mechanical and chemical effects that enhance permeate flux and reduce membrane fouling [52]. However, excessive power can worsen fouling. Mirzaie and Mohammadi [48] reported that while flux increased with power up to 31.57 W/cm², it declined at 39.47 W/cm² due to particle fragmentation and pore blockage.

US can be applied in pulsed or continuous modes. Pulsed mode (intermittent on/off cycles) saves energy while maintaining cavitation, whereas continuous mode boosts performance but at higher energy cost. Agi et al. [119] found that pulsed mode (0.8 s on/0.2 s off) reduced energy consumption by 20 % but had 33 % lower flux than in continuous mode. However, at equivalent effective power, pulsed mode can outperform continuous mode. For example, Heikkinen et al. [58] demonstrated that a 1-min-on/1-min-off pulsing pattern at 100 W apparent power (50 W effective power) and 20 kHz frequency achieved superior fouling control compared to continuous US at 50 W. Pulsed US also expands the cavitation zone and reduces acoustic shielding effects, highlighting the importance of optimizing pulse parameters for specific systems.

US can also be used as an offline cleaning tool. Lamminen et al. [49] showed that 30 s of US at 37.0–60.1 W restored up to 97 % of clean water flux in ceramic membranes. When combined with chemical cleaning, US can enhance cleaning performance and reduce chemical usage [120–122]. For example, US (25 kHz, 0.44 W/cm²) with NaClO (100 mg/L) achieved 84.6 % flux recovery in MF membranes, compared to 70.3 % with NaClO alone and 16.8 % with US alone [123]. US has also been effectively integrated with water flushing [124], backwashing [125,126], and EFs [127]. Despite promising results, further optimization and cost-benefit analysis are needed, especially for industrial-scale integration. Most studies have focused on flat-sheet membranes, while limited research has explored hollow fibre or spiral-wound

configurations, which are very common in industry [128]. Hollow fibre membranes have been reported to be more sensitive to US power [129], yet comparative studies on optimal US parameters across different membrane types remain lacking. Furthermore, pressure, one of the dominant factors governing cavitation dynamics, acoustic transmission, and foulant transport, has not yet been systematically assessed across different membrane processes. Its influence on US-assisted fouling control is inherently complex, as pressure simultaneously alters bubble formation, collapse intensity, cake-layer compressibility, and permeation drag, often in competing directions [11]. Given that UF, MF, NF, RO, FO and MD systems operate under fundamentally different hydraulic conditions, future studies should examine how operating pressure modulates US-fouling interactions within each membrane class. Such work, coupled with optimization of US frequency, power, duty cycle, and module design, will be crucial for achieving reliable and cost-effective implementation of US in full-scale membrane operations.

4.3. Micro/nanobubbles

MNBs have attracted growing interest in water and wastewater treatment, with an exponential increase in related publications since 2019. This renewed attention has driven increased efforts to integrate MNBs into membrane systems for fouling mitigation and cleaning, particularly following a significant surge in membrane fouling control studies and publications since 2022. **Table S5** in the Supplementary Material highlights recent advancements in the application of MNBs across diverse membrane processes.

MNBs have been predominantly applied to mitigate organic fouling and biofouling in membrane systems such as UF and MBR, where their ability to modify interfacial properties and weaken foulant-membrane interactions provide substantial performance benefits. MNBs have been shown to reduce organic fouling in UF membranes treating synthetic feedwater containing BSA, sodium alginate, and dyes, improving normalized flux by 117–149 % [130], primarily due to reduced apparent viscosity. During UF of chicken manure biogas slurry, water flux was enhanced by 58.1 % and recovery after regular cleaning improved by 19.6 % with MNB pre-treatment [131]. The improved membrane performance and alleviation of irreversible fouling is attributed to MNB-induced weakening of cation-dissolved organic matter interactions. Recent studies have shown that integrating nanobubbles into MBR systems can directly mitigate fouling and enhance operational stability. In a bench-scale study using nanobubble-assisted backwashing (NBB), membranes in MBRs exhibited markedly improved flux recovery and fouling control. Conventional tap-water backwashing (TWB) resulted in substantially greater surface fouling accumulation, with reversible fouling resistance 424 % higher than that observed with NBB, confirming the superior effectiveness of NBB in mitigating reversible fouling [69]. Beyond cleaning performance, nanobubbles can also enhance oxygen transfer under high mixed-liquor suspended solids (MLSS) conditions in MBRs, which reduces the production of soluble microbial products (SMP) and EPS that contribute to fouling [132]. Thus, integrating MNBs into MBR systems offers both biological and physicochemical advantages for fouling mitigation.

MNBs have also demonstrated utility in scaling control for RO, although such applications are less common. For instance, Dayarathne et al. [25] reported that introducing MNBs with diameters of 90 nm and 900 nm into an RO system inhibited the formation of CaSO_4 and CaCO_3 crystals, improving permeate flux to 83.0 ± 0.5 % and 86.5 ± 0.4 %, respectively, compared to 63.5 ± 0.4 % and 55.8 ± 1.0 % without MNBs. The improved antifouling performance was attributed to enhanced hydrodynamics and negative charge of MNBs with high interfacial adsorption capacity (zeta potential: -36 mV), which collectively hindered crystal growth on membrane surfaces. Additionally, MNBs have also been applied for membrane cleaning in RO, NF, and MD systems, helping reduce chemical cleaning demand [85,133–135]. However, most current studies focus on post-fouling cleaning

applications, with limited research exploring the use of MNBs for fouling prevention, indicating a need for further mechanistic and operational research [136].

Different gases used to generate MNBs can influence antifouling performance. Air-based MNBs are the most widely applied option for membrane cleaning due to their low cost, safety, and ease of operation. Their nanoscale size enhances bubble-surface interactions and localized physical effects, improving fouling mitigation, while their negatively charged surfaces help mobilize detached foulants away from the membrane. O_2 and O_3 offer additional oxidative capability through radical generation [74]. Meegoda et al. [137] reported zeta potentials of -27.0 , -22.4 , and -21.3 mV for O_3 -, O_2 -, and air-MNBs, respectively, with higher zeta potentials improving bubble stability by reducing coalescence [138]. The stronger $\bullet\text{OH}$ generation from O_2 - and O_3 -MNBs enhances mitigation of biofouling and organic fouling compared to air-MNBs [78]. Although $\bullet\text{OH}$ radicals effectively degrade organic foulants and inactivate microorganisms, their ability to prevent inorganic and particulate fouling is limited. Consequently, antifouling strategies mediated by O_2 - and O_3 -MNBs are most effective in systems dominated by biological and organic contaminants, but less efficient when inorganic or particulate foulants prevail [87]. CO_2 -MNBs can mitigate inorganic deposits by forming H_2CO_3 and locally lowering pH [139], while N_2 -MNBs (and other inert-gas bubbles) rely on non-oxidative physical and interfacial effects. Despite these functional differences, systematic comparisons under identical operating conditions are still needed to fully establish the relative performance of gas types.

It is believed that bubble size and concentration affect antifouling performance. Smaller MNBs provide higher mass transfer rates and can penetrate membrane pores to dislodge foulants more efficiently [69]. The generation of $\bullet\text{OH}$ also varies with bubble size, and higher MNB concentrations have been shown to enhance fouling removal efficiency [87]. Therefore, optimizing gas type, bubble size and concentration is critical for effective fouling control. By carefully selecting and adjusting these parameters, MNB characteristics can be optimized to effectively drive specific fouling control mechanisms.

4.4. Synergistic integration of MFs, EFs, EMFs, US, and MNBs for enhanced membrane cleaning

As discussed in Section 3.4, MFs, EFs, EMFs, US, and MNBs each exhibit distinct mechanisms for membrane fouling control each, while also sharing some mechanistic commonalities, particularly in radical oxidation, and electrostatic interactions. Each technology tends to exhibit its dominant mechanism depending on the specific operational conditions. To develop more energy-efficient and high-performance antifouling strategies, the integration of two or more complementary technologies offers promising potential. To clarify the applicability of each PTD across different membrane operations, **Table S6** in the Supplementary Materials provides a summary mapping of dominant fouling types and membrane processes addressed in recent studies. As summarized in **Table S6**, MFs and EMFs are predominantly applied in scaling-prone NF/RO/MD systems, EFs mainly target organic and biological fouling in UF/RO/MBR, US is effective across a wide range of reversible fouling types in most membrane operations, and MNBs are particularly suitable for organic and biofouling control in UF/MBR with emerging applications in RO scaling. This comparative overview enables systematic identification of optimal technology selection and potential hybrid combinations. Integration of these technologies can leverage their respective strengths or create synergistic effects, where interactive mechanisms provide performance enhancement greater than the sum of their individual contributions.

It has been found that external EFs can reduce MNB size and maintain their long-lived stability by increasing gas diffusion and reducing fluid viscosity [140]. Experimental observations further support this, showing MNBs in gas-water systems gradually increase in size after removing the static EFs [90]. In addition, EFs may contribute to dynamic

Table 1
Comparative summary of performance and economic characteristics of PTDs for membrane fouling control.

Approaches	Representative benefits	Representative drawbacks	Energy demand	Reference
MFs	No electrical input; minimal operating cost	Limited fouling mitigation effectiveness when used alone	No external power input	[26]
EFs	Effective for charged/colloidal foulants	High energy consumption at strong field intensities	Up to 8.84 kWh/m ³ (Direct energy input, baseline FO: 0.09–0.55 kWh/m ³)	[145,146]
EMFs	Reduced membrane cleaning frequency and downtime; lower operation and maintenance cost	Additional capital investment for electromagnetic modules	Energy consumption reduced from 4.7 to 4.1 kWh/m ³ compared with without EMF device (Net system energy impact)	[147]
US	Strong reversible fouling removal and cleaning capability	Energy-intensive; potential membrane surface damage at high power	23 kWh/m ³ (Direct energy input)	[143]
MNBs	Enhanced foulant detachment; potential chemical reduction	Economic data limited; generator lifespan and energy input uncertain	Insufficient quantitative cost data available	[148]

fluid behaviour by affecting the motion of MNBs in fluid. MNBs, typically exhibiting negative zeta potentials of -25 to -40 mV [90], are responsive to external EFs, influencing their movement and the surrounding fluid dynamics. When subjected to the direct or alternating EFs, MNBs can undergo electrophoresis or dielectrophoresis [90], resulting in directional migration or redistribution depending on the field strength and configuration. Such movement facilitates localized mixing and micro-convection, disrupting laminar boundary layers and enhancing mass transfer within the fluid. Moreover, the interplay between bubble movement and electro-osmotic flow can lead to increased turbulence, particularly near membrane or channel surfaces. These findings suggest that EFs not only facilitate the formation of smaller, more stable nanobubbles, but also actively contribute to dynamic fluid behaviour. Similarly, MFs have been hypothesized to be able to stabilise MNBs [141], though the combination of MFs with MNBs have not yet been explored in fouling control applications. For US, it has been studied intensively to generate MNBs through acoustic cavitation in recent years [142]. EFs can also generate MNBs [90] under specific conditions. These overlapping capabilities regarding MNB generation by EFs and US raise an interesting question: can combining EFs or US with MNBs reduce the demand of external MNB generation with other methods and lower overall energy demand? This possibility needs further exploration.

In addition, combining EFs and US has shown synergistic potential for fouling control and energy savings by integrating their complementary chemical and physical mechanisms [143]. Shen and Badireddy [92] demonstrated that simultaneous EFs and US recovered 21 % of clean-water flux, far exceeding the sum of either field alone ($4\% + 6\%$), confirming a true synergistic effect rather than additive improvement. EFs can promote electrolysis at electrode surfaces, generating MNBs of hydrogen and oxygen, which act as cavitation nuclei for US. This could reduce the acoustic cavitation threshold, enabling more intense and

frequent bubble collapses that produce localized shear forces and microjets to disrupt foulant layers more effectively. When electromotive forces alone are insufficient to repel all foulants particularly those with high mass-to-charge ratios [144], supplementing EFs with US can provide additional mechanical agitation to discourage the accumulation of foulants on the membrane surface [92].

From an energy consumption perspective, hybrid systems that combine energy-efficient methods such as MFs or EMFs with high-performance approaches like US or MNBs may enhance cost-effectiveness and operational feasibility. MFs offer low energy demand but offer limited fouling control effects. EMFs can operate at lower power while providing moderate fouling mitigation [10]. MNBs are relatively energy-efficient, leveraging ROS generation and hydrodynamic enhancement for fouling control. Their combination with EMFs could yield complementary effects of intrinsic mechanism of each. Therefore, carefully designed and evaluated combinations of technologies could balance performance enhancement with energy efficiency.

Overall, the selection of a combined antifouling strategy should not only the effectiveness of individual approach and their synergistic interactions but also the potential to minimize total energy consumption, ensuing practical and scalable implementation in real-world applications.

4.5. Economic considerations

From an economic perspective, these technologies differ in capital requirements and operational costs mainly in the form of electricity consumption, which must be considered for practical implementation. While each technology provides different levels of fouling mitigation, their economic performance varies widely depending on system configuration, operational conditions, and scale of application. To visually compare the economic and performance characteristics among PTDs, a comparative summary is provided in Table 1. MFs impose no additional electrical energy demand, since permanent magnets do not require power input during operation. The overall energy consumption therefore depends solely on the pumping requirements of the underlying membrane system, which vary with membrane type and operating configuration. Thus, MFs are considered as supplemental fouling control technologies with no energy consumption if permanent magnets are used, particularly suited for hybrid integration to enhance cost-performance balance.

EFs sometimes require higher energy input. An EF-assisted FO system may consume up to 8.84 kWh/m³ under the operating condition of 100 mA and 2.9 V [145]. This high value is dominated by the electrochemical process, as the baseline FO operation itself typically requires only 0.09–0.55 kWh/m³ for solution pumping [146]. Therefore, reducing the applied voltage (e.g., through low-overpotential electrodes) and optimizing membrane properties could substantially lower overall energy consumption.

EMF, however, offers more energy efficiency with regard to fouling control. Based on pilot-scale experiments, Vedavyasan [147] reported that EMF-assisted RO systems provide significant techno-economic advantages over conventional RO plants. While the capital cost of adding EMF is approximately 13 % higher, operation and maintenance costs are reduced by around 20 % due to lower cleaning and membrane replacement requirements, and downtime is decreased by roughly 30 %. Energy consumption per cubic meter decreases from 4.7 kWh/m³ to 4.1 kWh/m³, and high-silt density index feed water can be treated without chemical pretreatment, further lowering costs. These results highlight EMF-assisted RO as a cost-effective, energy-efficient, and low-maintenance approach for sustainable desalination.

US provides strong fouling control but is energy-intensive and may damage membranes over time. Tarleton and Wakeman [143] compared the energy efficiency of crossflow microfiltration using EFs and US and highlighted the benefits of their combined application. For a 1.4 % w/v china clay suspension, EFs alone reduced energy consumption from

39.3 kWh/m³ to 6.1 kWh/m³, whereas US increased it to 62.3 kWh/m³. Combining EFs and US offered a compromise, lowering energy to 16.5 kWh/m³ while maintaining rapid filtration. Although total power input was initially higher than in conventional filtration, energy per unit filtrate decreased substantially, and optimization could further reduce energy use by 25–60 %.

For MNBs, despite the promising potential of MNBs to enhance treatment performance and process efficiency, significant gaps remain in understanding its economic feasibility because the interest in it just surged in last few years [148]. While some pilot- and full-scale trials have provided preliminary estimates of energy and cost savings in applications such as dissolved air flotation, activated sludge aeration, and ozone production, very few studies have conducted comprehensive cost–benefit analyses for MNB-assisted membrane fouling control.

It should be noted that many reported energy-demand values are derived from laboratory- or pilot-scale studies and may therefore represent upper-bound estimates. At larger scales, improved energy efficiency, process integration, and economies of scale are expected to reduce the additional energy demand associated with these technologies. Overall, while individual physical treatment technologies offer distinct advantages in fouling control, energy efficiency, and operational costs, each also has limitations that may hinder practical implementation when used alone. MFs provide low-energy supplemental control while EFs and EMFs balance fouling mitigation with moderate energy input. US delivers strong cleaning but with high energy costs. MNBs show promise but require further economic evaluation. Therefore, when evaluating complementary characteristics of two or more of these technologies, economic cost should be considered at the same time to ensure its economic feasibility.

5. Limitations in existing research and future research directions

5.1. Mechanism understanding and systematic optimization

Despite growing interest in applying MFs, EFs, EMFs, US and MNBs to enhance membrane fouling control and validated experimental results, discrepancies in effectiveness were found in literature. These inconsistencies may stem from too many variables in different study systems.

One major source of variation is the feedwater composition, which can differ significantly in terms of solute concentration, pH, ionic strength, and the presence of colloids or particulates. Many studies also rely on model foulants such as CaCO₃, bovine serum albumin, humic acid, sodium alginate etc. at elevated concentrations to enable rapid testing. While such models are useful for assessing fouling control effectiveness and understanding the impact of physical treatments on specific foulant type, a direct comparison between different studies with difference in feedwater is challenging.

Membrane design and operational modes also vary widely. While flat-sheet membrane modules dominate laboratory-scale fouling control studies, real-world applications often use other configurations such as hollow fibre, spiral-wound, or tubular modules, for which the performance of these PTDs remains uncertain. Additionally, laboratory setups commonly use recirculation systems to facilitate testing, whereas single-pass configurations are more typical in practical operations, further complicating direct comparisons.

The design and operational parameters of the PTDs themselves introduce further variability. For field-based treatments, critical parameters include field strength, mode of application (pulsed vs. continuous), frequency, and waveform type (e.g., sinusoidal, square, triangular, sawtooth), all of which differ between studies. For MNB-based treatments, gas type, bubble size, and concentration must also be carefully selected. As shown in Tables 1–5, each study employed different sets of operational conditions, often spanning wide ranges. However, systematic optimization of these parameters is rare, as many

EMF and US devices are either commercially available units or custom-built with fixed settings, limiting the ability to control or vary treatment conditions. This lack of standardization complicates comparison and may partly explain the inconsistencies observed across studies.

The large number of variables also makes systematic investigation and relevant experimental design more challenging. To address these complexities, deeper mechanistic studies, along with the development of mathematical models and simulations, are increasingly essential for identifying the most critical factors influencing performance. It should be noted that establishing a unified mechanism for such integrated and variable-rich systems is unlikely. However, gaining detailed mechanistic insights within specific application scenarios remains both feasible and valuable.

5.2. Biofouling control and the interaction between biofilm and other types of foulants

Despite increasing interest in PTDs for membrane fouling control, many studies to date have focused on inorganic scaling. While the deposition of organic molecules, colloids and particulates on membrane surface and relevant control have also been investigated, biofouling mitigation remains relatively underexplored. EMFs, for instance, have been extensively studied for controlling CaCO₃ scaling in systems using secondary effluent, brackish groundwater, and static precipitation tests [32,103,104]. In contrast, investigation into their effects on biofilm formation are far more limited. Nonetheless, emerging evidence suggests that PTDs such as MFs, EFs, EMFs, US, and MNBs are promising in mitigating both scaling and biofouling [149,150]. For example, Xiao et al. [87,151–153] reported that EMF and MNB treatments reduced EPS production and biomineralization potential in reclaimed water systems and drip irrigation emitters. However, these studies often rely on simplified systems using model foulants or single bacterial strains such as *Pseudomonas aeruginosa* and *Escherichia coli* [154,155]. Such models fail to capture the complexity of multi-species biofilms commonly found in real water matrices, nor do they reflect microbial interactions and community dynamics that influence biofilm stability and resistance. Importantly, biofilms often interact with inorganic precipitates, particulates, and organic matter, further complicating fouling behaviour and mitigation. Biofilms can promote the formation of inorganic precipitates within the biofilm matrix. EPS typically contain high densities of ionizable functional groups, such as hydroxy, carboxy, and amide groups, facilitating the adsorption of metal ions and act as nucleation sites for mineral precipitation [156]. Particulates or inorganic precipitates in turn can act as carrier media for microbial attachment, further promoting biofilm development.

Organic molecules deposited on the membrane surface can facilitate the attachment of bacteria for biofilm formation. While nanobubbles have been shown to effectively control natural organic matter, colloids, and inorganic scaling, low concentration nanobubbles, particularly when generated using air or oxygen can increase dissolved oxygen levels, which unintentionally stimulates microbial growth, thereby aggravating biofouling. Thus, ineffective biofilm control, in turn, leads to a decline in controlling inorganic precipitation and particle deposition [87]. Therefore, in addition to the investigation of individual effects of EMFs, US or MNBs on specific foulant types, it is essential to investigate the interaction between biofilms and other types of foulants to comprehensively assess the overall effectiveness of PTDs.

5.3. Synergistic effects of integrated EMFs, US and MNBs for fouling control

As discussed in sections 3.4 and 4.4, there is great potential to create synergistic effects by combining EMFs with US, EMFs with MNBs, and MNBs with US based on mechanistic insights to overcome the inherent limitations of each individual technology. The synergistic effects from the combined EFs and MNBs, and EFs with US have been validated in

Table 2
Technology readiness and research needs of PTDs for membrane fouling control and cleaning.

Approaches	Technology readiness level (TRL)	Primary application scenarios	Key limitations	Priority future research needs
MFs	Medium (pilot-tested)	Pretreatment enhancement; supplemental fouling reduction	Limited as standalone strategy; strong dependence on feedwater chemistry	Mechanistic understanding; optimized hybrid integration
EFs	Medium (lab scale)	Surface and municipal water applications	High energy input; electrode degradation/corrosion	Low-voltage/high-efficiency systems; durable electrode materials; long-term stability
EMFs	High (pilot-verified)	RO desalination	Limited evidence of usage in other membrane systems and fouling types	Evaluation across multiple fouling types and membrane configurations; parameter optimization; mechanism exploration
US	High (pilot-tested)	Online/offline fouling control across module types	High power demand; risk of membrane damage	Intermittent/low-power optimization; integration for spiral-wound modules
MNBs	Low–Medium (emerging, lab scale)	Continuous fouling control; assisted physical cleaning	Limited cost, stability, and long-term performance data	Lifecycle assessment; long-duration operation

very recent research [92,157], but the combination of EMFs and MNBs, and US with MNBs for membrane fouling control remain unexplored despite their growing research in medical fields such as drug delivery [158]. The investigation on synergistic effects of integrated fouling control methods not only enables the development of robust, energy-efficient, and chemical-free fouling strategies at lower operational costs, but also advance our understanding of the underlying mechanisms governing each treatment method.

5.4. Engineering applicability, technology readiness, and future implementation challenges

To provide a clear engineering perspective, Table 2 summarizes the maturity level, application suitability, limitations, and key research needs of MFs, EFs, EMFs, US, and MNBs, enabling direct comparison of their deployment potential in practical membrane filtration systems. As shown in Table 2, EMF and US technologies currently exhibit the highest readiness for industrial application, whereas MFs function mainly as supplementary fouling control measures. MNBs and EFs remain promising but require further validation of long-term stability and cost-effectiveness prior to large-scale implementation. Although PTDs have been widely investigated as chemical-reducing strategies for membrane fouling mitigation, most systems remain confined to laboratory or small pilot scales.

A major knowledge gap remains in long-term performance under realistic operating conditions. Most studies are conducted over short durations with new membranes under simplified conditions, which do not fully represent the complexity of realistic water matrices and fouling dynamics. Consequently, the durability of membrane performance, structural integrity, and rejection stability under repeated PTD-assisted operation remains insufficiently understood. Encouragingly, a 60-day UF study employing intermittent US reported about a 50 % reduction in transmembrane pressure (TMP) development compared with a control system, along with decreased accumulation of high-molecular-weight biopolymers responsible for irreversible fouling [159]. No visible membrane damage was observed, suggesting that US can sustain mid-term performance while preserving surface integrity [159]. However, comprehensive long-term investigations (>6 months) covering diverse membrane types, foulant categories, and treatment cycles remain largely absent. Future research should prioritize long-term durability and aging studies, as well as optimization of energy efficiency and device–membrane compatibility.

Economic feasibility also requires further evaluation, as the additional energy demand associated with PTD operation may offset the benefits gained from reduced chemical cleaning and minimized operational downtime. Therefore, comprehensive techno-economic analyses and lifecycle environmental assessments are needed to determine their industrial viability. Such efforts are necessary to advance PTDs and their synergistic combinations from promising laboratory technologies to reliable and economically viable engineering solutions.

6. Conclusions

The adoption of PTDs presents promising, chemical-free or chemical-reducing approaches for mitigating membrane fouling in water treatment systems. MFs, EFs, and EMFs have demonstrated potential to inhibit scaling, biofilm formation, and organic fouling via mechanisms such as crystal nucleation modification and disruption of biofilm integrity. US enhances foulant removal through cavitation and shear forces, while MNBs contribute via physical disruption, oxidative stress, and improved mass transfer. Integrating these technologies can harness complementary or synergistic effects, enhancing fouling control beyond individual methods. Both EFs and US generate MNBs, potentially lowering energy demands when combined. Synergistic pairs like EFs with US intensify cavitation, producing stronger shear forces to disrupt foulants. Hybrid systems combining low-energy methods (MFs, EFs, EMFs) with effective but energy-intensive approaches (US, MNBs) offer a balance between performance and cost.

Moreover, challenges remain in translating PTDs to full-scale applications, including optimization of operational parameters, ensuring material compatibility, and managing performance variability under real-world water conditions. Future efforts should focus on the in-depth mechanism understanding and systematic parameter optimization, targeted strategies for biofouling control, especially considering its interaction with other types of foulants. The development of synergistic PTD combinations and integration with existing cleaning protocols also needs attention. In parallel, comprehensive techno-economic and environmental assessments are necessary to identify the most viable technologies. Long-term pilot-scale evaluations under practical conditions will be critical to validating real-world performance effectiveness, energy efficiency, and cost effectiveness. Addressing these knowledge gaps will support the implementation of PTDs as robust, sustainable fouling control solutions in next-generation membrane treatment systems, aligned with chemical-free operation and net-zero goals.

CRedit authorship contribution statement

Yu-Qi Li: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yong-Qiang Liu:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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