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Control strategies against algal fouling in membrane processes applied for microalgae biomass harvesting

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Abstract

Microalgae biomass is increasingly applied in a variety of high-end applications, such as biofuel production, CO_2 fixation, food, and cosmetics. As the demand for microalgae increases, improvements in biomass harvesting techniques are required since dewatering represents a significant fraction of the total algae production cost. While membrane technology is growing as a means to achieve effective biomass harvesting, fouling from microalgae suspensions is a major drawback, since these streams are rich in organic compounds, nutrients, and biological materials. The aim of this paper is to present the state-of-the-art of the control strategies to manage algal fouling. The control strategies are divided into: (i) mitigation strategies, including pre-treatment options, modified membrane surfaces, and hydrodynamic approaches; and (ii) adaptation strategies, which include physical, mechanical, and chemical cleaning. Fouling mitigation strategies are implemented in membrane separation processes seeking to maintain high productivity without compromising biomass quality, while minimizing the energy cost related to fouling control. Adaptation techniques include optimization of the cleaning time and effective removal of the irreversible foulants. Further, minimization in the use of chemicals and of the backflush permeate must be achieved to ensure an efficient performance in chemical cleaning and backwash approaches, respectively. Finally, the article discusses future research perspectives in membrane-based microalgae harvesting with a focus on zero liquid discharge and effective fouling control strategies within the water-energy nexus.

Keywords: Microalgae Dewatering; Fouling control; Membrane photobioreactor; Membrane filtration; Microalgae cultivation; Wastewater treatment;

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1. Introduction

Increasing stress in the water-energy system mirrors the challenges caused by rapid industrialization and population growth. In fact, water scarcity hits two-thirds of the global population for at least one month each year, putting a spotlight on the need for alternative water supply strategies [1, 2]. The use of large-scale solutions for desalination and water reuse has gained momentum owing their potential to increase the freshwater available worldwide; in turn, these technologies demand large amounts of energy and consequently, entail high greenhouse gas emissions [3]. Thus, a deeper understanding of the so-called water-energy nexus (WEN) is required to address the trade-offs between both resources [4, 5]. Coupling renewable energies to water production is a promising strategy to facilitate both sustainable development and water access. In this context, the production of algal biomass is a promising field owing a growing interest for commercial applications in biotechnology, wastewater treatment, food, and cosmetics [6, 7]. Further, applications in the energy sector, such as biofuel production and CO_2 fixation, pose great potential [8-11]. In fact, it is now possible to industrially produce more than three times higher oil per hectare using algae when compared to other feedstocks, e.g., corn , while a CO_2 fixation rate of 5 $g/CO_2\ L^{-1}\ day^{-1}$ can be reached in ambient air, which is roughly 10-50 times more efficient as compared to terrestrial plants [12]. In addition, microalgae can also be cultivated utilizing CO_2 from non-conventional sources, such as facilities which produce carbon dioxide as a by-product, thus reducing the overall CO_2 emissions [13].

The most used harvesting solutions for concentrating algae biomass are: (i) coagulation, (ii) dissolved air flotation, (iii) centrifugation, and (iv) membrane filtration. Briefly, (i) Coagulation consists of adding coagulants in the feed solution in order to reduce the electrostatic repulsion between the microalgae cells, thus causing their settling [14]. (ii) Dissolved air flotation (DAF) relies on air micro-bubble generation to promote microalgae flocs rising to the interface where the biomass is accumulated [15]. (iii) Centrifugation is based on a physical method which acts radially to separate colloids such as algae from their liquid medium according to their density difference [16]. Finally, (iv) membrane filtration uses a selective barrier to divide one stream (feed) into two different phases (concentrate and permeate) according to size differences under a pressure gradient applied across the membrane [17]. Among these solutions, membrane-driven separation is advantageous in terms of compactness, high water recovery rates and in maintaining high-quality biomass upon concentration [18, 19]. Microfiltration and ultrafiltration are the typical and the most effective membrane processes used for concentrating microalgae biomass [18, 20, 21].

To secure an efficient process performance, membrane fouling phenomena must be reduced: fouling causes a dramatic decrease of permeate water production and it requires stoppage periods for membrane cleaning and eventually replacement [22]. Biofouling and organic fouling are especially significant when the feed stream contains highly concentrated microalgae suspensions. Fouling-related loss in performance is a major challenge to membrane technologies for harvesting algal biomass and for the downstream processes seeking to recover value-added products [23, 24]. Numerous recent publications have addressed these phenomena, describing in detail the fouling mechanisms and effects when membranes are applied to concentrate microalgae [18, 25]. This review focuses on effective mechanisms for fouling control and mitigation during microalgae harvesting in membrane-driven separation technologies.

2. Mechanisms and characteristics of algal fouling

Membrane-driven algae separation is highly prone to extensive fouling [18]. Different factors, intrinsic to process design and algal biomass, determine the fouling severity. In this section, a summary of the main algal foulants and fouling regulating factors is reported. This information is discussed in the light of energy aspects related to loss of productivity and overall performance.

2.1. Main foulants

Microalgae are microorganisms with cell sizes ranging from 3 to 30 µm that exhibit cultivation concentrations lower than 1 kg/m^3 [26]. Microalgae suspensions also include other components, such as vitamins, proteins, pigments, nutrients, and organic substances [27]. Organic and biological foulants are regarded as dominant in microalgae separation processes, while inorganic fouling and scaling are considered negligible, as low amounts of total dissolved solids (TDS) and inorganic colloids are typically present in algae-rich streams, especially if compared to organic and biological components [28]. It is important to note that, in algae membrane-based processes, the distinction between biofouling and organic fouling often is not clear since they occur simultaneously. Therefore, algal fouling results mainly from the deposition of algal cells, algal organic matter (AOM), and transparent exopolymer particles (TEP) present in the feed solution [17, 28-31], together with the deposition and adsorption of organic compounds, such as proteins, carbohydrates, and fatty acids.

The algal cell characteristics are strongly dependent on the species of algae themselves, varying also within different strains [18, 29, 30]. Cells are larger than the pores of MF membranes (typically 0.1-10 µm) and UF membranes (typically <0.1 µm), so they are rejected by the membrane due to size exclusion. In this perspective, has been observed that large particles with spherical shape are responsible of the formation of a cake layer with high porosity values and good filterability properties. [32]. Furthermore, more stable and uniform cake layers in terms of porosity, which also generally guarantee higher filterability, were associated to algae strains characterized by rigid cell walls. The initial biomass concentration is another key aspect when dealing with fouling severity, since highly concentrated feed streams are associated to high viscosity values, in turn responsible for lowering the effects of air scouring. Lastly, several literature reports have shown direct correlations between biomass concentration of the starting stream and flux decline over time [31, 33].

Another major foulant is represented by the soluble organic matter, which includes compounds of diverse chemical composition and molecular weight, whose characteristics depend on factors such as algal strain characteristics and nutrients available. AOM that results from the algal metabolic activity is termed external organic matter (EOM), while internal organic matter (IOM) is the AOM fraction released due to cell ageing and lysis [34]. The latter occurs in tandem with the generation of smaller cell fragments and cell debris and is prone to cause pore blocking and narrowing [2]. The algal particle characteristics substantially affect the fouling propensity during membrane-based biomass harvesting, and their size distribution stems from the dynamic equilibrium between formation, transformation, and breakage of algal cells and AOM [35].

AOM is mainly characterized by negatively charged organics with high hydrophilicity and low specific ultraviolet absorbance [36]. AOM also includes other compounds, such as proteins, peptides, and amino acids, which are responsible for the heterogeneity of the algal stream [34, 37, 38]. However, AOM shows large variations among different algal species even if, in general, large molecules are usually biopolymers (e.g., proteins), while the small molecules are usually represented by acids and humic substances [28, 39]. High molecular weight (HMW) and low molecular weight (LMW) compounds in AOM act very differently in relation to membrane fouling. The formers are rejected mostly due to size exclusion and, similarly to what happens with algal cells, they tend to accumulate at the membrane surface and contribute to a formation of a cake layer. Contrarily, LMW compounds can more easily enter membrane pores, thus causing pore blocking, which represents the main cause of irreversible fouling [40-42]. It should also be noted that, cells and HMW compounds are instead prone to build a cake layer, which may act as a secondary sieving layer for LMW substances, thus protecting the membrane by reducing the likelihood of pore blocking and irreversible fouling.

The last main algal foulant is represented by TEPs, which are the high viscosity part of AOM. TEPs can be of different sizes ranging from 0.05 up to 200 μm [43-45]. Their characteristics in terms of viscosity are responsible for a gel-like structure that increases attachment probability and considerably hamper membrane permeability [18, 29, 46, 47]. Ideally, in an algal stream in the absence of AOM, the cake resistance would increase linearly with the number of deposited algal cells; in reality, TEPs generate a dynamic structure which links algal cells and AOM and significantly reduces membrane performance and productivity [40, 42].

2.2. Fouling regulating factors

Algal fouling is described as a multi-stages process, whose development is influenced by the interactions between feed stream and the membrane surface under a convective force that triggers the gradual deposition of fouling materials over time [46]. In most cases, algal fouling develops as: (i) a first rapid flux decline in the very first minutes of filtration, which is due to pore narrowing (irreversible and removed only by chemical methods), caused by the attachment of compounds and colloids smaller than the membrane pores, usually extracellular polymeric substances (EPS) released by algae [18, 48, 49]. This first effect is enhanced by the simultaneous adsorption of biopolymers on the membrane surface and inside the membrane pores. From here, (ii/a) the cake layer begins to develop during the first transitory filtration phase; its formation is due to particles and solutes larger than membrane pores that are rejected, creating additional resistance to water passage as they accumulate on the membrane surface, thereby referred as a dynamic membrane [17, 50, 51]. This characteristic effect is mostly due to cell-cell and cell-AOM interactions rather than feed-membrane interactions. Further, (ii/b) a gel layer structure, typical in algal harvesting processes, can be present and it is mostly associated to the presence of bacteria and to biopolymers dominance over algae cells when accumulating on the membrane surface. Finally, (iii) the last fouling mechanism stage exhibits flux stabilisation, resulting from the equilibrium reached between cake layer growth and the tangential transport imposed by the cross-flow hydrodynamics in the boundary layer. An illustrated representation of the foulants formation position and on fouling stages is displayed in Fig. 1.

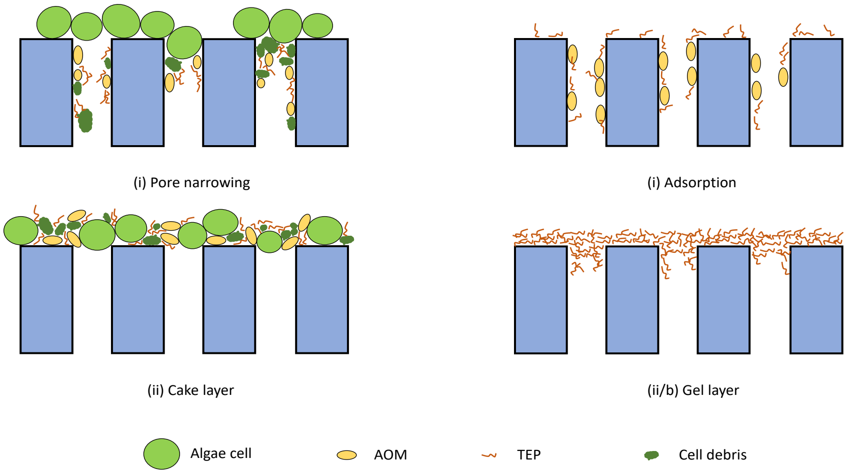


Fig. 1: Mechanisms of membrane fouling in membrane processes for biomass harvesting: (i) pore narrowing usually occurs first, due the action of compounds (algal organic matter (AOM), transparent exopolymer particles (TEP) and cell debris) smaller than membrane pores. Pore narrowing is enhanced by the simultaneous adsorption effect (i) related mainly to biopolymers, i.e., AOM and TEPs. Cake layers are instead associated to larger particles, such as algal cells, which are less likely to penetrate into the membrane pores and more prone to give rise to the so-called dynamic membrane. A gel-layer structure (ii/b) is formed when biopolymers and bacteria are more present than algal cells in the feed stream.

The hydrodynamic conditions, i.e., cross-flow velocity (CFV) and trans-membrane pressure (TMP), by controlling drag forces and shear stress have a fundamental influence on filtration performance and fouling mechanisms [52, 53]. On the other hand, the characteristics of the feed microalgae streams and of the membrane also play a crucial role. The impacts of microalgae biomass on fouling steam from species, cell dimensions, particle size distribution (PSD), hydrophobicity and zeta potential [54]. Moreover, feed streams with microalgae concentrations >0.6 g/L have been shown to result in a much faster cake layer formation while greater membrane porosity usually entails larger permeate fluxes [55].

The ratio between foulant and membrane pore size reportedly influences the extent of pore blockage, and hence fouling irreversibility. Some studies observed larger irreversible fouling rates when using less selective membranes, with larger pore sizes, when compared to less productive ones with smaller pores; this reportedly stems from a wider range of foulants passing through the membrane, henceforth inducing more pore blockage [47, 56]. On the contrary, opposite trends wherein large pore sizes are less prone to irreversible fouling are described as an archetype of a lower hydraulic resistance and decreased drag forces [57, 58]. Clearly, fouling phenomena is a complex mechanism, which depends upon numerous factors. In spite of several investigations on colloidal and biological fouling, there is a lack of models in the realm of algal membrane fouling [59, 60]. From this point of view, a considerable range of process optimization still potentially exists in algae harvesting by membrane filtration [61].

2.3. Fouling and productivity

In typical membrane operation, the productivity values (water fluxes) vary substantially depending on CFV and TMP. In general, medium and high pore-size membranes are more suitable for filtering algae since their selectivity is the most adequate. Their average mean productivities, once reached steady-state conditions, vary from 10 and 100 LMH [62-64], even if some mitigation strategies can ensure steady state fluxes up to > 200 LMH [65, 66]. Quantitatively, in terms of productivity loss, literature reports estimate that over sub-critical conditions, the fouling phenomena reduce the water fluxes approximatively between 50 to 90% [18, 29, 40, 67]. Specifically, Liu et al. observed that, without pre-treatments, an ultrafiltration module for algae-laden treatment recorded a decrease of water flux of around 85% [68], while Zhao et al. reported that an ultrafiltration process working under sub-critical conditions is subjected to productivity reductions of around 50% [69]. Thereupon, a direct correlation between flux decline due to fouling and increase in energy demand exists; these patterns are aligned with the pilot scale application analysis of Wang et al. [70] which found that fouling influence is the main bottleneck since capital and operating costs accounted for 9% and 91% respectively, and specifically power requirement contribution was ~50%. The estimated energy requirements were similar to those recorded in other membrane processes (0.17-2 kwh/m^3) reviewed by Mo et al. [71].

Fig. 2 qualitatively summarizes and compares the influence of the main parameters on the filtration performance. The microalgae species influences the process productivity because different strains may give rise to AOM, EPS, and TEP of different size and chemistry, which are then responsible of the interactions with the membranes described above. However, the strain shape and subsequent physical interaction with membrane pore size may even be more important than these effects. CFV typically shows a stronger impact on productivity than TMP, especially above the threshold flux, which is defined here as the maximum permeate flux at which no significant fouling occurs. Above this value, an increase in TMP does not translate into a consequent increase in water flux [72], while increasing CFV may still have a positive effect on productivity. Lastly, the membrane porosity is a critical parameter in relation to the extent of irreversible fouling, which may be argued to be the ultimate effect that should be avoided [56].

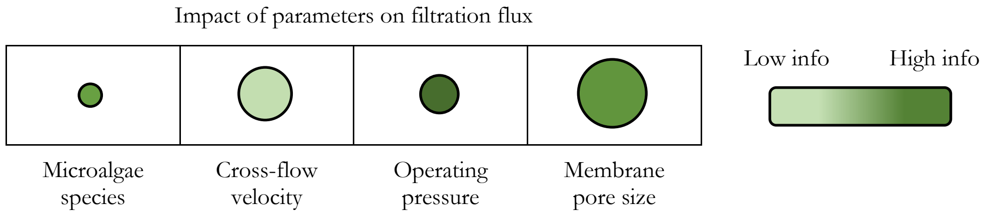


Fig. 2: Assessment of the influence of important parameters on processes productivity. The circle size is qualitatively proportional to the impact on process performance and does not refer to the process performance or fouling behaviour in absolute terms. The intensity of the colour filling each circle is a qualitatively representation of the amount of information available for each parameter.

3. Algal fouling control strategies

The fouling phenomena must be reduced and properly controlled to guarantee high process performance. In this section, a review of the fouling control strategies is reported; Fig. 3 summarizes the approaches, classified into mitigation and adaptation strategies. Briefly, mitigation strategies are aimed to reduce the impact of fouling phenomena by acting directly during the run of the process while adaptation (or cleaning) ones are applied at the end of each cycle in order to re-establish as much as possible the starting conditions.

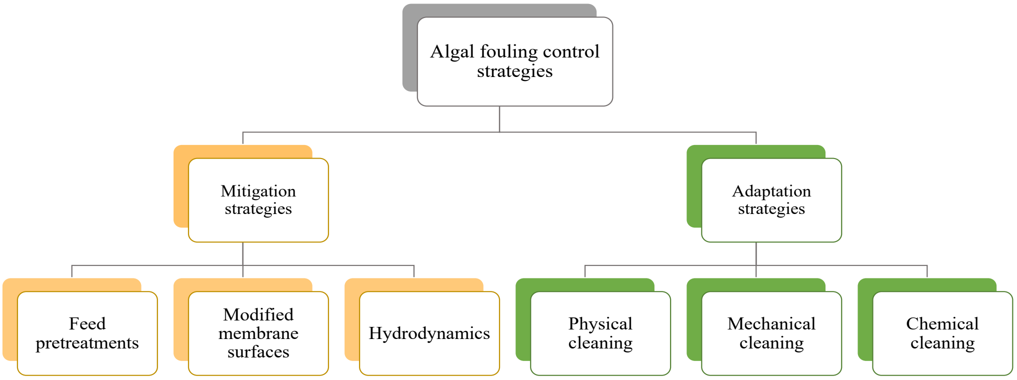


Fig. 3: Schematic of algal fouling control strategies. The objective of mitigation strategies is the reduction of fouling severity during membrane filtration cycles, while adaptation refers to actions carried out at the end of each filtration cycle to restore initial membrane performance.

3.1. Mitigation strategies

There are mainly three categories of mitigation strategies. Feed pretreatment is reported as an effective approach to control the accumulation of compounds known for aggravating reversible and irreversible fouling as well as precursors in the formation of undesired disinfection by-products [73].

They are increasingly studied for algal streams and include coagulation, adsorption, oxidation, air flotation, and their combination [29, 74-77]. Utilization of modified membranes and hydrodynamic approaches are also effective strategies to mitigate and reduce fouling. A detailed summary of the fouling mitigation strategies available in the field of membrane-based separation processes for algae biomass harvesting is presented in the Table 1 and further specific details are described in the next paragraphs.

Table 1: Fouling mitigation strategies resume

Fouling control strategy	Control mechanism	Main inputs	Control principle	Drawbacks	Findings	Ref.
Feed pretreatment (Section 3.1.1.)	**Coagulation**	Iron coagulants	Lower the surface tension between foulants Promote formation of big aggregates to form a porous cake layer	Large demand of chemicals and alteration of biomass properties.	Fe(IV) coagulant/oxidant have a dual effect that outperforms traditional $FeCl_3$ Fe(VI) ↑ removal LMW & biopolymers than $FeCl_3$	[36, 73, 78]
		Polymeric coagulants			Chitosan ↑removal LMW & biopolymers than $FeCl_3$ ↓concentration required to achieve high efficiency	[36, 79]
	Electrocoagulation	Electricity and iron/aluminum/steel electrodes	Apply dc to destabilize foulants by double layer compression or charge neutralization	High energy and equipment costs. Changing polarity and electrode passivation.	Low DC in electrode ↑ concentration of microalgae (CF>100) ↑ removal of DOC, proteins and carbohydrate	[80, 81]
	Oxidation	Ozone, ultraviolet light (UV), chlorine, Fe(II)/persulfate or cold plasma	Generate hydroxyl and sulfate radicals decompose organic foulants and mineralize the smaller fractions	High equipment and energetical cost. Cell breakage risks with consequent IOM release. In chlorine, generation of hazardous by-products.	0_3 & UV ↑ transform organics to LMW ↑ pore blockage ↑ release of IOM and cell debris ↑ pore blockage	[74, 82, 83]
					Fe(II)/persulfate ↓ cell breakage ↓ dose required	[83]
					UV/ persulfate ↑ specific flux	[84]
	Electro-oxidation	Boron-doped diamond anodes	Generation of reactive free radicals OH• that decompose organic foulants	High equipment and energy costs. Changing polarity and electrode passivation.	Mineralization of AOM responsible of irreversible fouling. ↓ resistance to aggregation → ↑ large flocs → ↑ filterability	[76, 85]
	Adsorption	Powdered activated carbon (PAC), kaolin, metal oxide	Adsorb LMW organics and particles	Low effect in biopolymers, large organics and algal cells	↓ LMW fractions ↓ irreversible fouling ↑ DOC removal ↑ floc stability ↑ cake filterability	[75, 86, 87]
	Pre-coagulation + pre-oxidation	a) $KMnO_4$ - Fe(II) b) Fe(III) - permonosulfate c) Sodium percarbonate - Fe^{2+}	Create a dual coagulation/oxidation effect	High demand of chemicals	$KMnO_4$ + Fe(II) → ↑ floc size → ↑ cake porosity ↓ pore blockage and irreversible fouling SPC + Fe^{2+} → ↑ formation of $Fe(OH)_3$ → ↑ floc size	[76, 84, 88]

Modified membrane surfaces (Section 3.1.2.)	**Nanomaterial blends**	TiO_2, Fe_2O_3, zeolites, silica, silver nanoparticles	Coat of blend membranes with particles capable of modifying hydrophilicity or surface charge	Demand of expensive membrane materials	TiO_2 / Fe_2O_3 → ↑ hydrophilicity → ↑ filterability Hydrophilic polymers → ↑ hydrophilicity → ↑ filterability Ag-polymers → ↑ surface roughness and permeability	[89-91]
	Nanomaterial blends + oxidation	Zero valent iron (ZVI) + peroxymonosulfate (PMS)	Activate PMS via ZVI, generating SO_4 and Fe^{3+} and a dual coagulation/oxidation	Cost of materials and chemicals	*In-situ* oxidation created on membrane-fouling interface significantly decreases the oxidative cell damage effect created in the feed by other oxidation methods, protecting algal cells from breaking Dual coagulative/oxidative effect → ↑ filterability	[65, 92]
	Modified membrane polymers	Equipment and membranes	Modify the membrane structure and pore geometry	Demand of equipment and materials	Solvent vapor treatment ↑ mechanical strength of membranes slight permeability ↓	[66]
	Customized tilted membrane panels	Energy, air and equipment	Maximize the membrane-bubbles interaction, maximizing shear	Equipment and energy costs Cell damage and release of IOM	Increasing the tilting angle to 20° improves water flux by 20-30%	[66, 93]
Hydrodynamics (Section 3.1.3.)	**Modifications in HRT, SRT in MPBRs**	-	Control growth stage and the generation/release of AOM	Alteration of biomass properties Decrease in productivity	↑ HRT → ↓ organic loading rate and fouling severity ↑ SRT → ↑ LMWO and irreversible resistance	[35, 41, 54, 94]
	Flux control	Pumping energy	Decrease convective forces that drag foulants towards the membrane	Need of large membrane areas to keep low fluxes	Subcritical flux → ↓ irreversible fouling ↑ filtration stability	[18, 29, 40]
	Cross-flow velocity	Pumping energy	Increase CFV to enhance turbulence and shear	High energy demand Cell damage and release of IOM at high CFV	↑CF → ↑ turbulence values which reduce the deposition of foulants	[52, 95]
	Membrane vibration	Energy and equipment to vibrate/rotate	Mechanically create shear in the surface-feed interface to disrupt cake and gel polarization layers	High equipment and energy costs. Cell damage and release of IOM	*In-situ* shear created on membrane-fouling interface decreases the shear stress created to the feed, protecting algal cells from breaking ↑ removal of cake and gel polarization layers ↑ collision → ↑ large algal aggregates with better filterability	[63, 96, 97]

3.1.1. Pretreatment of the algal stream

3.1.1.1. Coagulation and electrocoagulation

The use of iron-based coagulants with amphiphilic characteristics is commonly applied to lower the surface tension between liquids and solids and this technique may be applied to promote the formation of cell and AOM aggregates that form a porous cake layer with better filterability which can easily be removed by membrane cleaning. Iron in the ferric chloride ($FeCl_3$) form is widely used in water treatment for coagulation and flocculation processes [78]; however, the high doses required limits its application [36, 73]. Thereby, recent developments proved a better suitability for the use of alternative iron-based coagulants, such as Fe(IV)/Fe(II). Iron at high oxidation state, i.e., Fe(IV) (ferrate), is considered promising, as this acts simultaneously as coagulant, oxidant, and disinfectant. Alshahri et al. [78] reported an improvement in the AOM removal from 58-87% to 88-93% when comparing the performance of $FeCl_3$ with *in-situ* generated liquid ferrate (FeO_4^{-2}) in the coagulation of *Chaetoceros affinis*. A higher adsorptive and oxidative capacity was achieved through the formation of $Fe(OH)_3$ ions that resulted from the decomposition of ferrate and thus, dosing Fe(VI) led to a higher removal of LMW neutral organics and other biopolymers (38–65% and 97–100%, respectively) in comparison with Fe (III) (14–29% and 74%, respectively) [78]. In a following study, Alshahri et al. [73] found a similar trend when coupling liquid Fe(IV) and Fe(III) with dissolved air flotation (DAF); at a concentration of 3 mg Fe/L, Fe(IV) and Fe(III) enhanced the removal of AOM by 99% and 52% respectively, at a flotation time of 10 minutes.

Alternative inorganic coagulants have been found to form stable structures with negatively charged proteins. Such effect was reported by Huang et al. [87] when dosing a metallic chelator in the form of Cu^{+2}: increasing the Cu^{+2} concentration lessened the contribution of IOM to the overall fouling resistance. Similarly, the use of polymeric organic coagulants, e.g., chitosan, is gaining popularity due to a low production cost (>2 USD/kg) and high efficiency at algal flocculation at lower doses [36, 79]. Discart et al. [36] reported a 50% flux improvement by dosing 10 mg/L of $FeCl_3$, whilst the same improvement was achieved at a concentration of 2-5 mg/L of chitosan. Likewise, Du et al. [79] proved the efficiency of chitosan to remove LMW organics and alleviate pore blockage; in a comparison of the efficiency of aluminum sulfate and a composite aluminum sulfate-chitosan (AS-CS) coagulant, the presence of CS polymeric chains in the AS-CS composite led to a larger removal of LMW organics, thereby alleviating membrane fouling by 58.8%, compared to AS alone (23.7%).

Coagulation is widely regarded as a successful fouling control treatment. However, despite enhancing the cake layer compressibility, severe membrane fouling due to pore-blocking mechanism has been reported under certain conditions when coagulants combine with LMW organics. Thereby, recent developments explored ways to eliminate undesired chlorides or sulfates from conventional coagulation salts by using electrocoagulation [84]. This technique consists in the application of a direct current that destabilizes negatively charged foulants by double layer compression or charge neutralization. As a result, soluble AOM and algal cells coagulate, and the hydrogen bubbles resulting as a by-product trigger their removal by flotation [80, 81, 98]. Parmentier et al. [81] achieved a >100 algal concentration factor when applying low direct currents to iron and aluminum electrodes (0.8 and 0.3 A, respectively), concentrating suspensions of *Chlorella vulgaris* from 0.2 to 18.5 and 35.2 g/L when using iron and aluminum electrodes, respectively. Similarly, Rafiee et al. [80] reported the removal of proteins, carbohydrates and DOC by 21, 60 and 47%, respectively, when applying electrocoagulation to a mixed algal culture.

Overall, some energetic and economic evaluations were performed to evaluate the feasibility of the coagulation pretreatment, albeit not directly for algal streams separation. Yoo et al. [65] observed that in a water treatment plant the costs of chemicals rose from 0.0066 to 0.0146 $\$/m^3$ due to the high doses of needed coagulants, but the energy saving due to better treatment performance (permeate flux increased from 50 to 70 LMH) and the lower sludge production counteracted this effect, thus decreasing the total operating cost of 11.2%. Further studies are necessary to obtain an adequate assessment of the feasibility of coagulation in algae separation. In this context, new plant-based coagulants are gaining popularity as environmentally friendly solutions owing to their safety and biodegradability, being more sustainable compared to conventional chemical coagulants (i.e., Fe and Al salts, or polymers).

3.1.1.2. Oxidation and electro-oxidation

Oxidation is gaining spotlight in the mitigation of membrane fouling and in the degradation of AOM [83]. The pre-oxidation of feed water by means of, e.g., ozone, ultraviolet light (UV), chlorine, Fe(II)/persulfate, and cold plasma, has been reported as an effective fouling mitigation technique. The generated hydroxyl and sulfate radicals decompose organic foulants and mineralize the smaller fractions [74, 83, 99]. Nevertheless, large doses of an oxidant pose a risk for cell breakage and IOM release into the medium. Liu et al. [83] compared the oxidation effect of ozonation and oxidation/coagulation by Fe(II)/persulfate. Both oxidant strategies were found to trigger cell breakage and thus, to increase the concentration of IOM in solution. Specifically, cell breakage of 58 and 81% was observed when dosing ozone at 0.015 and 0.06 mM, respectively. In contrast, Fe(II)/persulfate reduced cell breakage (5%) at the lowest concentration (0.05 mM) of reagent investigated. Thereupon, ozonation was correlated with an increase in the irreversible fouling fraction, as it was found to degrade biopolymers into smaller foulants, prone to cause pore blockage. In contrast, dosing Fe(II)/persulfate at low concentrations (0.2 and 0.4 mM) improved the final specific flux. Moreover, ferric ions were *in-situ* generated during the oxidation with Fe(II)/persulfate, thereby promoting an additional coagulant effect that reduced fouling and favored the formation of a porous cake layer, by enhancing the agglomeration of cells and AOM into large flocs. Comparatively, Lee at al. [84] showed a significant decrease in the fouling membrane index and TOC concentration in solution (85% and 17%, respectively) when using UV/permonosulfate (PMS) oxidation in suspensions of *Pseudo Nitzchia*.

UV-driven advanced oxidation is advantageous owing to its great oxidative power. Coupled oxidation treatments have shown large performance in fouling control. Wan et al. [74] compared the fouling control efficiency of several composite UV-based oxidation processes (UV/persulfate (UV/PS), UV/chlorine, and UV/H_2O_2). Beyond a critical threshold of oxidative stress, UV-radiation was found to trigger cell lyses and therefore increase irreversible fouling caused by the IOM and cell debris released by dead cells. Upon experiments, the composite UV/PS was found to be more effective to control the membrane fouling, enhancing the final specific flux from 0.26 to 0.29 and 0.81 at PS doses of 0.25 and 1 mM, respectively. Better efficiency at controlling reversible fouling was associated with the coagulant effect of PF that decreased the concentration of irreversible foulants such as soluble hydrophobic LMW organics and debris. Analogously, a positive effect of UV/H_2O_2 in fouling control was exhibited at large doses (1 mM), reaching a final specific flux of 0.38. In contrast, UV/chlorine pretreatment exacerbated membrane fouling, and the resistance associated with irreversible fouling increased fivefold compared to raw water. The effect was due to the breakage of large biopolymers into LMW that progressively accumulated in membrane pores, indicating a low efficiency in biopolymer mineralization.

The use of UV oxidation allows reduction in the use and release of chemical oxidants into the water; nevertheless, the resulting cell damage limits its application. Alternatively, the use of cold plasma (CP) was proposed by Lee et al. [99] as a strategy to mitigate membrane fouling by active decomposition of AOM, as it displayed suitable removal of TSS, TOC, and COD. However, research on CP is needed to clarify its energy expenditure and fouling control.

Likewise, Liu et al. [85] proved as positive the effect of electrochemical pre-oxidation with boron-doped diamond anodes at reducing reversible and irreversible fouling; with an increase in the oxidation time, the zeta potential of algal biomass decreased from −18,2 to −8,9 mV, weakening the resistance to aggregation and thereby, leading to the formation of particles with sizes larger than 100 μm. These particles promoted the formation of a loose and fuzzy cake layer with a lower resistance to water permeation. Nevertheless, the high energy and equipment cost, along with the frequent changing polarity and electrode passivation, pose a bottleneck for the process, and thereby its efficiency on fouling control necessitates further research [76]. In general, some environmental issues must be considered when dealing with oxidation processes: some toxic by-products can be formed upon degradation of organic compounds as well as disinfection by-products associated to the use of chlorine [100].

3.1.1.3. Adsorption

The use of adsorption has been proved to remove the LMW fractions and micropollutants responsible of irreversible membrane fouling, as well as disinfection by-products [75, 86, 87]. The interactions between adsorbents and algal foulants have been found to correlate with the cake layer stratification and deformation properties [86]. Commonly used adsorbents include powdered activated carbon (PAC), kaolin, and metal oxide particles [75, 86, 87]. Zhang et al. [86] reported a stable efficiency in EOM adsorption and fouling mitigation when using pre-mixed PAC and kaolin particles. The fouling control efficiency increased for higher PAC sizes, as this parameter increased the cake layer porosity and thereby, enhanced the transport of the algal foulants back into the feed stream, lowering the overall fouling rates. On the other hand, smaller PAC/kaolin sizes led to micropores with a larger adsorptive capacity that was mirrored in higher DOC removal efficiencies and cake layer resistance. Thereby, when using PAC$_{12}$, PAC$_{25}$, and PAC$_{30}$, the DOC removal efficiencies reached 22.3%, 23%, and 15.9% respectively. Nevertheless, while large biopolymers in the EOM where difficult to remove by PAC adsorption, kaolin proved to be more efficient owing the hydrogen bonding between O atoms in the kaolin and OH groups of the EOM. The polyhedral face-edge structure of kaolin favored foulant-kaolin aggregates with low adhesion energies, thus building loose aggregates and a porous cake layer.

Furthermore, the sole use of PAC has been proven insufficient at removing high MW organics, and UV alone hardly degrades the AOM due to the limited and short lifetime of OH$^{\bullet}$ radicals in solution. Accordingly, Xing et al. [75] employed UV/Cl oxidation and PAC adsorption (UV/Cl/PAC) to offset the negative impacts of DBPs prior to filtration. UV/Cl pretreatment led to the formation of OH$^{\bullet}$ and Cl$^{-\bullet}$ radicals that triggered the decomposition of HMW organics into activated LMW that could be easily adsorbed by PAC. The combination of UV/PAC and UV/Cl/PAC enhanced the DOC removal to 7.2 and 9.3%, and this was mirrored in the TMP development along filtration operation. Raw feed water was associated to a final TMP of 0.81 bar, whereas UV/PAC and UV/Cl/PAC pre-treatment resulted in TMPs of 0.67 and 0.56 bar, respectively. The alleviating effect of UV/Cl/PAC was ascribed to the combined effects of oxidation and adsorption. The composite use of UV/PAC and UV/Cl/PAC proved to be efficient at degrading organic foulants and alleviating reversible and irreversible fouling, reducing them by 26-36% and 13-22%, and by 44-48 and 33-53%, respectively. In general, adsorbent materials do not present any relevant environmental issues. However, the steps involved with their management, regeneration, or disposal depend strongly on the types of adsorbent and algal process.

3.1.1.4. Blend pre-treatments

Pre-treatments are important to increase the efficiency and service time of the membrane operation, and improve water quality. On the other hand, the implementation of pre-treatment steps involves an increment of investment and maintenance costs, which might not always justify the overall benefit. Moreover, when the target is biomass harvesting and recovery, pre-treatments should not compromise the quality of the final product. To this extent, the application of strong oxidative products, such as hypochlorite, may be unfeasible. Compact and simple system designs combining the use of adsorbents, oxidants, and coagulants were recently reported as highly efficient approach toward fouling control. For example, Ma et al. [76] proposed the *in-situ* generation of Fe(III) by a composite pre-coagulation/pre-oxidation method, using $KMnO_4$- Fe(II) in the filtration of *Microcystis aeruginosa*. Larger floc sizes, generated when using $KMnO_4$-Fe(II), led to a porous cake layer that, translating into a lower TMP increase in comparison with the Fe(III) coagulation alone (0.25 bar vs 0.43 bar, respectively). Furthermore, pore blockage was alleviated during the $KMnO_4$-Fe(II) pretreatment, as the cake layer contribution increased from 31.6% to 54.6%. Similar results were reported by Lee at al. [84] when combining Fe(III) and permonosulfate to alleviate membrane fouling. Further, Ren et al. [88] coupled pre-oxidation and coagulation by using sodium percarbonate activated with ferrous ion (Fe^{2+}/SPC). The SPC was catalyzed by Fe^{2+} to generate $OH^{\bullet}$ oxidants, whilst the Fe^{2+} led the formation of $Fe(OH)_3$ as it was oxidized. The combined effect of Fe^{2+} and SPC enhanced the specific final flux (J_f/J_0) from 0.284 to 0.710, and reduced reversible fouling resistance by 80% at doses of 0.25 mmol/L.

3.1.2. Modified membrane surfaces

Increased understanding of the combined effect of membrane-foulant interaction forces, including electrostatic repulsion/attraction, hydrophobic forces, and Van der Waals forces, has brought momentum to research in modified membrane surfaces as a strategy to manipulate these colloidal forces on fouling development [18]. Thereby, growing attention is being devoted to modifying membrane antifouling properties by, e.g., blends and surface coatings with polymers and inorganic nanoparticles [91]. Compared to traditional pretreatments, membrane modification allows an easier management of the stream and is a potential strategy to reduce the number of pre-treatment steps. On the other hand, membrane modifications still involve high investment costs and challenges related to the scaling-up. The development of super hydrophilic cost-efficient membranes is required to improve the filtration performance while leading to considerable cost reduction within the harvesting process.

Membrane materials, such as PVDF, PES, PVC, and polysulfone (PSF), are highly prone to algal fouling because of their hydrophobic nature [101, 102]. For this reason, surface coatings with, e.g., hydrophilic monomers, polymer bushes, and nanomaterials have been applied to increase the hydrophilicity and to improve water filtration performance [29, 89, 91]. For example, TiO_2, Fe_2O_3, zeolites, silica, and silver particles have been shown to increase the water flux owing to their hydrophilic nature [89]. Hu et al. evaluated the antifouling properties of nano-TiO_2 particles incorporated into PVDF membranes, as TiO_2–modified surfaces reportedly became superhydrophilic. The resistance of PVDF/TiO_2 membranes was 49% lower than that observed with pristine PVDF membranes, and the effect was associated with an increase in membrane wettability, displayed by a decrease of the contact angle of water on the membrane (from 54.4 to 46°) [89]. Similar results were reported by Yogarathinam et al., as the addition of TiO_2 resulted in a better water recovery percentage and a more stable flux [90]. Additionally, Yogarathinam et al. incorporated a hydrophilic additive (polyethylene glycol), polyelectrolyte additive (polyethylenimine), inorganic additive (zinc chloride) and charged polymer (sulfonated polyether ether ketone) as pore formers in PES membranes. As a result, the water contact angle decreased from 76 to 55° and the water flux was enhanced [90]. Analogously, Liu et al. evaluated the performance of Fe_2O_3 incorporation into PVC membranes during their formation by phase inversion. Incorporating 1% of Fe_2O_3 into the membrane increased its hydrophilicity, lowering the water contact angle by 22%, and thereafter achieving a 66% flux increase by decreasing the deposition of irreversible fouling precursors, such as aromatic proteins, fulvic acids, and humic substances [91]. Similarly, Soleimani et al. evaluated graphene/polydimethylsiloxane (PDMS) with silver nanoparticle coatings (GOH-Ag) in PDMS membranes. The GOH-Ag membranes exhibited better antifouling efficiency by increasing the surface roughness and lowering the water contact angle [103].

Iron nanoparticles were studied by Huang et al., by incorporating zerovalent iron (ZVI) on polycarbonate (PC) membranes in combination with peroxymonosulfate (PMS) oxidation. ZVI activated the PMS oxidative effect, generating $SO_4^{\bullet}$ and Fe^{3+} that entailed a dual coagulative/oxidant antifouling effect during the filtration of *C. vulgaris* suspensions. The oxidation zone located solely on the membrane surface and therefore, minimized algal cell breakage as well as the formation of disinfection by-products. As a result, the ZVI-PMS approach led to a larger flux (345 LMH) in comparison with that of the pristine PC membranes (129 LMH) [65]. In contrast, the use of powdered activated carbon coatings was proved to be inefficient at fouling control. A recent approach discussed by Zhang et al. evaluated the pre-deposition of a powdered activated carbon (PAC) coatings onto the membrane surface: the resulting cake layer exhibited stratified layers with a higher resistance to water permeation that aggravated the cell deformation rate and decreased the back-transport of foulants to the bulk solution [92].

Differing from surface coatings and material blends, solvent vapor treatment (SVT) modifies the membrane structure by altering the links between fibers. Mat et al. enhanced the mechanical strength of 6,6 electrospun nanofiber membranes (NFM) by using SVT. As a result, the mechanical strength of NFM was increased. Pristine NFM proved to be efficient for algal filtration, although its low mechanical strength limited a prolonged use. In contrast, SVT enhanced the fusion and melting of overlapping fibers, increasing the mechanical resistance by 221% at the expense of a slight decrease in permeability; the thickness, porosity and mean pore size of the treated NFM were lowered by 18, 4, and 40%, respectively, in comparison with the pristine NFM [66]. Moreover, Mat et al. improved the fouling cleaning efficiency by tilting the nanofiber membranes panel to 20°. Increasing the aeration rates further enhanced the productivity, and intermittent aeration was found to produce a higher flux of around 7% when compared to continuous aeration [66]. Analogously, Eliseus et al. developed a customized tilted membrane panel to enhance the air scouring efficiency, improving the water flux up to 30% during the filtration of *Euglena sp* [93].

Electrically-enhanced membrane systems have gained momentum owing to their capacity to exploit the electrostatic repulsion between the foulants and the membrane surface: electricity applied across the membrane surfaces produces strong electrostatic repulsion forces that reduce the probability of foulants attachment onto the surfaces. Increasing the magnitude of the electric field on conductive membranes augments the electrostatic repulsion and lowers the fouling propensity [104]. So far, electrically-enhanced membranes lack research specifically on algal filtration, thereby demanding further study.

3.1.3. Hydrodynamics

Lower permeate drag force, smooth fluxes, and high surface shear are effective strategies to mitigate fouling [95]. A decrease of permeate flux leads to a reduction in the fouling rate but also requires larger active areas in order to increase the overall productivity [31]; this solution is seldom adopted in real plants due to capital costs and footprint.

The relationship between TMP and fluxes is not so straightforward. For example, Sun et al. [23] found that a TMP increase in the range from 1.3 to 1.8 bar brought an increase in permeate flux and productivity, while TMPs above 1.8 bar led to a decrease of productivity. This result is rationalized with the formation of a thicker foulant layer with reduced porosity generated by high compression of microalgae cells and low turbulence values associated to higher TMPs. Adopting optimal CFV values allows direct control over turbulence and shear rates, which are closely connected to foulant accumulation on the membrane surface [52, 95]. Typically, higher CFV values are associated with larger permeate fluxes.

In membrane photobioreactor (MPBRs) configurations, i.e., membrane immersed directly into the algal growth reactor, there are also other parameters that regulate the performance, including the hydraulic retention time (HRT) and the solid retention time (SRT). A take-home message from the main literature reported is that an increase in HRT can reduce the organic loading rate and the amount of the nutrients during microalgal cultivation, thus causing a decrease of fouling and cake layer development [35, 41, 54].

Shear rates are commonly applied in membrane systems to promote a turbulent flow regime that facilitates the back-transport of foulants to the feed solution [50, 66]. They might be provided from the feed via crossflow velocity, from the scouring systems via air bubbles, or by mechanical means such as vibration or rotation of the membrane modules [105]. These strategies are based on the so-called dynamic filtration systems (DMF): a relative movement between fouling interface and membrane surface in the range of 0 to 0.5 mm is created in order to protect the algal cells from damage due to shear. [18, 96]. Furthermore, the shear force applied on the membrane surface disrupts both the cake and the concentration polarization layers, although careful consideration should be made to maintain the shear forces below the threshold of cell breakage, which varies among algal species [18, 105, 106]. This effect was reported by Ladner et al. [106] in a study whereby an exponential flux decline resulting from the cell lysis and the release of organelles and organic matter was observed under shear force conditions.

The use of vibration membranes is a recent development applied for fouling mitigation. It relies on high vibration frequencies or amplitudes to create a share rate at the membrane-feed interface [96, 97]. Jiang et al. [96] found an increase in the antifouling performance when the vibration frequency was increased from 1 to 5 Hz. The balance in the total interfacial forces was shifted to increase the lifting forces with respect to the drag forces, thereby alleviating membrane fouling. Furthermore, mild vibrations enhanced the inter-foulant collision, thus promoting the formation of large algal aggregates with a lower tendency to deposit on the membrane, although no impact was observed on the relieving of reversible fouling by EOM. Similar results were reported by Zhao et al. [97] within the same frequency range in a uniform shearing vibration membrane (USVM) with constant shear rate by uniform circular motion. By increasing from 1 to 5 Hz, the water flux rose from 296 to 1527 LMH and the final specific flux rose from 0.13 to 0.69, respectively. Furthermore, as the tendency to cell deposition decreased, the biomass was reduced from 0.64 to 0.08 g/m^2 at 1 and 5 Hz.

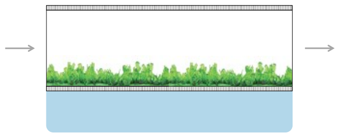
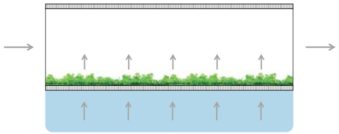
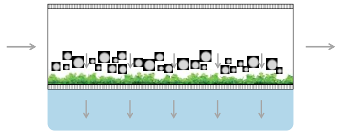
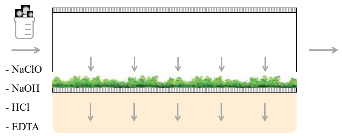
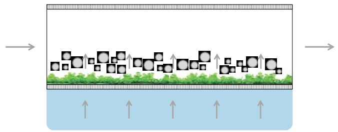
Recent developments created a composited fouling control system made of vibration, negative charge, and patterned polysulfone/sulfonated polysulfone (PSf/sPSf) membrane blends [63]. The waves-patterned membranes exhibited larger pore size, porosity and hydrophilicity when increasing the sPSf concentration, thereby displaying higher water permeability. The patterns promoted turbulence, generating a shear effect that was also triggered by the turbulent regime, induced by vibrations of frequencies above 7 Hz. Patterns and vibrations promoted the generation of turbulence eddies between patterns, thereby scouring the foulants with a high efficiency. Furthermore, turbulence and the negatively charged membranes induced a joint effect that minimized irreversible fouling. Altogether, the energy consumption was significantly lower than that of traditional pumping systems that induce shear through a cross-flow velocity, and the synergistic fouling removal relied mostly on the eddy mixing, shear and scouring effects, according to a computer fluid dynamic modeling. The composited fouling control displayed a higher clean water permeance and critical flux, as well as a lower membrane intrinsic resistance.

Fortunato et al. [50] reported the impacts of cleaning on the cake layer morphology using *in-situ* non-destructive real-time monitoring for the filtration of *Chlorella vulgaris*. Despite significantly reducing the biomass deposition on the membrane surface (5-10 µm thickness) and the fouling rates (−60%), air scouring was found to be inefficient against irreversible fouling caused by AOM and small colloids. In contrast, the shear stress created by air scouring was found to actually increase irreversible fouling by breaking algal foulants into smaller particles, as also elsewhere reported [105, 107]. Similarly, scouring does not prevent small proteins and carbohydrates from depositing on the membrane surface, and higher shear stress conditions increase the formation of submicron particles that transport through the cake layer into the membrane [40]. Thereafter, as the filtration time increases, scouring leads to the formation of a thin packed layer that cannot be removed by physical cleanings [50, 107]. According to Alipourzadeh et al. [29], there is an optimal air sparging intensity which guarantee the minimum fouling, as stable hydrodynamic conditions can enhance the membrane filtration capacity, whereas the extreme opposite might strongly exacerbate the fouling rate.

3.2. Adaptation strategies

As fouling occurs, control mechanisms can be applied to maintain or recover membrane performance; they are generally classified as physical, mechanical, and chemical strategies. Their efficiencies rely on both environmental scenario and operating conditions. When productivity or permeate quality reach a threshold low value, cleaning procedures are necessary to recover the performance. Unfortunately, cleaning becomes less effective at each new cycle, reduces membranes lifetime, and requires pausing the harvesting process [97]. Therefore, selecting the proper membrane cleaning strategy is of capital importance in terms of energy consumption and process performance [97]. Table 2 reports the main working principles of cleaning strategies, their effect on fouling layers and the main challenges.

Table 2. Fouling adaptation strategies resume

Fouling adaptation strategy	Cleaning mechanism	Schematic Conceptualization	Control principle	Drawbacks	Challenges	Ref.
Physical cleaning (Section 3.2.1.)	**Relaxation**		Stop the flux and convective drag forces towards membrane	– Decrease in filtration time. – Lower efficiency over time.	↑ back-transport ↓ reversible fouling ↑ decompressing → ↑ cake porosity ↓ gel polarization layer → ↑ filterability	[40, 50, 66]
	Backwash		Reverse the permeate flow to fluidize cake layer and remove the deposited particles from membrane surface	– Loss of permeate. – Extra pumping energy input. – Lower efficiency over time.	↓ compaction of cake layer ↑ cake porosity and filterability ↓ pore blockage, irreversible fouling (decreased efficiency over time)	[33, 40, 50, 82, 108]
	Air scouring		Air bubbles scrap-off the foulants from the top of the cake layer. Induce shear stress to facilitates back-transport of particles	– High equipment and energy costs. – Cell damage and release of IOM.	↑ IOM and cell debris → ↑ irreversible fouling ↓ cake thickness → ↓ reversible fouling ↓ efficiency in removing LMW organics ↑ air flow rates → ↑ bubble size and fouling removal	[93]
Chemical and combined cleaning (Sections 3.2.2. and 3.2.3.)	**Membrane soaking**		Soaking membranes in a cleaning solution with a consequent flush aimed to remove both used chemicals and detached foulants	– Membrane deterioration. – Formation of by-products. – Chemical and energy consume.	Choosing the adequate cleaning solution for each situation. Problems to achieve high recovery efficiencies, especially when numerous cleaning cycle are performed on the same membrane.	[48, 109, 110]
Mechanical cleaning (Section 3.2.4.)	**Backwash + air-water flushing**		Backwash disturbs foulants deposited on the membrane surface and the following forward flushing remove the debris	– High equipment and energy costs. – Wasn't proved to be more efficient than backwash.	Flux recovery of 29%- 66% achieved by forward air–water flushing. Flux recovery of 90% - 100% was achieved by backwash.	[111]

3.2.1. Physical cleaning

The main physical strategies aimed to control the fouling phenomena in membrane filtration are: relaxation, backwash, and air scouring. Briefly, relaxation consists of a temporary interruption of the filtration, facilitating the back transport of the foulants from the cake layer toward the bulk of the feed solution [50, 66]. When the relaxation period ends, the foulants are redistributed more uniformly along the cake layer, which typically becomes more porous [50]. On the other hand, long relaxation periods inevitably reduce the filtration time, thus lowering the overall productivity [50, 66].

Backwashing instead consists of reversing the direction of the flux across the membrane using the permeate itself as cleaning solution to exert a physical force aimed at removing the particles attached on the membrane surface, reducing pore blocking and cake layer effects [33, 82, 108]. The bottleneck of this approach steams from a large permeate loss, especially when dealing with LMW compounds that demand large permeate backwash flow rates [50]. Lastly, air scouring consists of gas bubbles injected across the membrane surface that generate localized shear stress zones aimed to detach foulants, and also creating a turbulent regime that enhance the compounds back-transport into the feed. Furthermore, cleaning via air bubbles is largely affected by the bubble sizes; achieving optimal slug-flow conditions demands high energy to pump large volumetric air flow rates [93]. The energy-intensive nature of the process hampers its operational efficiency, and flows above an optimal bubble number might hinder the contact between the liquid feed and the membrane surface, thus reducing the liquid flow across the membrane [50, 66].

Cake layer is largely considered to be the main contributor to fouling resistance in algal filtration systems and for this reason much attention has been drawn to its responses to membrane physical cleaning [40, 50, 54]. Fortunato et al. [50] found that relaxation and backwash can both alleviate the final fouling rates by nearly 50%. Nevertheless, differences were found on their impact in the distribution of foulants across the cake layer and thereby, in the mechanisms affecting the flux; during backwash, the cake layer was partially detached from the membrane, but quick redeposition occurred during the following filtration stage with the formation of a similar cake layer. Moreover, the protection exerted by the cake layer against LMW organics deposition was not available upon its detachment. In fact, Kanchanatip et al. [40] reported a decrease in the fouling control efficiency as the number of backwash cycles increased the share of irreversible fouling. Comparatively, relaxation resulted in a thicker and rougher cake layer with similar filterability properties to that of backwash, cutting off the expenses of permeate and energy required for the backflow. It is important to highlight that, prolonging relaxation periods reduce the productivity and has been found to also impact the process negatively by resistance related to irreversible fouling [66, 93]. Mat et al. [66] found that, in a filtration cycle of 5 minutes, relaxation periods of 1-2 minutes resulted in the highest steady-state flux. Accordingly, carefully adjusting the filtration/relaxation intervals is required to mitigate fouling without severely reducing the permeability [66]. It is also important to highlight that, cake layer thickness has been found inadequate at predicting fouling severity: the distribution of foulants across the layer, surface roughness, and cake porosity determine together the degree of compression and resistance to water filtration [40, 111].

3.2.2. Chemical cleaning

As physical cleaning can counteract only reversible membrane fouling, chemical cleaning has been applied to remove irreversible fouling. This approach consists of soaking membranes in a cleaning solution with a consequent flush aimed to remove both used chemicals and detached foulants [112, 113]. It is clear that the optimal cleaning approach depends on a multitude of factors, such as feed composition, fouling nature and severity, cleaning frequency, temperature, pH [114]. Chemical cleaning could be realized in different scenarios: (i) in-situ (without removing the membrane from its vessel), (ii) ex-situ (outside the vessel in an ad hoc tank), (iii) by adding chemicals during the filtration cycle, (iv) by chemical backwash, i.e., adding reagents during the physical cleaning phase [115]. The cleaning agents are classified in: alkaline; acidic; metal chelators; enzymes; oxidizing agents. A combination of these is typically applied.

Liang et al. [48] observed a suitable cleaning efficiency during the combined use of NaOH (0.02 N) and NaClO (100 mg/L) when dealing with UF membranes fouled by algae reservoir water. Moreover, mirroring other literature results, they discovered that cleaning by NaOH for 2–6 h ensured lower recovery than that obtained using NaClO. The citric acid instead was not effective in cleaning the membrane, providing only 40–60% flux recovery. The advantages of using NaClO are that it is a strong oxidant, which is able to attack NOM and to inactivate algae cells and bacteria [48, 116]. On the other hand, Ding et al. [109] showed that proteins, amino acids, and polysaccharides adsorbed on the membrane surface strongly contributed to halogenated by-products formation upon NaClO addition. Moreover, the increase of NaClO concentration, as well as temperature, promoted the formation of these hazardous compounds, which are recognized as serious threats to water quality and human health. In accordance with the previous results, Zhang et al. [110] found that cleaning fouled PVC membranes with 500 mg/L NaOH for 1.0 hours exhibited a negligible effect on irreversible fouling resistance (1.5% ± 1.0%) while much higher efficiencies (88.4 ± 1.1)% were registered using 100 mg/L NaClO. Intermediate cleaning performances in terms of efficiency (47.1% ± 1.2% and 21.6% ± 3.5%) were obtained with HCl (500 mg/L) and EDTA (150 mg/L). However, it is worth noting that most of these studies have focused only on the flux recovery without considering the potential negative impact of invasive cleaning on long-term operation.

3.2.3. Combined cleaning

New research approaches are focusing on the combination of the shear effect provided by air scouring systems with traditional cleaning methods. Dual membrane cleaning techniques applying backwash and air-water flushing were studied by Huang et al. [111] for harvesting *Chlorella sp.* Backwash using permeate water was found to be more effective than forward air-water flushing in the fouling control, reaching flux recoveries of 90-100% and 29-66%, respectively. Additionally, a cleaning strategy whereby a first hydraulic cleaning by backwash is followed by a second forward flushing was recommended based on the hypothesis that backwash can disturb foulant deposits on the membrane surface and the following forward flushing may hopefully remove the fluidized foulants detached during backwash.

Recent applications on Chemically Enhanced Backwash (CEB) whereby, a dosage of chemical reagents such as NaCl and NaClO is applied in parallel with backwash, have proved to confer supplementary effects between both processes and particularly, to minimize irreversible biofouling. By means of oxidation and dissociation, the chemicals weaken cohesive in the foulant-membrane interface and enhance the effect of backwash, although this is highly reliant on dosages and frequencies applied and further investigation is required on this realm. Tang et al. [117] found in that in freshwater-containing algae, NaOCl applied at a dosage of 10 ml/L twice per day was optimal in fouling control due to the dissociation of cross-linked gel structures and to the inhibitory effect in microorganisms; differently, NaCl is cheaper and greener in terms of biodegradation and toxicity, yet it led to a lower fouling control effect and demanded large dosages of 500 mg/L. Similarly, Kang et al. [118] used dosages of 300 mg/L in CEB to cope with algal inflow in membrane desalination, reaching recovery rates of 98.1% TMP upon CEB treatment.

3.2.4. Mechanical cleaning

Shear rates are commonly applied in membrane systems to promote a turbulent flow regime that facilitates the back-transport of foulants into the feed solution [66]. They might be provided from the feed via crossflow velocity, from the scouring systems via air bubbles, or by mechanical means, such as vibration or rotation of the membrane modules [105]. The latter techniques are termed dynamic membrane filtration systems (DMF) [86, 105]. In DMFs, a relative motion between the membrane surface and the fouling interface is applied within a 0 to 0.5 mm distance; this is intended to protect the algal cells in the feed from shear-induced damage [96]. The shear force applied on the membrane surface disrupts both the cake layer and the concentration polarization layer, although shear forces should be kept below a threshold to prevent cell breakage [106].

The vibration.based systems use high vibration frequencies or amplitudes to create a shear rate at the membrane-feed interface. Jiang et al. [96] found an increase in the antifouling performance when the vibration frequency was increased from 1 to 5 Hz. This result was due to a shift in interfacial forces, becoming lifting forces predominant over drag forces at higher frequencies, thus minimizing the deposition on foulants on the membrane. Further, mild vibrations enhanced the inter-foulant collision, promoting the formation of large algal aggregates with a lower tendency to deposit on the membrane. Recently, Zhao et al. [97] created a composited fouling control system made of vibration, negative charge, and patterned polysulfone/sulfonated polysulfone (PSf/sPSf) membrane blends. The waves-patterned membranes exhibited larger pore size, porosity and hydrophilicity when increasing the sPSf concentration, thereby displaying higher water permeability. The patterns promoted turbulence, generating a shear effect that was enhanced by the turbulent regime that the vibrations induced at frequencies above 7 Hz. Patterns and vibrations promoted the generation of turbulence eddies between patterns, thereby scouring the foulants with a higher efficiency.

4. Sustainable microalgae membrane-based separation perspectives

Membrane-driven separation processes have the several advantages respect other possible algae harvesting solutions due to lower equipment footprint, high recovery, and the ability to preserve high quality of the concentrated biomass for downstream processing [18, 19]. However, membrane fouling is responsible for the increase in energy consumption and for membrane deterioration [119]. While a slight flux decline is observed when filtering algae-free growth medium alone, high values of flow reduction occur only during the filtration of the algal suspension, indicating that the algal cake layer dominates the process performance efficiency [37, 120]. A reduction of fouling and its better control will translate directly into energy savings due to the easier filterability linked to higher algae harvesting performances [51].

Based on this literature review, further necessary research investigations in microalgae harvesting and fouling control have been identified in the following areas, which are also summarized in **Fig. 4**:

(i) Optimization of membrane configurations for an efficient fouling control and sustainable algal harvesting.

(ii) In-depth investigation of microalgae and AOM composition and their interactions with membranes.

(iii) Integration of effective and standardized fouling characterization procedures, fundamental for a comprehensive understanding of fouling dynamics. To this extent, a variety of parameters such as flux, retention rate, fouling resistance, and concentration factors have been used as reference performance and fouling indicators, but without uniformity among research protocols; different studies can hardly be compared with each other.

(iv) Understanding the role of algae biofilm and cake layer developed on the membrane, in both separation efficiency and biochemical transformations during algae separation [29].

(v) Develop models to predict the fouling mechanism in algal processes for biomass harvesting.

(vi) Quantitative environmental and energetic assessments of membrane-based algae concentration processes aimed to precisely estimate and reduce the energy demand during production of biofuels from algae biomass.

(vii) Develop tailored fouling control strategy to allow the simultaneous recovery of valuable algal by-products and restoration of membrane performance [121].

(viii) Processes scale-up, crucial to link the lab-scale literature results with full scale applications, focusing on the energetic aspect [71].

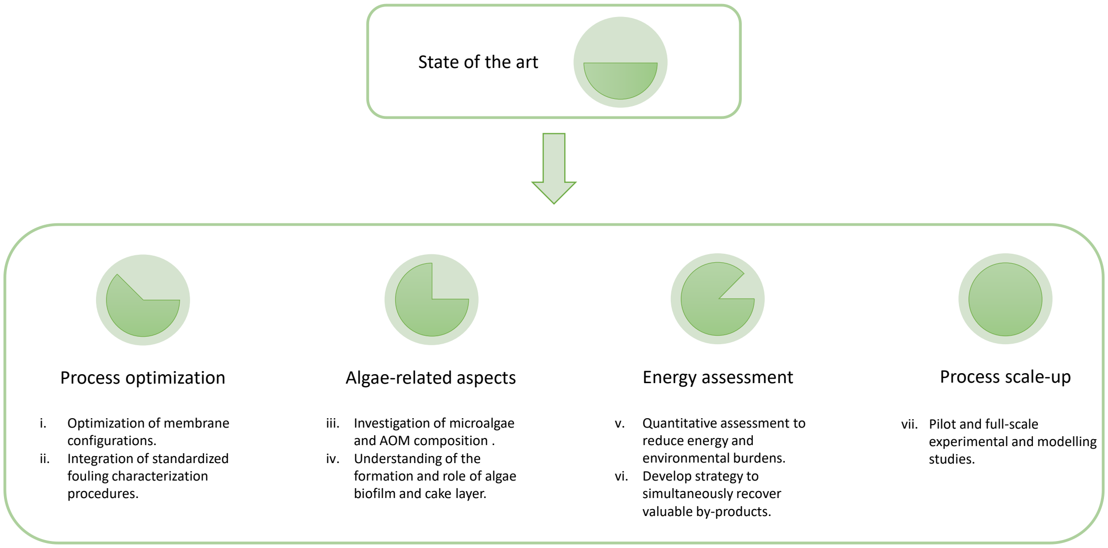


Fig. 4: Summary of the main research needs to step up microalgae harvesting processes.

The harvesting and concentration process of microalgae still requires large water volumes, high energy consumption and investments, which combined are estimated to account for over 30% of the total production cost of algal biomass [122-124]. Research is required to investigate the possibility to reuse the collected permeate directly or indirectly as a new growth medium for subsequent microalgae growth cycles, thus approaching zero liquid discharge (ZLD) perspectives, improving the process sustainability. This goal will require high-quality permeate streams that can only be achieved if the fouling phenomena is carefully controlled. Moreover, to reduce the water footprint of algae cultivation systems, seawater, saline aquifer water, and wastewater may be also used as lower-value water sources for algae production with careful consideration about the content of N and P, and other micronutrients [125-127].

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5. References

[1] R. M. DuChanois, C. J. Porter, C. Violet, R. Verduzco, M. Elimelech, Membrane Materials for Selective Ion Separations at the Water–Energy Nexus, Adv. Mater. 33 (2021) 2101312, https://doi.org/10.1002/adma.202101312.

[2] F. Almomani, A. Al Ketife, S. Judd, M. Shurair, R. R. Bhosale, H. Znad, M. Tawalbeh, Impact of CO2 concentration and ambient conditions on microalgal growth and nutrient removal from wastewater by a photobioreactor, Sci. Total Environ. 662 (2019) 662-671, https://doi.org/10.1016/j.scitotenv.2019.01.144.

[3] J. R. Werber, C. O. Osuji, M. Elimelech, Materials for next-generation desalination and water purification membranes, Nat. Rev. Mater. 1 (2016) 16018, https://doi.org/10.1038/natrevmats.2016.18.

[4] V. Fthenakis, H. C. Kim, Life-cycle uses of water in U.S. electricity generation, Renew. Sust. Energ. Rev. 14 (2010) 2039-2048, https://doi.org/10.1016/j.rser.2010.03.008.

[5] J.-M. Do, S.-W. Jo, H.-T. Yeo, D. H. Shin, H. Oh, J. W. Hong, H.-S. Yoon, Biological treatment of reverse osmosis concentrate by microalgae cultivation and utilization of the resulting algal biomass, J. Water Process Eng. 42 (2021) 102157, https://doi.org/10.1016/j.jwpe.2021.102157.

[6] A. Kusmayadi, Y. K. Leong, H.-W. Yen, C.-Y. Huang, J.-S. Chang, Microalgae as sustainable food and feed sources for animals and humans – Biotechnological and environmental aspects, Chemosphere 271 (2021) 129800, https://doi.org/10.1016/j.chemosphere.2021.129800.

[7] S. S. Oncel, Microalgae for a macroenergy world, Renew. Sust. Energ. Rev. 26 (2013) 241-264, https://doi.org/10.1016/j.rser.2013.05.059.

[8] T. Mathimani, N. Mallick, A comprehensive review on harvesting of microalgae for biodiesel – Key challenges and future directions, Renew. Sust. Energ. Rev. 91 (2018) 1103-1120, https://doi.org/10.1016/j.rser.2018.04.083.

[9] A. Rempel, J. P. Gutkoski, M. T. Nazari, G. N. Biolchi, B. Biduski, H. Treichel, L. M. Colla, Microalgae growth with a high concentration of emerging pollutants and phytotoxicity evaluation of cultivation wastewater, J. Water Process Eng. 46 (2022) 102616, https://doi.org/10.1016/j.jwpe.2022.102616.

[10] S. Yuan, S. Ye, S. Yang, G. Luo, Purification of potato wastewater and production of byproducts using microalgae Scenedesmus and Desmodesmus, J. Water Process Eng. 43 (2021) 102237, https://doi.org/10.1016/j.jwpe.2021.102237.

[11] B. H. H. Goh, H. C. Ong, M. Y. Cheah, W.-H. Chen, K. L. Yu, T. M. I. Mahlia, Sustainability of direct biodiesel synthesis from microalgae biomass: A critical review, Renew. Sust. Energ. Rev. 107 (2019) 59-74, https://doi.org/10.1016/j.rser.2019.02.012.

[12] Y. A. Lim, M. N. Chong, S. C. Foo, I. M. S. K. Ilankoon, Analysis of direct and indirect quantification methods of CO2 fixation via microalgae cultivation in photobioreactors: A critical review, Renew. Sust. Energ. Rev. 137 (2021) 110579, https://doi.org/10.1016/j.rser.2020.110579.

[13] V. Senatore, A. Buonerba, T. Zarra, G. Oliva, V. Belgiorno, J. Boguniewicz-Zablocka, V. Naddeo, Innovative membrane photobioreactor for sustainable CO2 capture and utilization, Chemosphere 273 (2021) 129682, https://doi.org/10.1016/j.chemosphere.2021.129682.

[14] N. A. Oladoja, J. Ali, W. Lei, N. Yudong, G. Pan, Coagulant derived from waste biogenic material for sustainable algae biomass harvesting, Algal Res. 50 (2020) 101982, https://doi.org/10.1016/j.algal.2020.101982.

[15] L. d. S. Leite, M. T. Hoffmann, L. A. Daniel, Coagulation and dissolved air flotation as a harvesting method for microalgae cultivated in wastewater, J. Water Process Eng. 32 (2019) 100947, https://doi.org/10.1016/j.jwpe.2019.100947.

[16] Y. S. H. Najjar, A. Abu-Shamleh, Harvesting of microalgae by centrifugation for biodiesel production: A review, Algal Res. 51 (2020) 102046, https://doi.org/10.1016/j.algal.2020.102046.

[17] M. R. Bilad, H. A. Arafat, I. F. J. Vankelecom, Membrane technology in microalgae cultivation and harvesting: A review, Biotechnol. Adv. 32 (2014) 1283-1300, https://doi.org/10.1016/j.biotechadv.2014.07.008.

[18] Y. Zhang, Q. Fu, Algal fouling of microfiltration and ultrafiltration membranes and control strategies: A review, Sep. Purif. Technol. 203 (2018) 193-208, https://doi.org/10.1016/j.seppur.2018.04.040.

[19] G. Singh, S. K. Patidar, Microalgae harvesting techniques: A review, J. Environ. Manage. 217 (2018) 499-508, https://doi.org/10.1016/j.jenvman.2018.04.010.

[20] M. Xu, X. Wang, B. Zhou, L. Zhou, Pre-coagulation with cationic flocculant-composited titanium xerogel coagulant for alleviating subsequent ultrafiltration membrane fouling by algae-related pollutants, J. Hazard. Mater. 407 (2021) 124838, https://doi.org/10.1016/j.jhazmat.2020.124838.

[21] D. Ghernaout, Water Reuse: Extenuating Membrane Fouling in Membrane Processes, Am. J. Chem. Eng. 6 (2018) 25, https://doi.org/10.11648/j.ajche.20180602.12.

[22] Q. Cai, K. Song, C. Tian, X. Wu, Y. Li, Y. Huang, C. Wang, B. Xiao, Harvesting of Microcystis from waterbody by flocculation and filtration: the essential role of extracellular organic matters, J. Water Process Eng. 41 (2021) 102053, https://doi.org/10.1016/j.jwpe.2021.102053.

[23] L. Sun, Y. Tian, H. Li, Q. Wang, Fouling potentials and properties of foulants in an innovative algal-sludge membrane bioreactor, Environ. Int. 151 (2021) 106439, https://doi.org/10.1016/j.envint.2021.106439.

[24] R. Shi, R. M. Handler, D. R. Shonnard, Life cycle assessment of novel technologies for algae harvesting and oil extraction in the renewable diesel pathway, Algal Res. 37 (2019) 248-259, https://doi.org/10.1016/j.algal.2018.12.005.

[25] A. F. Novoa, J. S. Vrouwenvelder, L. Fortunato, Membrane Fouling in Algal Separation Processes: A Review of Influencing Factors and Mechanisms, Front. Chem. Eng. 3 (2021), https://doi.org/10.3389/fceng.2021.687422.

[26] X. Chen, C. Huang, T. Liu, Harvesting of microalgae Scenedesmus sp. using polyvinylidene fluoride microfiltration membrane, Desalin. Water Treat. 45 (2012) 177-181, https://doi.org/10.1080/19443994.2012.692034.

[27] I. L. C. Drexler, D. H. Yeh, Membrane applications for microalgae cultivation and harvesting: a review, Rev. Environ. Sci. Biotechnol. 13 (2014) 487-504, https://doi.org/10.1007/s11157-014-9350-6.

[28] L. Li, Z. Wang, L. C. Rietveld, N. Gao, J. Hu, D. Yin, S. Yu, Comparison of the Effects of Extracellular and Intracellular Organic Matter Extracted From Microcystis aeruginosa on Ultrafiltration Membrane Fouling: Dynamics and Mechanisms, Environ. Sci. Technol. 48 (2014) 14549-14557, https://doi.org/10.1021/es5035365.

[29] Y. Liao, A. Bokhary, E. Maleki, B. Liao, A review of membrane fouling and its control in algal-related membrane processes*,* Bioresour. Technol. 264 (2018) 343-358, https://doi.org/10.1016/j.biortech.2018.06.102.

[30] H. Zhou, C.-c. Ji, J.-Q. Li, Y.-X. Hu, X.-H. Xu, Y. An, L.-H. Cheng, Understanding the interaction mechanism of algal cells and soluble algal products foulants in forward osmosis dewatering*,* J. Membr. Sci. 620 (2021) 118835, https://doi.org/10.1016/j.memsci.2020.118835.

[31] H. Fletcher, B. Verrecht, I. Nopens, *Appendix B - MBR Biotreatment Base Parameter Values*, in *The MBR Book (Second Edition)*, S. Judd and C. Judd, Editors. 2011, Butterworth-Heinemann: Oxford. p. 457-461.

[32] M. R. Bilad, V. Discart, D. Vandamme, I. Foubert, K. Muylaert, I. F. J. Vankelecom, Harvesting microalgal biomass using a magnetically induced membrane vibration (MMV) system: Filtration performance and energy consumption*,* Bioresour. Technol. 138 (2013) 329-338, https://doi.org/10.1016/j.biortech.2013.03.175.

[33] M. Bagheri, S. A. Mirbagheri, Critical review of fouling mitigation strategies in membrane bioreactors treating water and wastewater*,* Bioresour. Technol. 258 (2018) 318-334, https://doi.org/10.1016/j.biortech.2018.03.026.

[34] N. Her, G. Amy, H.-R. Park, M. Song, Characterizing algogenic organic matter (AOM) and evaluating associated NF membrane fouling*,* Water Res. 38 (2004) 1427-1438, https://doi.org/10.1016/j.watres.2003.12.008.

[35] A. F. Novoa, L. Fortunato, Z. U. Rehman, T. Leiknes, Evaluating the effect of hydraulic retention time on fouling development and biomass characteristics in an algal membrane photobioreactor treating a secondary wastewater effluent*,* Bioresour. Technol. 309 (2020) 123348, https://doi.org/10.1016/j.biortech.2020.123348.

[36] V. Discart, M. R. Bilad, R. Moorkens, H. Arafat, I. F. J. Vankelecom, Decreasing membrane fouling during Chlorella vulgaris broth filtration via membrane development and coagulant assisted filtration*,* Algal Res. 9 (2015) 55-64, https://doi.org/10.1016/j.algal.2015.02.029.

[37] M. T. Hung, J. C. Liu, Microfiltration for separation of green algae from water*,* Colloids Surf. B: Biointerfaces. 51 (2006) 157-164, https://doi.org/10.1016/j.colsurfb.2006.07.003.

[38] F. Qu, H. Liang, J. He, J. Ma, Z. Wang, H. Yu, G. Li, Characterization of dissolved extracellular organic matter (dEOM) and bound extracellular organic matter (bEOM) of Microcystis aeruginosa and their impacts on UF membrane fouling*,* Water Res. 46 (2012) 2881-2890, https://doi.org/10.1016/j.watres.2012.02.045.

[39] M. Pivokonsky, J. Safarikova, M. Baresova, L. Pivokonska, I. Kopecka, A comparison of the character of algal extracellular versus cellular organic matter produced by cyanobacterium, diatom and green alga*,* Water Res. 51 (2014) 37-46, https://doi.org/10.1016/j.watres.2013.12.022.

[40] E. Kanchanatip, B.-R. Su, S. Tulaphol, W. Den, N. Grisdanurak, C.-C. Kuo, Fouling characterization and control for harvesting microalgae Arthrospira (Spirulina) maxima using a submerged, disc-type ultrafiltration membrane*,* Bioresour. Technol. 209 (2016) 23-30, https://doi.org/10.1016/j.biortech.2016.02.081.

[41] Y. Luo, P. Le-Clech, R. K. Henderson, Simultaneous microalgae cultivation and wastewater treatment in submerged membrane photobioreactors: A review*,* Algal Res. 24 (2017) 425-437, https://doi.org/10.1016/j.algal.2016.10.026.

[42] O. Morineau-Thomas, P. Jaouen, P. Legentilhomme, The role of exopolysaccharides in fouling phenomenon during ultrafiltration of microalgae (Chlorellasp. and Porphyridium purpureum): advantage of a swirling decaying flow*,* Bioprocess Biosyst. Eng. 25 (2002) 35-42, https://doi.org/10.1007/s00449-001-0278-1.

[43] T. Berman, Biofouling: TEP – a major challenge for water filtration, Filtr. Sep. 47 (2010) 20-22, https://doi.org/10.1016/S0015-1882(10)70076-8.

[44] T. Berman, M. Holenberg, Don't fall foul of biofilm through high TEP levels, Filtr. Sep. 42 (2005) 30-32, https://doi.org/10.1016/S0015-1882(05)70517-6.

[45] U. Passow, R. F. Shipe, A. Murray, D. K. Pak, M. A. Brzezinski, A. L. Alldredge, The origin of transparent exopolymer particles (TEP) and their role in the sedimentation of particulate matter, Cont. Shelf Res. 21 (2001) 327-346, https://doi.org/10.1016/S0278-4343(00)00101-1.

[46] S. Babel, S. Takizawa, Microfiltration membrane fouling and cake behavior during algal filtration, Desalination 261 (2010) 46-51, https://doi.org/10.1016/j.desal.2010.05.038.

[47] L. Marbelia, M. Mulier, D. Vandamme, K. Muylaert, A. Szymczyk, I. F. J. Vankelecom, Polyacrylonitrile membranes for microalgae filtration: Influence of porosity, surface charge and microalgae species on membrane fouling, Algal Res. 19 (2016) 128-137, https://doi.org/10.1016/j.algal.2016.08.004.

[48] H. Liang, W. Gong, J. Chen, G. Li, Cleaning of fouled ultrafiltration (UF) membrane by algae during reservoir water treatment, Desalination 220 (2008) 267-272, https://doi.org/10.1016/j.desal.2007.01.033.

[49] A. L. Ahmad, N. H. Mat Yasin, C. J. C. Derek, J. K. Lim, Chemical cleaning of a cross-flow microfiltration membrane fouled by microalgal biomass, J. Taiwan Inst. Chem. Eng. 45 (2014) 233-241, https://doi.org/10.1016/j.jtice.2013.06.018.

[50] L. Fortunato, A. F. Lamprea, T. Leiknes, Evaluation of membrane fouling mitigation strategies in an algal membrane photobioreactor (AMPBR) treating secondary wastewater effluent, Sci. Total Environ. 708 (2020) 134548, https://doi.org/10.1016/j.scitotenv.2019.134548.

[51] A. Nędzarek, A. Drost, F. Harasimiuk, A. Tórz, M. Bonisławska, Application of ceramic membranes for microalgal biomass accumulation and recovery of the permeate to be reused in algae cultivation, J. Photochem. Photobiol. B: Biol. 153 (2015) 367-372, https://doi.org/10.1016/j.jphotobiol.2015.09.009.

[52] H. Elcik, M. Cakmakci, Harvesting microalgal biomass using crossflow membrane filtration: critical flux, filtration performance, and fouling characterization, Environ. Technol. 38 (2017) 1585-1596, https://doi.org/10.1080/09593330.2016.1237560.

[53] F. Wicaksana, A. G. Fane, P. Pongpairoj, R. Field, Microfiltration of algae (Chlorella sorokiniana): Critical flux, fouling and transmission, J. Membr. Sci. 387-388 (2012) 83-92, https://doi.org/10.1016/j.memsci.2011.10.013.

[54] S. L. Low, S. L. Ong, H. Y. Ng, Characterization of membrane fouling in submerged ceramic membrane photobioreactors fed with effluent from membrane bioreactors, Chem. Eng. J. 290 (2016) 91-102, https://doi.org/10.1016/j.cej.2016.01.005.

[55] A. Alipourzadeh, M. R. Mehrnia, A. Hallaj Sani, A. Babaei, Application of response surface methodology for investigation of membrane fouling behaviours in microalgal membrane bioreactor: the effect of aeration rate and biomass concentration, RSC Adv. 6 (2016) 111182-111189, https://doi.org/10.1039/C6RA23188H.

[56] F. Qu, H. Liang, J. Zhou, J. Nan, S. Shao, J. Zhang, G. Li, Ultrafiltration membrane fouling caused by extracellular organic matter (EOM) from Microcystis aeruginosa: Effects of membrane pore size and surface hydrophobicity, J. Membr. Sci. 449 (2014) 58-66, https://doi.org/10.1016/j.memsci.2013.07.070.

[57] F. Zhao, X. Han, Z. Shao, Z. Li, Z. Li, D. Chen, Effects of different pore sizes on membrane fouling and their performance in algae harvesting, J. Membr. Sci. 641 (2022) 119916, https://doi.org/10.1016/j.memsci.2021.119916.

[58] S. Zhang, Y. Chen, X. Zang, X. Zhang, Harvesting of Microcystis aeruginosa using membrane filtration: Influence of pore structure on fouling kinetics, algogenic organic matter retention and cake formation, Algal Res. 52 (2020) 102112, https://doi.org/10.1016/j.algal.2020.102112.

[59] M. A. Al Mamun, M. Sadrzadeh, R. Chatterjee, S. Bhattacharjee, S. De, Colloidal fouling of nanofiltration membranes: A novel transient electrokinetic model and experimental study, Chem. Eng. Sci. 138 (2015) 153-163, https://doi.org/10.1016/j.ces.2015.08.022.

[60] J. Wu, C. He, Y. Zhang, Modeling membrane fouling in a submerged membrane bioreactor by considering the role of solid, colloidal and soluble components, J. Membr. Sci. 397-398 (2012) 102-111, https://doi.org/10.1016/j.memsci.2012.01.026.

[61] F. Feng, Y. Li, B. Latimer, C. Zhang, S. S. Nair, Z. Hu, Prediction of maximum algal productivity in membrane bioreactors with a light-dependent growth model, Sci. Total Environ. 753 (2021) 141922, https://doi.org/10.1016/j.scitotenv.2020.141922.

[62] R. Castro-Muñoz, O. García-Depraect, Membrane-Based Harvesting Processes for Microalgae and Their Valuable-Related Molecules: A Review, Membranes 11 (2021), https://doi.org/10.3390/membranes11080585.

[63] Z. Zhao, B. Liu, A. Ilyas, M. Vanierschot, K. Muylaert, I. F. J. Vankelecom, Harvesting microalgae using vibrating, negatively charged, patterned polysulfone membranes, J. Membr. Sci. 618 (2021) 118617, https://doi.org/10.1016/j.memsci.2020.118617.

[64] S. Azizi, A. Hashemi, F. Pajoum Shariati, H. Tayebati, A. Keramati, B. Bonakdarpour, M. M. A. Shirazi, Effect of different light-dark cycles on the membrane fouling, EPS and SMP production in a novel reciprocal membrane photobioreactor (RMPBR) by C. vulgaris species, J. Water Process Eng. 43 (2021) 102256, https://doi.org/10.1016/j.jwpe.2021.102256.

[65] R. Huang, Z. Liu, B. Yan, Y. Li, H. Li, D. Liu, P. Wang, F. Cui, W. Shi, Interfacial catalytic oxidation for membrane fouling mitigation during algae-laden water filtration: Higher efficiency without algae integrity loss, Sep. Purif. Technol. 251 (2020) 117366, https://doi.org/10.1016/j.seppur.2020.117366.

[66] N. I. Mat Nawi, N. S. Abd Halim, L. C. Lee, M. D. H. Wirzal, M. R. Bilad, N. A. H. Nordin, Z. A. Putra, Improved Nylon 6,6 Nanofiber Membrane in A Tilted Panel Filtration System for Fouling Control in Microalgae Harvesting, Polymers 12 (2020), https://doi.org/10.3390/polym12020252.

[67] S. Jiang, S. Xiao, H. Chu, J. Sun, Z. Yu, W. Zhang, Y. Chen, X. Zhou, Y. Zhang, Performance enhancement and fouling alleviation by controlling transmembrane pressure in a vibration membrane system for algae separation, J. Membr. Sci. 647 (2022) 120252, https://doi.org/10.1016/j.memsci.2022.120252.

[68] W. Liu, K. Yang, F. Qu, B. Liu, A moderate activated sulfite pre-oxidation on ultrafiltration treatment of algae-laden water: Fouling mitigation, organic rejection, cell integrity and cake layer property, Sep. Purif. Technol. 282 (2022) 120102, https://doi.org/10.1016/j.seppur.2021.120102.

[69] F. Zhao, H. Chu, Z. Yu, S. Jiang, X. Zhao, X. Zhou, Y. Zhang, The filtration and fouling performance of membranes with different pore sizes in algae harvesting, Sci. Total Environ. 587-588 (2017) 87-93, https://doi.org/10.1016/j.scitotenv.2017.02.035.

[70] L. Wang, B. Pan, Y. Gao, C. Li, J. Ye, L. Yang, Y. Chen, Q. Hu, X. Zhang, Efficient membrane microalgal harvesting: Pilot-scale performance and techno-economic analysis, J. Clean. Prod. 218 (2019) 83-95, https://doi.org/10.1016/j.jclepro.2019.01.321.

[71] W. Mo, L. Soh, J. R. Werber, M. Elimelech, J. B. Zimmerman, Application of membrane dewatering for algal biofuel, Algal Res. 11 (2015) 1-12, https://doi.org/10.1016/j.algal.2015.05.018.

[72] P. Bacchin, P. Aimar, R. W. Field, Critical and sustainable fluxes: Theory, experiments and applications, J. Membr. Sci. 281 (2006) 42-69, https://doi.org/10.1016/j.memsci.2006.04.014.

[73] A. H. Alshahri, L. Fortunato, N. Zaouri, N. Ghaffour, T. Leiknes, Role of dissolved air flotation (DAF) and liquid ferrate on mitigation of algal organic matter (AOM) during algal bloom events in RO desalination, Sep. Purif. Technol. 256 (2021) 117795, https://doi.org/10.1016/j.seppur.2020.117795.

[74] Y. Wan, P. Xie, Z. Wang, J. Ding, J. Wang, S. Wang, M. R. Wiesner, Comparative study on the pretreatment of algae-laden water by UV/persulfate, UV/chlorine, and UV/H2O2: Variation of characteristics and alleviation of ultrafiltration membrane fouling, Water Res. 158 (2019) 213-226, https://doi.org/10.1016/j.watres.2019.04.034.

[75] J. Xing, H. Liang, S. Xu, C. J. Chuah, X. Luo, T. Wang, J. Wang, G. Li, S. A. Snyder, Organic matter removal and membrane fouling mitigation during algae-rich surface water treatment by powdered activated carbon adsorption pretreatment: Enhanced by UV and UV/chlorine oxidation, Water Res. 159 (2019) 283-293, https://doi.org/10.1016/j.watres.2019.05.017.

[76] B. Ma, J. Qi, X. Wang, M. Ma, S. Miao, W. Li, R. Liu, H. Liu, J. Qu, Moderate KMnO4-Fe(II) pre-oxidation for alleviating ultrafiltration membrane fouling by algae during drinking water treatment, Water Res. 142 (2018) 96-104, https://doi.org/10.1016/j.watres.2018.05.031.

[77] L. Li, W. Chen, Y. Wang, Y. Zhang, H. Chen, Effect of hydrodynamics on autoflocculation and gravity sedimentation of Chlorella vulgaris, J. Water Process Eng. 43 (2021) 102259, https://doi.org/10.1016/j.jwpe.2021.102259.

[78] A. H. Alshahri, L. Fortunato, N. Ghaffour, T. Leiknes, Advanced coagulation using in-situ generated liquid ferrate, Fe (VI), for enhanced pretreatment in seawater RO desalination during algal blooms, Sci. Total Environ. 685 (2019) 1193-1200, https://doi.org/10.1016/j.scitotenv.2019.06.286.

[79] P. Du, X. Li, Y. Yang, Z. Zhou, X. Fan, J. Feng, Algae-Laden Fouling Control by Gravity-Driven Membrane Ultrafiltration with Aluminum Sulfate-Chitosan: The Property of Floc and Cake Layer, Water 12 (2020) 1990, https://doi.org/10.3390/w12071990.

[80] P. Rafiee, S. Ebrahimi, M. Hosseini, Y. W. Tong, Characterization of Soluble Algal Products (SAPs) after electrocoagulation of a mixed algal culture, Biotechnol. Rep. 25 (2020) e00433, https://doi.org/10.1016/j.btre.2020.e00433.

[81] D. Parmentier, D. Manhaeghe, L. Baccini, R. Van Meirhaeghe, D. P. L. Rousseau, S. Van Hulle, A new reactor design for harvesting algae through electrocoagulation-flotation in a continuous mode, Algal Res. 47 (2020) 101828, https://doi.org/10.1016/j.algal.2020.101828.

[82] H. Fletcher, B. Verrecht, I. Nopens, *Chapter 2 - Fundamentals*, in *The MBR Book (Second Edition)*. 2011, Butterworth-Heinemann: Oxford. p. 55-207.

[83] B. Liu, F. Qu, H. Yu, J. Tian, W. Chen, H. Liang, G. Li, B. Van der Bruggen, Membrane Fouling and Rejection of Organics during Algae-Laden Water Treatment Using Ultrafiltration: A Comparison between in Situ Pretreatment with Fe(II)/Persulfate and Ozone, Environ. Sci. Technol. 52 (2018) 765-774, https://doi.org/10.1021/acs.est.7b03819.

[84] H. Lee, J. Lim, M. Zhan, S. Hong, UV-LED/PMS preoxidation to control fouling caused by harmful marine algae in the UF pretreatment of seawater desalination, Desalination

467 (2019) 219-228, https://doi.org/10.1016/j.desal.2019.06.009.

[85] B. Liu, T. Zhu, W. Liu, R. Zhou, S. Zhou, R. Wu, L. Deng, J. Wang, B. Van der Bruggen, Ultrafiltration pre-oxidation by boron-doped diamond anode for algae-laden water treatment: membrane fouling mitigation, interface characteristics and cake layer organic release, Water Res. 187 (2020) 116435, https://doi.org/10.1016/j.watres.2020.116435.

[86] Y. Zhang, B. Fu, X. Wang, C. Ma, L. Lin, Q. Fu, S. Li, Algal fouling control in low-pressure membrane systems by pre-adsorption: Influencing factors and mechanisms, Algal Res. 52 (2020) 102110, https://doi.org/10.1016/j.algal.2020.102110.

[87] W. Huang, X. Qin, B. Dong, W. Zhou, W. Lv, Fate and UF fouling behavior of algal extracellular and intracellular organic matter under the influence of copper ions, Sci. Total Environ. 649 (2019) 1643-1652, https://doi.org/10.1016/j.scitotenv.2018.08.077.

[88] Z. Ren, X. Cheng, P. Li, C. Luo, F. Tan, W. Zhou, W. Liu, L. Zheng, D. Wu, Ferrous-activated sodium percarbonate pre-oxidation for membrane fouling control during ultrafiltration of algae-laden water, Sci. Total Environ. 739 (2020) 140030, https://doi.org/10.1016/j.scitotenv.2020.140030.

[89] W. Hu, J. Yin, B. Deng, Z. Hu, Application of nano TiO2 modified hollow fiber membranes in algal membrane bioreactors for high-density algae cultivation and wastewater polishing, Bioresour. Technol. 193 (2015) 135-141, https://doi.org/10.1016/j.biortech.2015.06.070.

[90] L. T. Yogarathinam, A. Gangasalam, A. F. Ismail, P. Parthasarathy, Harvesting of microalgae Coelastrella sp. FI69 using pore former induced TiO2 incorporated PES mixed matrix membranes, J. Chem. Technol. Biotechnol. 93 (2018) 645-655, https://doi.org/10.1002/jctb.5495.

[91] Q. Liu, E. Demirel, Y. Chen, T. Gong, X. Zhang, Y. Chen, Improving antifouling performance for the harvesting of Scenedesmus acuminatus using Fe2O3 nanoparticles incorporated PVC nanocomposite membranes, J. Appl. Polym. Sci. 136 (2019) 47685, https://doi.org/10.1002/app.47685.

[92] Y. Zhang, X. Wang, H. Jia, B. Fu, R. Xu, Q. Fu, Algal fouling and extracellular organic matter removal in powdered activated carbon-submerged hollow fiber ultrafiltration membrane systems, Sci. Total Environ. 671 (2019) 351-361, https://doi.org/10.1016/j.scitotenv.2019.03.371.

[93] A. Eliseus, M. R. Bilad, N. Nordin, Z. A. Putra, M. D. H. Wirzal, Tilted membrane panel: A new module concept to maximize the impact of air bubbles for membrane fouling control in microalgae harvesting, Bioresour. Technol. 241 (2017) 661-668, https://doi.org/10.1016/j.biortech.2017.05.175.

[94] M. Zhang, K.-T. Leung, H. Lin, B. Liao, The biological performance of a novel microalgal-bacterial membrane photobioreactor: Effects of HRT and N/P ratio, Chemosphere 261 (2020) 128199, https://doi.org/10.1016/j.chemosphere.2020.128199.

[95] B. S. B. Bamba, C. C. Tranchant, A. Ouattara, P. Lozano, Harvesting of Microalgae Biomass Using Ceramic Microfiltration at High Cross-Flow Velocity, Appl. Biochem. Biotechnol. 193 (2021) 1147-1169, https://doi.org/10.1007/s12010-020-03455-y.

[96] S. Jiang, S. Xiao, H. Chu, F. Zhao, Z. Yu, X. Zhou, Y. Zhang, Intelligent mitigation of fouling by means of membrane vibration for algae separation: Dynamics model, comprehensive evaluation, and critical vibration frequency, Water Res. 182 (2020) 115972, https://doi.org/10.1016/j.watres.2020.115972.

[97] F. Zhao, Y. Zhang, H. Chu, S. Jiang, Z. Yu, M. Wang, X. Zhou, J. Zhao, A uniform shearing vibration membrane system reducing membrane fouling in algae harvesting, J. Clean. Prod. 196 (2018) 1026-1033, https://doi.org/10.1016/j.jclepro.2018.06.089.

[98] M. V. A. Corpuz, L. Borea, V. Senatore, F. Castrogiovanni, A. Buonerba, G. Oliva, F. Ballesteros, T. Zarra, V. Belgiorno, K.-H. Choo, S. W. Hasan, V. Naddeo, Wastewater treatment and fouling control in an electro algae-activated sludge membrane bioreactor, Sci. Total Environ. 786 (2021) 147475, https://doi.org/10.1016/j.scitotenv.2021.147475.

[99] J.-C. Lee, R. Park, K. S. Yoo, H.-W. Kim, Coupling cold plasma and membrane photobioreactor for enhanced fouling control during livestock excreta treatment, Chemosphere 265 (2021) 129031, https://doi.org/10.1016/j.chemosphere.2020.129031.

[100] S. Zhou, W. Zhang, J. Sun, S. Zhu, K. Li, X. Meng, J. Luo, Z. Shi, D. Zhou, J. C. Crittenden, Oxidation Mechanisms of the UV/Free Chlorine Process: Kinetic Modeling and Quantitative Structure Activity Relationships, Environ. Sci. Technol. 53 (2019) 4335-4345, https://doi.org/10.1021/acs.est.8b06896.

[101] W. Huang, H. Chu, B. Dong, M. Hu, Y. Yu, A membrane combined process to cope with algae blooms in water, Desalination 355 (2015) 99-109, https://doi.org/10.1016/j.desal.2014.09.037.

[102] H. Jiang, Q. Zhao, P. Wang, M. Chen, Z. Wang, J. Ma, Inhibition of algae-induced membrane fouling by in-situ formed hydrophilic micropillars on ultrafiltration membrane surface, J. Membr. Sci. 638 (2021) 119648, https://doi.org/10.1016/j.memsci.2021.119648.

[103] S. Soleimani, A. Jannesari, M. Yousefzadi, A. Ghaderi, A. Shahdadi, Eco-friendly foul release coatings based on a novel reduced graphene oxide/Ag nanocomposite prepared by a green synthesis approach, Prog. Org. Coat. 151 (2021) 106107, https://doi.org/10.1016/j.porgcoat.2020.106107.

[104] K. C. Ho, T. Y. Haan, A. Mohammad, A. W. Lun, An overview of electrically-enhanced membrane bioreactor (EMBR) for fouling suppression, J. Eng. Sci. Technol. 10 (2017) 128-138, https://doi.org/10.25103/JESTR.103.18.

[105] M. Zhang, L. Yao, E. Maleki, B.-Q. Liao, H. Lin, Membrane technologies for microalgal cultivation and dewatering: Recent progress and challenges, Algal Res. 44 (2019) 101686, https://doi.org/10.1016/j.algal.2019.101686.

[106] D. A. Ladner, D. R. Vardon, M. M. Clark, Effects of shear on microfiltration and ultrafiltration fouling by marine bloom-forming algae, J. Membr. Sci. 356 (2010) 33-43, https://doi.org/10.1016/j.memsci.2010.03.024.

[107] N. Javadi, F. Zokaee Ashtiani, A. Fouladitajar, A. Moosavi Zenooz, Experimental studies and statistical analysis of membrane fouling behavior and performance in microfiltration of microalgae by a gas sparging assisted process, Bioresour. Technol. 162 (2014) 350-357, https://doi.org/10.1016/j.biortech.2014.03.160.

[108] Z. Wang, J. Ma, C. Y. Tang, K. Kimura, Q. Wang, X. Han, Membrane cleaning in membrane bioreactors: A review, J. Membr. Sci. 468 (2014) 276-307, https://doi.org/10.1016/j.memsci.2014.05.060.

[109] J. Ding, S. Wang, P. Xie, Y. Zou, Y. Wan, Y. Chen, M. R. Wiesner, Chemical cleaning of algae-fouled ultrafiltration (UF) membrane by sodium hypochlorite (NaClO): Characterization of membrane and formation of halogenated by-products, J. Membr. Sci. 598 (2020) 117662, https://doi.org/10.1016/j.memsci.2019.117662.

[110] Y. Zhang, J. Tian, H. Liang, J. Nan, Z. Chen, G. Li, Chemical cleaning of fouled PVC membrane during ultrafiltration of algal-rich water, J. Environ. Sci. 23 (2011) 529-536, https://doi.org/10.1016/S1001-0742(10)60444-5.

[111] C. Huang, X. Chen, T. Liu, Z. Yang, Y. Xiao, G. Zeng, Harvesting of Chlorella sp. using hollow fiber ultrafiltration, Environ. Sci. Pollut. Res. (2012) 1416-1421, https://doi.org/10.1007/s11356-012-0812-5.

[112] X. Shi, G. Tal, N. P. Hankins, V. Gitis, Fouling and cleaning of ultrafiltration membranes: A review, J. Water Process Eng. 1 (2014) 121-138, https://doi.org/10.1016/j.jwpe.2014.04.003.

[113] R. Bergamasco, L. C. Konradt-Moraes, M. F. Vieira, M. R. Fagundes-Klen, A. M. S. Vieira, Performance of a coagulation–ultrafiltration hybrid process for water supply treatment, Chem. Eng. J. 166 (2011) 483-489, https://doi.org/10.1016/j.cej.2010.10.076.

[114] W. S. Ang, S. Lee, M. Elimelech, Chemical and physical aspects of cleaning of organic-fouled reverse osmosis membranes, J. Membr. Sci. 272 (2006) 198-210, https://doi.org/10.1016/j.memsci.2005.07.035.

[115] J. C.-T. Lin, D.-J. Lee, C. Huang, Membrane Fouling Mitigation: Membrane Cleaning, Sep. Sci. Technol. 45 (2010) 858-872, https://doi.org/10.1080/01496391003666940.

[116] G. Farinelli, M. Giagnorio, F. Ricceri, S. Giannakis, A. Tiraferri, Evaluation of the effectiveness, safety, and feasibility of 9 potential biocides to disinfect acidic landfill leachate from algae and bacteria, Water Res. 191 (2021) 116801, https://doi.org/10.1016/j.watres.2020.116801.

[117] X. Tang, T. Guo, H. Chang, X. Yue, J. Wang, H. Yu, B. Xie, X. Zhu, G. Li, H. Liang, Membrane Fouling Alleviation by Chemically Enhanced Backwashing in Treating Algae-Containing Surface Water: From Bench-Scale to Full-Scale Application, Engineering (2021), https://doi.org/10.1016/j.eng.2021.01.013.

[118] J.-S. Kang, S.-G. Park, J.-J. Lee, H.-S. Kim, Application of chemically enhanced backwash coping with algal inflow in desalination pretreatment using ceramic membrane, KSWW 32 (2018) 97-106, https://doi.org/10.11001/jksww.2018.32.2.097.

[119] B. S. Bamba, P. Lozano, A. Ouattara, H. Elcik, Pilot-scale microalgae harvesting with ceramic microfiltration modules: evaluating the effect of operational parameters and membrane configuration on filtration performance and membrane fouling, J. Chem. Technol. Biotechnol. 96 (2021) 603-612, https://doi.org/10.1002/jctb.6573.

[120] X. Zhang, Q. Hu, M. Sommerfeld, E. Puruhito, Y. Chen, Harvesting algal biomass for biofuels using ultrafiltration membranes, Bioresour. Technol. 101 (2010) 5297-5304, https://doi.org/10.1016/j.biortech.2010.02.007.

[121] L. Fortunato, F. Lipnizki, L. F. Dumée, Editorial: Fouling in Membrane Filtration Systems, Front. Chem. Eng. 3 (2021), https://doi.org/10.3389/fceng.2021.812625.

[122] X. Wu, C. Zhou, K. Li, W. Zhang, Y. Tao, Probing the fouling process and mechanisms of submerged ceramic membrane ultrafiltration during algal harvesting under sub- and super-critical fluxes, Sep. Purif. Technol. 195 (2018) 199-207, https://doi.org/10.1016/j.seppur.2017.12.001.

[123] D. Vandamme, I. Foubert, K. Muylaert, Flocculation as a low-cost method for harvesting microalgae for bulk biomass production, Trends Biotechnol. 31 (2013) 233-239, https://doi.org/10.1016/j.tibtech.2012.12.005.

[124] S. Li, T. Hu, Y. Xu, J. Wang, R. Chu, Z. Yin, F. Mo, L. Zhu, A review on flocculation as an efficient method to harvest energy microalgae: Mechanisms, performances, influencing factors and perspectives, Renew. Sust. Energ. Rev. 131 (2020) 110005, https://doi.org/10.1016/j.rser.2020.110005.

[125] L. Christenson, R. Sims, Production and harvesting of microalgae for wastewater treatment, biofuels, and bioproducts, Biotechnol. Adv. 29 (2011) 686-702, https://doi.org/10.1016/j.biotechadv.2011.05.015.

[126] P. M. Schenk, S. R. Thomas-Hall, E. Stephens, U. C. Marx, J. H. Mussgnug, C. Posten, O. Kruse, B. Hankamer, Second Generation Biofuels: High-Efficiency Microalgae for Biodiesel Production, Bioenergy Res. 1 (2008) 20-43, https://doi.org/10.1007/s12155-008-9008-8.

[127] M. Li, A. Zamyadi, W. Zhang, L. F. Dumée, L. Gao, Algae-based water treatment: A promising and sustainable approach, J. Water Process Eng. 46 (2022) 102630, https://doi.org/10.1016/j.jwpe.2022.102630.

6. Abbreviation appendix

Nomenclature

AOM	Algal organic matter	MPBR	Membrane photobioreactor
AS-CS	Sulfate-chitosan coagulant	NFM	Nanofiber membrane
CEB	Chemically enhanced backwash	PAC	Powdered activated carbon
CFV	Cross-flow velocity	PES	Polyethersulfone
CP	Cold plasma	PS	Persulfate
DAF	Dissolved air flotation	PSD	Particle size distribution
DBP	Disinfection by-products	PSF	Polysulfone
DMF	Dynamic membrane filtration system	PMS	Permonosulfate
DC	Direct current	PVDF	Polyvinylidene fluoride
DOC	Dissolved organic carbon	SPC	Sodium percarbonate
EOM	External organic matter	SRT	Solids retention time
EPS	Extracellular polymeric substances	TDS	Total dissolved solids
HMW	High molecular weight compounds	TEP	Transparent exopolymer particles
HRT	Hydraulic retention time	TMP	Transmembrane pressure
IOM	Internal organic matter	UF	Ultrafiltration
LMH	Flow in liters per square meter per hour	WEN	Water-energy nexus
LMW	Low molecular weight compounds	ZLD	Zero liquid discharge
MF	Microfiltration		