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Review

Mini critical review: Membrane fouling control in membrane bioreactors by microalgae

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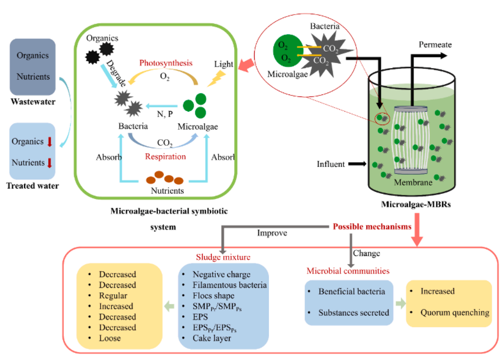
HIGHLIGHT

- Microalgae is a promising strategy for controlling membrane fouling in MBRs.
- Microalgae-MBRs can remove pollutants, save energy, and meanwhile control fouling.
- Microalgae improve the properties of sludge mixtures in MBRs to mitigate fouling.
- Microalgae influence the microbial communities to impact the extent of fouling.
- Future studies based on microalgae-MBRs is required to solve existing challenges.

GRAPHICAL ABSTRACT



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ABSTRACT

Membrane bioreactors (MBRs) hold significant promise for wastewater treatment, yet the persistent challenge of membrane fouling impedes their practical application. One promising solution lies in the synergy between microalgae and bacteria, offering efficient nutrient removal, reduced energy consumption, and potential mitigation of extracellular polymeric substances (EPS) concentrations. Inoculating microalgae presents a promising avenue to address membrane fouling in MBRs. This review marks the first exploration of utilizing microalgae for membrane fouling control in MBR systems. The review begins with a comprehensive overview of the evolution and distinctive traits of microalgae-MBRs. It goes further insight into the performance and underlying mechanisms facilitating the reduction of membrane fouling through microalgae intervention. Moreover, the review not only identifies the challenges inherent in employing microalgae for membrane fouling control in MBRs but also illuminates prospective pathways for future advancement in this burgeoning field.

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1. Introduction

Membrane bioreactors (MBRs) have gained widespread acceptance in wastewater treatment, thanks to their benefits such as minimal spatial requirements, superior effluent quality, and reduced sludge production (Mannina et al., 2023; Wang et al., 2022a). However, the persistent issue of membrane fouling requires resolution for practical application (Gao et al., 2024). Frequent physical and chemical cleanings, along with the replacement of membrane modules and mechanical aeration, significantly escalate operating costs and energy demands (He et al., 2022; Yang et al., 2022). Furthermore, excessive aeration can inhibit denitrifying bacteria and phosphate-accumulating organisms, jeopardizing the efficient removal of total nitrogen (TN) and total phosphorus (TP) (Wang et al., 2021; Zuo et al., 2024). Supplementing additional auxiliary units often becomes necessary to enhance nutrient removal, albeit at the expense of increased operational costs and footprint (Li et al., 2023; Wang et al., 2021). Consequently, the dual challenge of mitigating membrane fouling while achieving high-quality effluent persists.

The algae-bacterial symbiotic system represents an emerging methodology in wastewater treatment, where microalgae play a pivotal role in absorbing carbon dioxide (CO_2) released by bacterial respiration through photosynthesis. Concurrently, they release oxygen (O_2) which is utilized by bacteria (Huang et al., 2023). In this symbiotic relationship, bacteria degrade organics and synthesize nutrients and carbon sources necessary for algae photosynthesis (Tang et al., 2016). Numerous studies have demonstrated the efficacy of this process in efficiently removing organics and nutrients from wastewater (Sayara et al., 2021; Tang et al., 2018), thereby reducing the need for aeration (Tang et al., 2016; Zhang et al., 2023b). Consequently, it presents a promising approach for nitrogen and phosphorus removal alongside a simultaneous reduction in energy consumption. However, several critical issues constrain its full-scale application. These include the high hydraulic retention time (HRT) required to prevent microalgae washout and the insufficient biomass settleability, which compromises effluent clarity (Arango et al., 2023; Ji et al., 2018). Therefore, integrating membranes with an algae-bacterial symbiotic system is a promising technique to retain biomass and keep clarified effluent effectively (Arango et al., 2023).

Moreover, Huang et al. (2015) investigated the impact of algae growth on sequencing batch reactors (SBRs) and observed a significant decrease of about 25.0 % in the concentration of extracellular polymeric substances (EPS) (Huang et al., 2015). EPS is a major contributor to membrane fouling in MBRs. Hence, integrating microalgae with MBRs holds potential for mitigating membrane fouling. Several studies have evidenced a reduction in membrane fouling following the introduction of microalgae into MBRs (Cheng et al., 2024; Sun et al., 2021; Zhang et al., 2022). Thus, a comprehensive examination of the performance of microalgae-MBRs can furnish a robust theoretical foundation for devising pertinent fouling control strategies.

Most studies on microalgae-MBRs have predominantly focused on assessing their effectiveness in nutrient removal from wastewater and their potential for bioenergy conversion, with limited attention given to addressing membrane fouling (Arango et al., 2023; Ji et al., 2018; Li et al., 2021; Zhao et al., 2019). Mishra et al. (2023) conducted a review specifically on the remediation of textile wastewater by microalgae, highlighting their advantageous role in wastewater treatment. Additionally, Cheng et al. (2019) provided a comprehensive examination of microalgae's performance in treating swine wastewater for pollutant removal and bioenergy production. However, there is a notable absence of reviews focusing on how microalgae can alleviate membrane fouling in MBRs.

Given this gap in the literature, it is imperative to identify the shortcomings in this area to elucidate the potential of microalgae in mitigating membrane fouling and propose viable solutions to address this issue. This review aims to fill this gap by offering a critical analysis of microalgae-MBRs, delineating their potential and mechanisms for mitigating membrane fouling. Furthermore, it outlines the challenges associated with applying microalgae for controlling membrane fouling in MBRs and proposes prospective strategies to overcome these challenges. Overall, this review serves as the first comprehensive examination of microalgae-MBRs, shedding light on their role in mitigating membrane fouling and presenting avenues for future research and development.

2. Microalgae-MBR systems

Microalgae, characterized by their diminutive size and uncomplicated structures (Diao et al., 2024), play a vital role in the ecosystem as photosynthetic autotrophs. They adeptly absorb CO_2 from their surroundings, harnessing it to synthesize biomass for growth and proliferation, while liberating O_2 in the process (You et al., 2024). The symbiotic rapport between algae and bacteria, initially proposed in the 1950s, has since led to significant advancements in wastewater treatment (Sun et al., 2018a). This biological treatment method capitalizes on the collaborative capabilities of microalgae and bacteria to cleanse wastewater.

Illustrated in Fig. 1, microalgae absorb CO_2 emanating from bacterial respiration to fuel their growth and reproductive processes, concurrently releasing O_2 through photosynthesis. Simultaneously, bacteria utilize the O_2 generated by microalgae to facilitate metabolic activities and degrade organic matter (Uggetti et al., 2014). Consequently, the wastewater undergoes purification via the microalgae-bacterial symbiotic system.

Research conducted by Su et al. (2012) demonstrates that algae-bacterial symbiotic photobioreactors exhibit exceptional nutrient removal efficacy in municipal wastewater treatment. These systems achieve removal efficiencies of 97.8 % for TN and 72.6 % for TP, surpassing conventional activated sludge methods by over 20.0 % and 50.0 %, respectively (Su et al., 2012). Moreover, the need for external O_2 supplementation is significantly diminished, rendering the process more energy-efficient compared to conventional activated sludge treatments.

Studies indicate that aeration, often necessary in wastewater treatment, can consume a substantial portion of energy, comprising 40.0 % to 60.0 % of the total energy input, and accounting for up to 60.0 % of the total operational costs in wastewater treatment plants (Ji et al., 2020; Wang et al., 2015). However, the challenge of biomass loss poses a bottleneck to the widespread implementation of this process. Such losses can compromise effluent quality and destabilize microalgae-bacterial systems (Sun et al., 2018a).

The membrane filtration technique effectively retains biomass while separating HRT and solid retention time (SRT), ensuring the stability of MBRs (Chen et al., 2017; Xu et al., 2014). Consequently, the recent focus on inoculating microalgae with membranes to maintain system stability has garnered significant attention (Fan et al., 2023; Marbelia et al.,

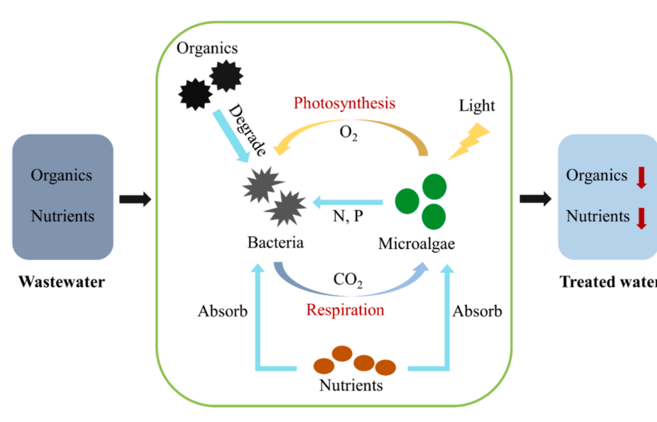

Fig. 1. Schematic diagram of wastewater treatment by microalgae-bacterial symbiotic system.

2014). Marbella et al. (2014) demonstrated the effectiveness of a microalgae membrane photobioreactor (without activated sludge) in preventing microalgae from washing away during wastewater treatment. They reported that the retained biomass and volumetric productivity were 3.5 and 2 times higher, respectively, than those of a typical photobioreactor, effectively reducing footprint and ensuring stable reactor operation (Marbelia et al., 2014).

However, many studies combining membrane modules with photobioreactors, without activated sludge, have focused on algae cultivation for energy recovery, resulting in limited nutrient removal from wastewater (Babaei and Mehrnia, 2018; Singh and Thomas, 2012; Sun et al., 2018b). Furthermore, these studies often involved long HRT (more than one day) and external CO_2 supply, increasing energy consumption (Honda et al., 2012). In contrast, microalgae-MBRs in the presence of activated sludge can remove organics and nutrients simultaneously and reduce energy consumption through O_2 released by microalgae (Sayara et al., 2021; Tang et al., 2016). For instance, Wang et al. (2024) proposed a novel non-aerated microalgae-bacterial membrane photobioreactor (with activated sludge) and found that with a proper inoculation ratio (microalgae: bacteria was 3:2), the removal rates of chemical oxygen demand (COD), TN, NH_4^+, and TP could reach 95.9 %, 74.5 %, 98.5 %, and 42.0 %, respectively (Wang et al., 2024). In this study, the microalgae seeds were placed in several clear cylinders to be pre-cultivated and fed with a modified Mineral Salt Medium with constant aeration and light illumination. Subsequently, the microalgae were moved into the bioreactor once the target quantity was attained. Furthermore, most microalga can convert CO2 and sunlight into carbohydrates through photosynthesis when integrated into activated sludge (AS) systems, thereby mitigating greenhouse gas emissions. Additionally, research indicated that incorporating algae can enhance anaerobic fermentation efficiency, resulting in increased production of valuable byproducts such as methane and biohydrogen (Devi et al., 2023).

Meanwhile, there are conflicting claims regarding the performance of microalgae on membrane fouling. Qu et al. (2015) suggested that some algae cells increased fouling on ultrafiltration membranes due to their large size, leading to their deposition on the membrane surface (Qu et al., 2015). Wicaksana et al. (2012) found that deposition of microalgae cells (*Chlorella sorokiniana*) would occur even at low permeate flux, gradually forming a layer of microalgae cells and resulting in heavy fouling (Wicaksana et al., 2012). Conversely, Xu et al. (2014) observed that the growth rate of *trans*-membrane pressure (TMP) in the microalgae-membrane reactor (without activated sludge) was significantly lower than that in the activated sludge MBR (Xu et al., 2014). Huang et al. (2015) also found that the concentration of proteins and polysaccharides in the bound-EPS was reduced by 25.7 % and 22.5 %, respectively, in the microalgae-SBR (with activated sludge) compared to the control SBR (without microalgae) (Huang et al., 2015). The reduction of EPS plays a vital role in mitigating membrane fouling. The introduction of microalgae to control membrane fouling in MBRs shows promising application prospects.

3. Alleviation of membrane fouling by microalgae-MBR systems

Based on the study by Huang et al. (2015), microalgae-MBR systems (with activated sludge) might be a feasible option to control membrane fouling. Therefore, researchers further explored this system's performance and mechanism in wastewater treatment. Table 1 displays the performance of membrane fouling mitigation by microalgae-MBRs.

As shown in Table 1, Sun et al. (2018) developed a microalgae-MBR symbiotic system with activated sludge aimed at achieving efficient wastewater treatment while controlling membrane fouling (Sun et al., 2018a). In comparison with conventional MBRs, the novel system incorporating microalgae demonstrated enhanced removal rates for COD, NH_4^+, TN, and PO_4^{3-} by 4.6 %, 6.7 %, 10.1 %, and 8.2 %, respectively. Moreover, the increase in TMP was halved, significantly mitigating membrane fouling (Sun et al., 2018b). Additionally, they investigated the impact of different inoculation ratios and identified that the highest removal rates for COD, TN, and phosphorus were achieved at a ratio of 1:5 (microalgae: activated sludge), whereas the optimal NH_4^+ removal efficiency was observed at a ratio of 1:1. However, serious membrane fouling was observed at a ratio of 1:5, suggesting a significant influence of microalgae concentration on MBR performance, including fouling degree and treatment efficacy. Higher concentrations of microalgae might exacerbate membrane fouling in MBRs. Radmehr et al. (2023) conducted further investigations into the performance of seven microalgae strains, including two commercialized ones (Radmehr et al., 2023b). Among these, *Chlamydomonas*, *Selenastrum*, and their combination exhibited optimal performance in wastewater treatment and fatty acid production, thus selected for further analysis of their ability to mitigate membrane fouling. Results indicated a significantly slower TMP increase in microalgae-MBRs (with activated sludge), particularly with *Selenastrum*, requiring less frequent membrane cleaning compared to conventional MBRs. Over the course of 40 days, the membranes were cleaned 12, 4, 4, and 6 times in MBRs, microalgae (mixed)-MBRs, microalgae (*Selenastrum*)-MBRs, and microalgae (*Chlamydomonas*)-MBRs, respectively.

Contrastingly, Najafi Chaleshtori et al. (2022) presented divergent findings when employing the microalgae-MBR system (with activated sludge) for municipal and treated wastewater treatment (Najafi Chaleshtori et al., 2022). The results showcased excellent removal efficiencies for ammonium and phosphorus, reaching 94.4 % and 88.4 %, respectively. Nonetheless, the TMP growth rate surged significantly after 14 days, potentially due to excessive microalgae concentrations. This study utilized a 5:1 ratio (microalgae: activated sludge).

Aerobic granular sludge (AGS) boasts a more densely packed granular structure compared to activated sludge, thereby enhancing its settleability and fostering microbial diversity (Zhang et al., 2021). Various studies suggest that AGS can enhance the permeability of biofouling layers, with its stable granular configuration exerting a mechanical scouring force on membrane surfaces (Iorhemen et al., 2017; Wang et al., 2017). Moreover, research by Zhang et al. (2020) indicates that AGS mitigates membrane fouling by improving cake layer permeability due to its larger particle size and denser structure.

Furthermore, AGS comprises aerobic, anoxic, and anaerobic zones along its mass transfer direction, enabling simultaneous removal of organics and nutrients from wastewater (Iorhemen et al., 2018; Zhang et al., 2023a). Building upon this, Zhang et al. (2023) pioneered a novel approach by integrating AGS with microalgae to create a microalgae-granular sludge MBR (ABGMBR), aimed at enhancing pollutant removal and mitigating membrane fouling (Zhang et al., 2023a). This innovative system extended operational longevity to 152 days, effectively combating membrane fouling. Moreover, analysis of membrane resistance unveiled that fouling resistance (R_f), pore blocking resistance (R_p), and cake layer resistance (R_c) in the ABGMBR were notably lower compared to systems devoid of microalgae. This underscores the significant reduction in fouling resistance achieved by combining microalgae with AGS, presenting a promising solution for membrane fouling mitigation.

4. Mechanisms of membrane fouling mitigation by microalgae-MBR system

Currently, proposed strategies for mitigating membrane fouling by microalgae encompass enhancing the properties of sludge mixture and cake layer, quorum quenching, altering microbial communities, and more (Radmehr et al., 2023b; Sun et al., 2018a; Sun et al., 2018b). Sun et al. (2018) proposed that microalgae reduce the negative charge on floc surfaces, diminishing electrostatic repulsion between flocs, thus enhancing flocculation and diminishing fouling accumulation on the membrane surface (Sun et al., 2018a). This aligns with the observations of Ra et al. (2023), indicating that contaminants' high negative charge

Table 1
The performance of membrane fouling mitigation by microalgae.

Microalgae	Configuration	Wastewater types	Performance	References
Collected from the secondary clarifier wall	MBR Working volumes: 6 L; Materials: transparent glass; Aeration system: 0.15 m^3/h; Operating flux: 9 L/(m^2 h); HRT: 8 h; SRT: 15 days; Inoculation ratio: 1:10 (algae/sludge); Temperature: 22 ± 3 °C; Lighting system: 12 h light-12 h dark cycle	Synthetic municipal wastewater	TMP increasing rate decreased by 50.0 %	(Sun et al., 2018a)
Collected from the secondary clarifier wall	MBR Working volumes: 6.5 L; Materials: transparent polyvinyl chloride (PVC); Aeration system: 0.11 m^3/h; Operating flux: 6.8 L/(m^2 h); HRT: 12 h; Inoculation ratio: 1:10 (algae/sludge); Temperature: 22 ± 3 °C; Lighting system: 12 h light-12 h dark cycle	Synthetic municipal wastewater	Operation time extended by 7 days TMP increasing rate decreased by 26.7 %	(Sun et al., 2018b)
Collected from the secondary clarifier wall	MBR Working volumes: 6.5 L; Materials: transparent PVC; Aeration system: 0.11 m^3/h; Operating flux: 6.8 L/(m^2 h); HRT: 12 h; Inoculation ratio: 1:5 (algae/sludge); Temperature: 22 ± 3 °C; Lighting system: 12 h light-12 h dark cycle	Synthetic municipal wastewater	Operation time extended by 23 days TMP increasing rate decreased by 54.0 %	(Sun et al., 2018b)
Collected from the secondary clarifier wall	MBR Working volumes: 6.5 L; Materials: transparent PVC; Aeration system: 0.11 m^3/h; Operating flux: 6.8 L/(m^2 h); HRT: 12 h; Inoculation ratio: 1:1 (algae/sludge); Temperature: 22 ± 3 °C; Lighting system: 12 h light-12 h dark cycle	Synthetic municipal wastewater	Operation time decreased by 6 days TMP increasing rate increased by 42.7 %	(Sun et al., 2018b)
Chlamydomonas	MBR Working volumes: 3.0 L; Materials: plexiglass; Aeration system: 0.09 m^3/h; Operating flux: 9.0 L/(m^2 h); HRT: 16 h; SRT: 20 days; Inoculation ratio: 1:2 (algae/sludge); Temperature: room temperature; Lighting system: 12 h light-12 h dark cycle	Municipal wastewater	TMP increasing rate decreased by 46.7 %	(Radmehr et al., 2023b)
Selenastrum	MBR Working volumes: 3.0 L; Materials: plexiglass; Aeration system: 0.09 m^3/h; Operating flux: 9.0 L/(m^2 h); HRT: 16 h; SRT: 20 days; Inoculation ratio: 1:2 (algae/sludge); Temperature: room temperature; Lighting system: 12 h light-12 h dark cycle	Municipal wastewater	TMP increasing rate decreased by 63.7 %	(Radmehr et al., 2023b)
Chlamydomonas & Selenastrum	MBR Working volumes: 3.0 L; Materials: plexiglass; Aeration system: 0.09 m^3/h; Operating flux: 9.0 L/(m^2 h); HRT: 16 h; SRT: 20 days; Inoculation ratio: 1:2 (algae/sludge); Temperature: room temperature; Lighting system: 12 h light-12 h dark cycle	Municipal wastewater	TMP increasing rate decreased by 57.7 %	(Radmehr et al., 2023b)
Collected from the laboratory	Aerobic granular sludge MBR (AGMBR) Working volumes: 41.8 L; Materials: plexiglass; Aeration for 335–347 min and settling for 3–15 min; Membrane flux: 10.0 L/(m^2 h); Surface updraft velocity:1.23 cm/s; Lighting system: 12 h light-12 h dark cycle	Synthetic domestic wastewater	Operation time extended by 27 days TMP increasing rate decreased by 18.7 %	(Zhang et al., 2023a)
Chlorella vulgaris	MBR Working volumes: 2.5 L; Materials: plexiglass; Aeration system: 5 mL/min; Operating flux: 17.3 L/(m^2 h); HRT: 3 days; Inoculation ratio: 5:1 (algae/sludge); Temperature: 25 ∼ 28℃; Light intensity: 6000 lx	Municipal wastewater	TMP increasing rate increased by 33.3 %	(Najafi Chaleshtori et al., 2022)
Chlorella vulgaris	MBR Working volumes: 2.5 L; Materials: plexiglass; Aeration system: 5 mL/min; Operating flux: 17.3 L/(m^2 h); HRT: 3 days; Inoculation ratio: 5:1 (algae/sludge); Temperature: 25 ∼ 28℃; Light intensity: 6000 lx	Treated municipal wastewater	TMP increasing rate increased by 47.9 %	(Najafi Chaleshtori et al., 2022)
Chlorella vulgaris	MBR Working volumes: 3.0 L; Materials: plexiglass; Aeration system: 1.5 L/min; Operating flux: 9.0 L/(m^2 h); HRT: 18 h; SRT: 15 days; Inoculation ratio: 1:5 (algae/sludge); Lighting system: 12 h light-12 h dark cycle	Synthetic wastewater	Operation time extended by 4 days TMP increasing rate decreased by 22.0 %	(Radmehr et al., 2023a)
Chlorella vulgaris	MBR with biocarrier Working volumes: 3.0 L; Materials: plexiglass; Aeration system: 1.5 L/min; Operating flux: 9.0 L/(m^2 h); HRT: 18 h; SRT: 15 days; Inoculation ratio: 1:5 (algae/sludge); Lighting system: 12 h light-12 h dark cycle	Synthetic wastewater	Operation time extended by over 90 days TMP increasing rate decreased by 98.6 %	(Radmehr et al., 2023a)
Chlorella vulgaris	MBR Working volumes: 2.5 L; Materials: plexiglass; Aeration system: 2.0 L/min; Operating flux: 9.0 L/(m^2 h); HRT: 16 h; SRT: 15 days; Inoculation ratio: 1:5 (algae/sludge); Lighting system: 12 h light-12 h dark cycle; Light intensity: 1000 lx	Synthetic domestic wastewater	Operation time extended by 15 days TMP increasing rate decreased by 57.0 %	(Radmehr et al., 2022)
Chlorella vulgaris	MBR Working volumes: 2.5 L; Materials: plexiglass; Aeration system: 2.0 L/min; Operating flux: 9.0 L/(m^2 h); HRT: 16 h; SRT: 15 days; Inoculation ratio: 1:2 (algae/sludge); Lighting system: 12 h light-12 h dark cycle; Light intensity: 1000 lx	Synthetic domestic wastewater	Operation time extended by 15 days TMP increasing rate decreased by 73.5 %	(Radmehr et al., 2022)
Chlorella vulgaris	MBR Working volumes: 2.5 L; Materials: plexiglass; Aeration system: 2.0 L/min; Operating flux: 9.0 L/(m^2 h); HRT: 16 h; SRT: 15 days;	Synthetic domestic wastewater	Operation time extended by 15 days TMP increasing rate decreased by 78.5 %	(Radmehr et al., 2022)

(continued on next page)

Table 1 (*continued*)

Microalgae	Configuration	Wastewater types	Performance	References
	Inoculation ratio: 1:1 (algae/sludge); Lighting system: 12 h light-12 h dark cycle; Light intensity: 1000 lx			
Collected from the secondary clarifier supernatant	MBR Working volumes: 6.5 L; Materials: PVC; Aeration system: 0.11 m^3/h; Operating flux: 6.8 L/(m^2 h); HRT: 12 h; Inoculation ratio: 1:5 (algae/sludge); Lighting system: 12 h light-12 h dark cycle; Light intensity: 3000 lx	Synthetic wastewater	Slow TMP increasing rate decreased by 52.6 % Rapid TMP increasing rate decreased by 32.2 %	(Sun et al., 2020)
Mixed polyculture species of algae	MBR Working volumes: 6.0 L; Aeration system: 0.15 m^3/h; Operating flux: 9.0 L/(m^2 h); HRT: 8 h; SRT: 15 days; Inoculation ratio: 1:10 (algae/sludge); Temperature: 22 ± 3 °C; Lighting system: 12 h light-12 h dark cycle;	Synthetic municipal wastewater	TMP increasing rate decreased by 47.0 %	(Sun et al., 2018c)
Chlorella vulgaris	Electric field MBR Working volumes: 19.0 L; Materials: poly(methyl methacrylate); Operating flux: 15.0 L/(m^2 h); Inoculation ratio: 1:5 (algae/sludge); Lighting system: 12 h light-12 h dark cycle	Synthetic municipal wastewater	TMP increasing rate decreased by 50.2 %	(Corpuz et al., 2021)
Chlorella pyrenoidosa	MBR (Encapsulated algae) Working volumes: 10.0 L; Operating flux: 8.2 L/(m^2 h); Aeration system: 2.5 L/min; HRT: 72 h; SRT: 30 days;	Synthetic high-ammonia nitrogen wastewater	Total membrane filtration resistance reduced by 3.8 ~ 4.5 times	(Qin et al., 2020)
Chlorella pyrenoidosa	Oscillating membrane photoreactor Working volumes: 30.0 L; Operating flux: 4.2 L/(m^2 h); HRT: 72 h; SRT: 30 days; Lighting system: 12 h light-12 h dark cycle	leachates	Cake layer filtration resistance decreased by 88.5 %	(Fan et al., 2018)
Chlorella vulgaris	MBR Working volumes: 5.0 L; Materials: acrylic plastic; Crossflow velocity: 3 m/s; Filtration modes:intermittent filtration; HRT: 24 h; Lighting system: 12 h light-12 h dark cycle; Light intensity: 2500 lx	Synthetic secondary wastewater effluent	Permeate flux decline slower (smoothly reduced by around 26 %)	(Wu et al., 2021)

contributes to severe membrane fouling (Radmehr et al., 2023b). Moreover, microalgae-MBRs (with activated sludge) maintain relatively high levels of dissolved oxygen (DO), effectively inhibiting filamentous bacteria overgrowth, thereby mitigating membrane fouling (Sun et al., 2018b). Overgrown filamentous bacteria tend to produce irregularly shaped flocs that are difficult to aggregate, predisposing them to deposition on the membrane surface.

Yao et al. (2011) demonstrated that the ratio of proteins to polysaccharides (Pr/Ps) in soluble microbial products (SMP) influences fouling severity. A higher ratio tends to mitigate membrane fouling by reducing cake layer formation (Yao et al., 2011). Microalgae enhance activated sludge activity, promoting polysaccharide degradation and increasing the Pr/Ps value in SMP. Additionally, the combination of microalgae significantly reduces bound-EPS concentration and the Pr/Ps ratio (Sun et al., 2018a). Previous research has indicated that bound-EPS negatively impacts membrane fouling (Nabi et al., 2023; Wang et al., 2022b). Li et al. (2011) illustrated that bound-EPS damages sludge floc structure, delays sludge-water separation, and increases floc viscosity, exacerbating fouling accumulation on the membrane surface (Li and Yang, 2007). Furthermore, studies have shown a positive correlation between the Pr/Ps ratio in bound-EPS and the hydrophobicity and negative surface charge of sludge flocs, indirectly influencing fouling severity (Liao et al., 2001; Massé et al., 2006). Lower Pr/Ps values can reduce floc surface charge, weaken hydrophobicity, and thus enhance floc stability and flocculation ability. However, excessive microalgae addition can exacerbate membrane fouling due to smaller floc sizes and higher DO (Najafi Chaleshtori et al., 2022). Najafi Chaleshtori et al. (2022) demonstrated that a high oxygen production rate (OPR) prompts microbial communities to produce more EPS in microalgae-MBRs (with activated sludge), worsening membrane fouling (Najafi Chaleshtori et al., 2022).

As for the cake layer, Sun et al. (2018) showed that the cake layer in microalgae-MBRs (with activated sludge) had better filtration ability (Sun et al., 2018a). It was because low EPS concentrations could decrease the cake layer's resistance. Inoculation with microalgae would produce higher DO concentration in MBR, which could reduce bacterial death and alleviate the release of EPS. Zhang et al. (2023) found the structure of microalgae-bacterial was stable, which can significantly retard sludge decomposition, facilitating to form looser cake layers and control membrane fouling (Zhang et al., 2023a). Interestingly, Yang et al. (2018) observed a sharp decrease in TMP in the microalgae-MBR system (with activated sludge) after an operation without cleaning (Yang et al., 2018). This study's starting concentrations of algae and activated sludge were 900 mg/L and 900 mg/L, respectively. Additionally, the peristaltic pumps continuously supplied the influent and effluent. It was worth noting that the membrane module in this system was a dynamic filter made of denim fabric and support materials. With this kind of filter, the loose fouling layer that results from filtering an anaerobic microbial bulk solution can be readily eliminated with mild gas flushing. Therefore, they speculated that turbulence in the reactor could easily remove the loose cake layer formed by microalgae bacteria.

In summary, microalgae might effectively relieve membrane fouling by improving sludge mixture characteristics and cake layer characteristics.

On the flip side, Radmehr et al. (2023) conducted an analysis of microbial communities within the microalgae-MBR setup (with activated sludge). The findings revealed a higher presence of EPS-degrading strains and a lower abundance of EPS-producing strains in this system, suggesting an influence of microalgae on the composition and distribution of microbial communities (Radmehr et al., 2023b). Notably, the introduction of microalgae into the MBR led to a decrease in *Cloacibacterium* and *Flavobacterium*, known culprits in membrane fouling (Radmehr et al., 2023a). These outcomes highlight the potential of microalgae inoculation in MBRs to enhance the prevalence of beneficial bacteria. Furthermore, various studies have demonstrated that microalgae secrete compounds that modulate bacterial activity by altering signaling pathways (Radmehr et al., 2023a; Santo et al., 2022). For instance, it has been documented that *Chlorella vulgaris* releases substances capable of deactivating bacterial acyl-homoserine lactones (AHLs), thereby mitigating bacterial toxicity (Dao et al., 2018). Additionally, Dao et al. (2018) identified indole acetic acid as a crucial signaling molecule facilitating communication between microalgae and bacteria, ultimately promoting microalgae growth. Interestingly, microalgae also stimulate the secretion of indole acetic acid (Dao et al., 2018). This suggests that microalgae may produce substances that suppress quorum sensing and decrease EPS levels, thus mitigating fouling formation. Nevertheless, there remains a paucity of research delving into the mechanistic analysis of membrane fouling mitigation from this perspective, warranting further in-depth exploration.

In summary, Fig. 2 illustrates the potential mechanisms for minimizing membrane fouling in microalgae-MBRs. As depicted, the introduction of microalgae inoculation can alter the morphology and metabolic activities of activated sludge and microalgae, thereby inducing changes in the sludge mixture's properties within the reactors. Favourable alterations such as reduced negative charge and filamentous bacteria, formation of regular flocs, elevated SMP_{Ps}/SMP_{Pr} ratios, decreased levels of EPS and EPS_{Pr}/EPS_{Pr}, and the absence of cake layers all contribute to mitigating membrane fouling in MBRs. Thus, investigating the hybrid solution's properties is essential for comprehending the mechanisms behind membrane fouling control facilitated by microalgae. Moreover, microalgae have the potential to influence the microbial communities within microalgae-MBRs, consequently impacting bacterial metabolism and, consequently, membrane fouling (Sun et al., 2020). The enrichment of microbial diversity and functional microorganisms may contribute to mitigating membrane fouling. Therefore, it is imperative to assess the characteristics of microbial communities in microalgae-MBRs to elucidate the mechanism of membrane fouling alleviation through microalgae.

5. Challenges and future directions

5.1. Challenges

Microalgae shows excellent potential in mitigating membrane fouling, but it still has numerous challenges to resolve.

1. Numerous studies about microalgae-MBRs concentrated on nutrient removal efficiency in wastewater or its potential for bioenergy recovery. There is limited research on inoculating microalgae to alleviate membrane fouling in MBRs. Besides, most of the explorations on the mechanisms focused on the characteristics of sludge mixture but with a deficiency discussion on microbial communities.
2. The internal environment in the microalgae-MBRs is highly complex. Microalgae and bacteria have different life cycles, and factors such as operating conditions, external environment and nutrient concentration might lead to the overgrowth or expense of certain species (Radmehr et al., 2023a). Therefore, balancing the growth of microalgae and bacteria in the system is challenging to achieve a stable operation. For instance, excessive concentrations of microalgae may negatively affect the properties of activated sludge and specific bacterial species. Additionally, operating with microalgae involves several other disadvantages, such as the availability of sunlight and darkness caused by activated sludge.
3. Limited types of microalgae were explored in MBRs for fouling control. It is challenging to select and cultivate more suitable microalgae strains. Additionally, most studies were conducted by inoculating single microalgae, with limited discussion on mixed microalgae.
4. Most research was conducted in synthetic wastewater and lab-scale trials. The confirmation of microalgae's growth status in practical industry remains to be explored. It remains uncertain whether microalgae can control membrane fouling under real-world scenarios.

5.2. Future direction

In addressing the current challenges, the most important thing is to confirm the mechanisms of membrane fouling control by microalgae.

1. The diversity and complexity of microbial communities within the reactor might compromise the system's performance, impeding fouling mitigation. Therefore, it is essential to investigate the characteristics and changes of microbial communities to establish a robust theoretical foundation for developing microalgae-MBRs.
2. Exploring favourable operating conditions, such as inoculation ratio, microalgae species, nutrient concentration, photoperiod, and aeration rate, is significant for cultivating suitable microbial communities and constructing a balanced internal environment.
3. It is helpful to optimize the system configuration to improve the stability and efficiency of microalgae-MBRs, such as adding biological carriers, using AGS, applying electric fields, etc. As for microalgae, selecting and developing more beneficial strains for alleviating membrane fouling is significant for future development.

Additionally, mixed microalgae may have better potential to alleviate membrane fouling than inoculated single microalgae, which needs further exploration. Most importantly, it is necessary to undertake an in-depth analysis of actual wastewater to achieve large-scale industrial applications. This approach provides a thorough understanding of the impact of actual wastewater to enhance the system's feasibility.

6. Conclusion

Microalgae-MBRs present notable advantages, such as efficient elimination of organics and nutrients from wastewater, decreased energy usage, and the capacity to combat membrane fouling. The introduction of microalgae can enhance the properties of sludge mixtures and cake layers within MBRs, crucial for controlling membrane fouling. Additionally, microalgae release compounds that modulate the metabolic functions of bacteria in MBRs, thereby influencing the extent of membrane fouling. Future research endeavours should prioritize unravelling the mechanisms by which microalgae alleviate membrane fouling, refining operational parameters, diversifying microalgae strains, exploring co-inoculation strategies involving multiple microalgae species, and delving into real-world applications in wastewater treatment.

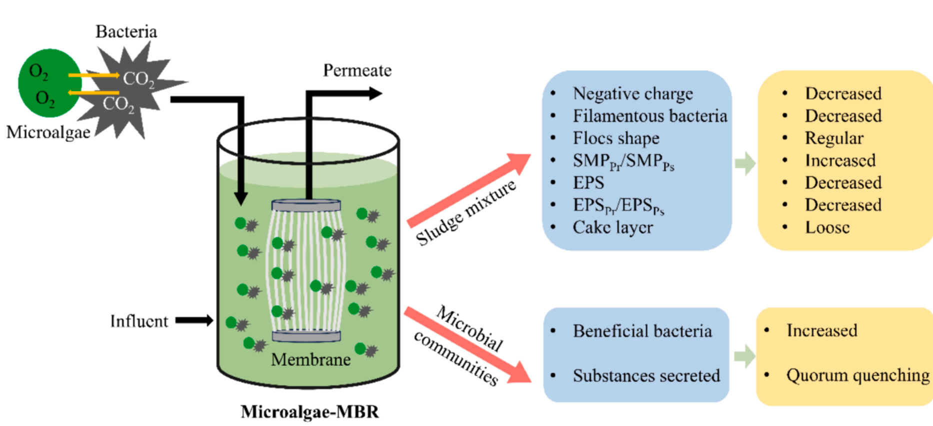

Fig. 2. Possible mechanisms of membrane fouling minimization by microalgae-MBRs.

CRediT authorship contribution statement

Yuanying Yang: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Wenshan Guo:** Writing – review & editing, Supervision, Conceptualization. **Huu Hao Ngo:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Xinbo Zhang:** Writing – review & editing, Resources. **Yuanyao Ye:** Resources, Conceptualization. **Lai Peng:** Resources, Formal analysis. **Chunhai Wei:** Writing – review & editing, Formal analysis. **Huiying Zhang:** Writing – review & editing, Project administration, Funding acquisition, Formal analysis, 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.

Data availability

Data will be made available on request.

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