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Electro-enhanced membrane separation technology for fouling mitigation in wastewater treatment: A review

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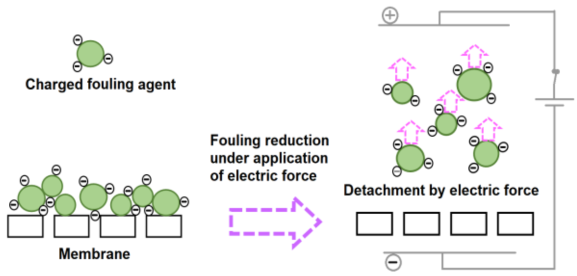
GRAPHICAL ABSTRACT



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ABSTRACT

The research on membrane-based filtration technology for water treatment has expanded in recent years. Membrane fouling is a major challenge that decreases the permeability and decreases the lifetime and selectivity of the membrane. Recently, it was found that fouling mitigation and better control of membrane fouling can be attained under the application of the electric field. This paper provides an overview of the application of the electric field to the filtration process and its antifouling mechanism. Utilization of conductive polymeric membranes and application of electric field in membrane bioreactors are reviewed as well. The presented review demonstrates that the introduction of negative charge into the membrane surface via preparing conductive membranes or applying an external electric field onto the membrane surface suggests several advantages. These are fouling alleviation, better control of membrane fouling, an increase of membrane resistance to cake deposition on the membrane surface, and superior possible applications such as better salt rejection and antibacterial activity.

Contents

1. Introduction

Scarcity of water resources coupled with population growth and increasingly precise environmental legislation results in the development of new water treatment methods that can make available clean water supply (Moradi et al. 2015). Membrane-based filtration technology has attracted growing interest in wastewater treatment owing to its easy operation, relatively low cost, simple scale-up, no need for chemical additives and so on (Moradi et al. 2018). Although the fast rise in the application of membrane filtration technology, the susceptibility of the membrane materials to fouling hinders the real-time application of membranes (Shaabani et al. 2018). Both operation and capital costs of the membrane filtration process are remarkably increased as a result of membrane fouling (Rana and Matsuura, 2010). Lowering the interactions between fouling agents and membrane surface through improvement in surface hydrophilicity of membrane surface is one of the commonly used methods for fouling alleviation (Zinadini et al. 2014). Therefore, several methods like grafting of hydrophilic monomers/materials into the membrane surface, the introduction of hydrophilic nanofiller into the membrane matrix, hydrophilic coatings, and blending with hydrophilic polymers are commonly used for ameliorating the membrane fouling (Moradi et al. 2018). However, these antifouling methods are often expensive and time-consuming. Moreover, these modified membranes are often not sufficient for real-time applications owing to the fact that they may lose their properties over time. It has been proved that the application of electric field in membrane filtration systems is an effective method to

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improve antifouling performance and fouling control (Akamatsu et al. 2010; Bani-Melhem and Elektorowicz, 2010). Since most foulants inherently carry a negative charge, the antifouling behavior of the membrane can be ameliorated by increasing the negative charge density of the membrane surface due to the higher electrostatic repulsion effect (Huang et al. 2015). An increase in surface negative charge of the membrane can be proved by external electric field or usage of negatively charged material for membrane preparation. As shown in Fig. 1, as the electric field is applied, the negatively charged fouling agents and extra-cellular polymeric substance (EPS) move away from the membrane surface, resulting in the decreased foulants depositions on the membrane surface, especially near pore entry (Liu et al. 2013a). Hence, fouling mitigation and better control of membrane fouling can be attained under the application of an electric field (Won et al. 2012). The advantages and disadvantages of different antifouling methods including the electro-enhanced membranes and others are summarized in Table 1. According to Table 1, electrofiltration can be regarded as a potential candidate for industrial applications. The present review summarizes the preparation of conductive polymeric membranes and the antifouling mechanisms under the presence of an external electric field. The separation properties of the polymeric conductive membranes in various electrofiltration and electro-membrane bioreactor (EMBR) systems were also reviewed.

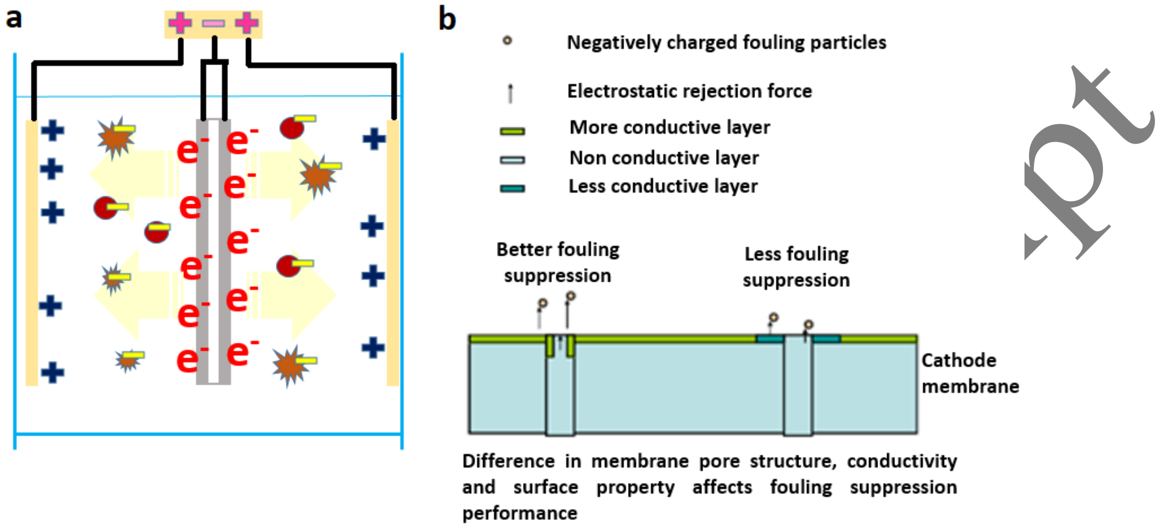

Fig. 1. The schematic diagram of the fouling alleviation under the application of electric field (Liu et al. 2013a).

Table 1. The advantages and disadvantages of different antifouling methods.

Method	Advantages	Disadvantages
Coating	Simple fabrication method	Low permeability
Blending	Simple fabrication method High permeability	Leaching of filler Agglomeration of filler
Surface functionalization	High permeability	Complicated procedure High cost
Plasma grafting	High permeability	Complicated procedure High cost
Electrofiltartion	High permeability Efficient non-destructive cleaning method for membrane Cost effectiveness Enhanced separation of charged species	How to adjust the perparation parameters is challenging

2. Antifouling mechanism

The antifouling mechanisms in electrofiltration can be divided into three main types as listed in Table 2 (Den and Huang, 2005; Guizard et al. 1989; Huang et al. 2015). First, since most of the folulants molecules are generally negative in charge, it would be feasible to reduce membrane fouling by enhancing the electrostatic repulsion force between the negatively charged foulants and membrane using appending the external electric field. In other words, the negatively charged foulants molecules are repelled by the membrane surface in the presence of the electric field. Second, introducing an electric field into the membrane puts electrophoresis away from the surface of the membrane leading to hindering the deposition of extracellular polymeric substances (EPS) and sludge particles on the membrane surface. Third, in the electro-coagulation process, by electrolytic oxidation of sacrificial anodic electrode, several positively charged coagulates react with negatively charged foulants and neutralize them, therefore decreasing the accumulation of foulants on the membrane surface.

Table 2. Three main mechanisms of fouling reduction in electrofiltartion.

Fouling mechanism	Description
Electrostatic repulsion	Electrostatic repulsion force between the negatively charged foulants and negatively charged membrane.
Electrophoresis	Under the application of an electric field onto the membrane, electrophoresis puts away from the surface of the membrane leading to hindering the deposition of foulants on the membrane surface.
Electro-coagulation	Due to electrolytic oxidation of sacrificial anodic electrode, the foulants are neutralized. Therefore the accumulation of foulants on the membrane surface is decreased.

Fouling mitigation using the electrofiltration process has been investigated by many researchers (Moulik, 1971). One of the first attempts to explain the electrofiltration process was carried out by Moulik (Moulik, 1971) via the electrofiltration unit in which a filter was located between two selective membranes, as shown in Fig. 2.

The solution containing colloid particles inters into the top side at the left half of the electrofiltration unit and the permeate exits from the top side at the right half. In the case of filtration without the application of the electric field, both the suspended particles and the liquid were transferred toward the filter surface at the same velocity. Hence, the particles deposit of the filter surface and create a cake layer. The thickness of cake layer gradually increases leading to flux decline at constant pressure (Fig. 2a). Deposition of suspended particles on the filter is decreased by applying an electric voltage (Fig. 2b), while at the critical voltage or higher in which the liquid and suspended particles have the same velocity in the opposite direction no cake layer is formed (Fig, 2c). Fig. 3 shows the various forces that apply to a suspended particle under different experimental conditions. In Fig. 3a, where no electric voltage is applied, the suspended particle moves toward the filter surface leading to the formation of the cake layer. By introducing the electric voltage lower than the critical value, a thinner cake layer is formed (Fig. 3b,c). At the critical voltage, equal forces act in opposite directions, where no cake layer is formed (Fig, 3d), and at a voltage higher than the critical value, no cake layer is formed as well (Fig. 3e).

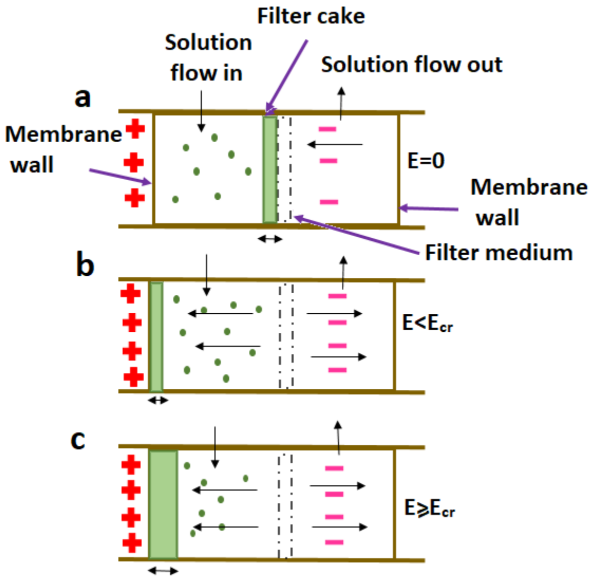

Fig. 2. schematic illustration of electrofiltration unit in which a) no voltage, b) inadequate voltage (lower than critical value), and c) adequate voltage (critical value or higher) is applied (Moulik, 1971).

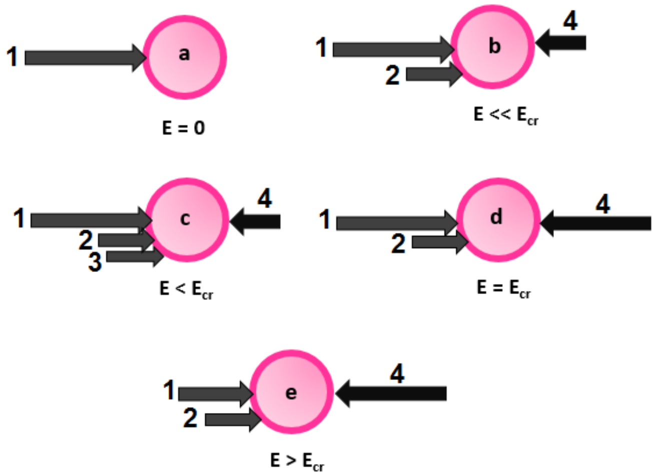

Fig. 3. Different applied forces on suspended particles at the applied voltage of a) zero, b) much lower than the critical value (without cake electroosmosis), c) lower than the critical value (with cake electroosmosis), d) critical value, and e) higher than the critical value. 1, 2, 3, 4, represent the forces of typical filtration, filter medium electrophoresis, cake electroosmosis, and electrophoresis, respectively (Moulik, 1971).

4. Conductive membranes

Conductive polymers such as polyaniline (PANI) and polypyrrole (PPy) with a conjugated backbone have been utilized for the perpetration of a conductive membrane with the aim of fouling mitigation (Ateh et al. 2006; Formoso et al. 2017). However, similar to other plastic materials, these conductive polymers are not easy to be flexibly processed. Therefore, membranes fabricated from these materials have low permeation flux, brittle features, not-sufficient separation performance, and often low electrical conductivity. Hence, modification is necessary to improve the property of these membranes. With the aim of further improving the characteristics of conductive membranes, Liu et al. (2017) fabricated the conductive PPy-SDBS/PVDF composite membrane. It demonstrated a great antifouling resistance. In an attempt to improve the antifouling properties and separation performance of polyester filter membranes, the PPy modification of polyester membrane was carried out through in-situ formation via polymerization of sodium dodecyl benzene sulfonate and pyrrole at different mass ratios. Polyester membrane modified with polymerization of 0.5 g/L sodium dodecyl benzene sulfonate and 3.868 g/l pyrrole showed a decrease in water contact angle from 51.77° (for bare membrane) to 17.76°. The fabricated membranes were used as the cathode in EMBR system. Applying a small electric field of 0.2 V/cm resulted in an increased fouling resistance of the membranes for 18 days (Liu et al. 2013). PPy-PVDF conductive membranes were fabricated via vapor polymerization. At a voltage of 1 V, the PPy-PVDF membranes showed stable antifouling resistance over repeated filtration runs. They concluded that the alleviation of membrane fouling and better effluent quality in the presence of the electric field may be ascribed to the smooth surface with more hydrophilicity of the conductive membranes (Liu et al. 2018). Wang et al. (2019a) prepared a new conductive PANI membrane doped with dodecylbenzene sulfonic acid. The water contact angle and conductivity of the modified PANI membrane were 38.9° and 2.2×10^{-4} S/cm, respectively. Their results revealed that, as the applied voltage raised from 0.1 to 1 V, the modified PANI membranes showed better antifouling resistance due to an increase of electrostatic repulsion between membrane surface and foulant.

To overcome the limitations of polymeric insulating materials and to introduce the negative charge to the membrane surface, nano formed materials such as carbon black, metal oxides nanoparticles, carbon nanotubes, graphene oxides and their derivatives were added to the membrane matrix. For instance, the nano formed poly(1,5-diaminoanthraquinone)-reduced graphene oxide incorporated PVDF membranes were fabricated by Liu et al. (2015). These conductive membranes showed high porosity and hydrophilicity compared with the pristine ones (PVDF). Under the application of the external electric field of 1.0 V/cm, the poly(1,5-diaminoanthraquinone)-reduced graphene oxide incorporated PVDF membranes exhibited outstanding antifouling behavior, high permeation flux, and flux recovery ratio (Li et al. 2015a). Furthermore, Liu et al. (2014) applied graphene oxide nanoparticles to modify polyaniline-polyamide (PANI-PA) membrane supported by a polyester filter cloth. The antifouling behavior of the resulting membrane was studied in an EMBR under the electric field of 0.2 V/cm, MLSS concentration of 2000 ppm, and pressure of 5.0 kPa. As they reported, along with the introduction of graphene oxide nanoparticles to the To PANI-PA, the permeate flux was increased. Moreover, the positive effect of graphene oxide nanoparticles on the permeation flux was clearly observed. Carbon nanotubes have been of research interest with most former studies focusing on the fabricating of conductive membranes. Surface coating, covalent cross-linking, direct blending, and surface deposition have been utilized to fabricate the carbon nanotube/polymer composite membranes. These composite show adjustable electrical conductivity, mechanical characteristics, and porosity that all together may ascribe to the growth of permeable channel electrodes. Both graphene oxide and multi-walled carbon nanotubes were used to enhance the electrical conductivity of the PVDF membrane. Under both continuous and intermittent electric field, the graphene oxide/multi-walled carbon nanotubes embedded PVDF membranes showed lower fouling mitigation and high permeation flux (Ho et al. 2018). Table 3 gives a summary of applications of the conductive composite membranes for fouling mitigation in electrofiltration process.

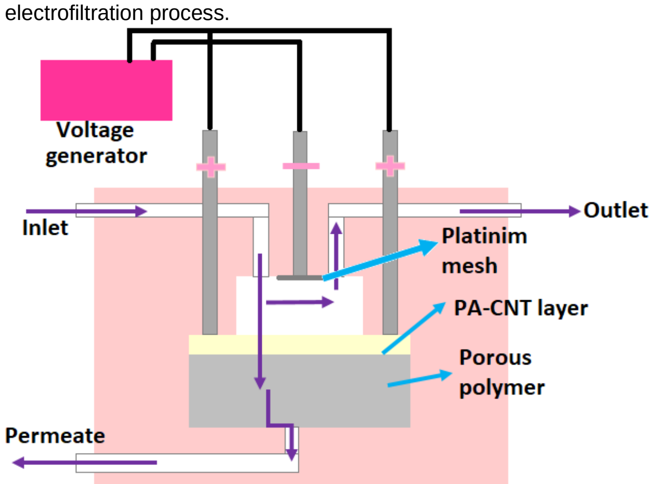

Fig. 4. The cross-flow electrofiltration setup used by de Lannoy et al. (2013).

de Lannoy et al. (2013) fabricated the electrically conductive Polyamide (PA) nanofiltration membranes with carboxylated carbon nanotubes (CNTs) through cross-linking method. The electrical conductivity of the PA-CNTs membrane was 20 times higher than PA membrane. To compare the antifouling behavior of the the PA-CNTs membrane with the bare one in the presence of electric potential, experiments were carried out in a modified cross-flow electrofiltration setup as shown in Fig. 4. The insulated steel electrodes and a counter platinum electrode placed on the surface of the setup at the distance of 5 cm to the membrane surface to transfer charge across the testing membrane. Their results obtained showed that the PA membrane had low flux recovery. In contrast, the PA-CNTs conductive membrane maintained its high permeation flux following a short physical cleaning (rinse with water). (Wang et al. 2018) investigated the effect of blending of sodium lignosulfonate functionalized multi walled carbon nanotubes into polyethersulfone (PES) membrane for application in electrical cross-flow filtration as schematically shown in Fig. 5. They discovered that the PES membranes embedded with sodium lignosulfonate functionalized multi walled carbon nanotubes can provide a synergistic antibacterial impact in the presence of a weak electric potential.

Table 3. Summary of applications of the conductive composite membranes for fouling mitigation in electrofiltration process

Membrane	Pressure (bar)	PWF (L/m²h)	Flux decline (%)	Voltage	FRR	Ref.
PANI UF	1.0	14.0	60	1 V	-	(Wang et al. 2019b)
DBSA/PANI UF	1.0	60.0	22	1 V	-	(Wang et al. 2019b)
PVDF-NI UF	1.0	137.5	45	1.23 V	94	(Yu et al. 2019)
PVDF UF	5	3393	75	1 V	-	(Yu et al. 2019)
PPY/PVDF UF	5.0	569	25	1 V	-	(Liu et al. 2018)
Ag electroplated nanofibrous membrane	1.0	680	25	30 V/mm	-	(Mushtaq et al. 2019)
Cu/PDA/PVDF UF	1.0	597	-	3 V/mm	63	(Li et al. 2018)
LIG-GO/PES UF	1.0	420	-	3 V	87	(Thakur et al. 2019)
US100	1.0	1245	-	3 V	84	(Thakur et al. 2019)
Graphene/PANI FO	5.0	6	-	2 V	96	(Shakeri et al. 2019)
Thermal treated graphene/PANI FO	5.0	8	-	2 V	99	(Shakeri et al. 2019)
rGO/PVDF UF	2.5	79	-	1 V/cm	72	(Liu et al. 2015b)
PDAAQ/PVDF UF	2.5	145	-	1 V/cm	83	(Liu et al. 2015b)
PDAAQ/rGO/PVDF UF	2.5	175	-	1 V/cm	86	(Liu et al. 2015b)
rGO/PANI UF	2.7	238	30	2 V	70	(Karkooti et al. 2020)

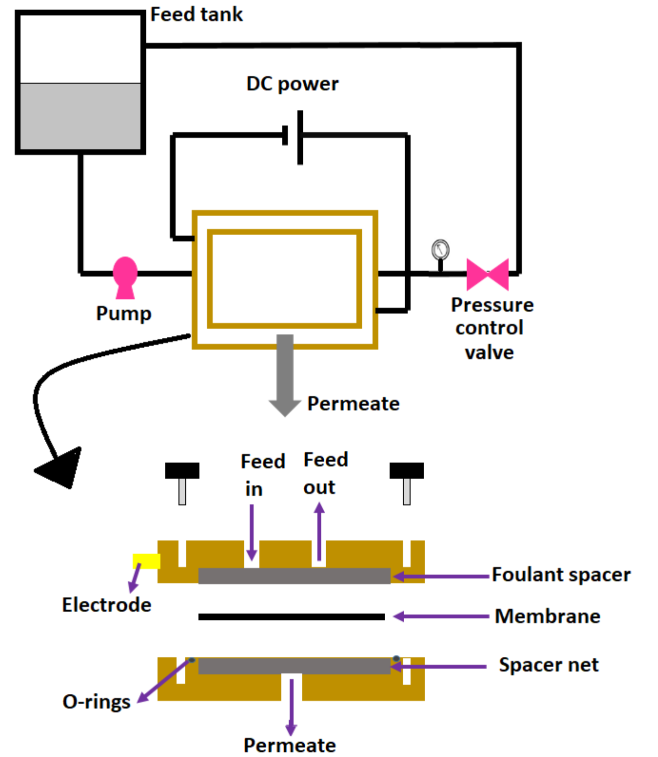

Fig. 5. Schematic of the electrical cross-flow ultrafiltration cell used by Wang et al. (2018).

5. Application of electric field in MBR

Membrane bioreactors (MBRs) have been extensively used for municipal and industrial swedge purification regard to their considerable advantages over the other conventional biological swedge treatment such as superior quality of the effluent, smaller footprint, greater automation level, lower generation of sludge (Moradi et al. 2018). However, membrane fouling still remains a great challenge that hinders MBR implementation (Meng et al. 2009). In most cases, membrane fouling in MBR has mainly corresponded to the gradual deposition of dissolved particulates such as soluble microbial products, negatively charged clumped particles of sludge, and extracellular polymeric substances (EPS) on the membrane surface. In addition, in some cases, membrane fouling in MBR is related to the pores wall, which results in partial or complete pore clogging, and thus negatively affects the membrane filtration (Yang et al. 2018). Newly, the application of the external electric field within the MBR has been efficiently used with the aim of fouling mitigation to push electrophoresis away from the membrane surface by hindering the deposition of negatively charged foulant on the membrane surface (Ozbey Unal et al. 2019). It was reported that the electric field strength of 6 or 15-20 V/cm was suitable enough to put the colloid and foalants away from the membrane surface, considerably increasing the membrane flux in MBRs (Akamatsu et al. 2007). For instance, Chen et al. (2007) developed a new type of MBR by placing a hollow fibrous membrane between a pair of stainless steel electrodes; they observed that the membrane flux was increased by increasing the electric field strength (Fig. 6). They reported that the flux drop over the operation time at an electric field strength of 0 and 15 V/cm was lower compared to the others (5, 10, and 20 V/cm). In one attempt to mitigate membrane fouling caused by activated sludge, one of the main negatively charged foulants with MBR, Akamatsu et al. (2010) (Akamatsu et al. 2010) studied the effect of the intermittent electric field (e.g. 90 s off- 90 s on mood) on filtration in MBR. They observed that the permeate flux of the used microfiltration membrane recovered after appending an electric field of 6 V/cm for 90 s, indicating the effective cleaning of foulant from the membrane surface by electrorepulsive force. By the application of a submerged MBR system occupied with iron mesh electrodes connected to the DC power supply, the fouling rate was decreased up to 16.3% without any cleaning of the membrane (Bani-Melhem and Elektorowicz, 2010).

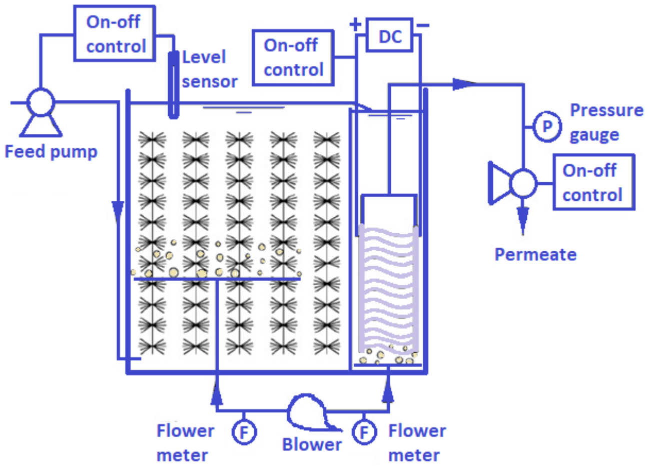

Fig. 6. Schematic diagram of EMBR (Chen et al. 2007).

Some studies also reported the efficient usage of iron electrodes connected with an electrical field for fouling mitigation in MBR systems (Bani-Melhem and Elektorowicz, 2010; Liu et al. 2013a). However, there remains a lot of limitation for iron consumption as electrodes, including higher cost and generation of chemical precipitates with a high risk of environmental exposure (Iversen et al. 2009). Besides, the effect of ferric hydroxide precipitation on the sludge characteristics such as pH and biomass community, ought to be further studied (Judd, 2008). Up to now, several cleaning reagents such as hydrogen peroxide (H_2O_2), caustic soda (NaOH), citric acid ($C_6H_8O_2.1H_2O$) and sodium hypochlorine (NaOCl) have been used to regenerate the membrane permeability (Grelot et al. 2008). But, some chemicals like NaOCl are dangerous for user health and can cause ecological and environmental problems (Formoso et al. 2017). Moreover, the overdose of these chemicals increases the additional costs and might accelerate the membrane deterioration (Ahmed et al. 2016; Ho et al. 2017). The in-situ approaches for membrane fouling control are extremely favorable but still challenging. Based on recent studies, the generation of H_2O_2 through bioelectrochemical oxidation of wastewater organics opens up the opportunity (Fu et al. 2010; Rozendal et al. 2009). Wang et al. (2013) developed an electrochemical membrane bioreactor system for in-situ fouling control in which the stainless steel mesh and graphene rod were used as cathode and anode, respectively. As elucidated in Fig. 7, in this system, membrane fouling was suppressed due to the following possible reasons (Wang et al. 2013):

1. Appending the external voltage induces an electric field between the cathode and graphene rod anode which increases the electrostatic repulsive force between the negatively charged sludge and cathode. As a result, the deposited sludge could be easily detached leading to membrane fouling mitigation.
2. Some reactive oxygen forms such as H_2O_2 and hydroxyl radical could be continually produced at the cathode by reduction of oxygen (Huang et al. 2015). These reactive chemicals help to in-situ cleaning the deposited foulants from the membrane surface.

Other literature also reported that H_2O_2 could be formed at the cathode as a result of oxygen reduction reaction in bioelecrochemical process which could chemically deteriorate the pollutants of water (Yu et al. 2015). Utilization of electric filed to reduce membrane fouling in MBRs has been focused by many researchers (Akamatsu et al. 2010; Chang et al. 2002; Chen et al. 2007). However, all these experiments involved high electric energy consumption (high applied voltage up to 100 V), which must be decreased (Jagannadh and Muralidhara, 1996). Membrane fouling in EMBR is affected by the intensity of the electric field, the density of negative charge with the membrane or sludge, the arrangement of electrodes and shape of the membrane modules (Ang et al. 2015; Ho et al. 2017). Hence, several ways including the more efficient application of electric field, providing an efficient electrorepultion force between the foulants and the membrane, utilization of superior electrode position and membrane modules have been used for decreasing energy consumption in EMBRs (Mohan et al. 2008; Wei et al. 2009; Zhou et al. 2015). The physicochemical properties and microbial activity of microorganisms can be inherently changed under the application of an electric field (Ahmed et al. 2016). Accordingly, the application of lower electric field within MBR results in decreasing unintentional interference with MBR efficiency and reducing the electric consumption, as well. It was demonstrated that the optimum range of DC electric field strength for microorganisms is 0.28-1.14 V/cm (Bani-Melhem and Elektorowicz, 2010). In an attempt to find the minimum efficient electric energy consumption and the best configuration of the electric field in fouling alleviation of MBR, Liu et al. (2012) developed the new configuration of electrode and membrane. In this configuration, the electrostatic force was against the deposition of EPS or sludge on each side of the membrane. This was done by locating the membrane with many copper wires inside, between two stainless mesh anodes. In order to decrease the negative influence of the electric field on the microorganisms and to decrease the electric energy consumption, electric field strength of 0.036 and 0.073 V/cm were applied. This new configuration led to significant fouling mitigation and flux increment at very low electric energy consumption. Recently, great efforts have been done to configure the conductive membrane as a cathode, which has been identified as a versatile and simple way of mitigating fouling, increasing flux and facilitating electric energy consumption toward fouling control in EMBRs (Liu et al. 2012; Zhang et al. 2016). In these systems, deposited or adsorbed foulants on the membrane surface or within the pore walls would be inherently repelled by the catholic conductive membrane (Liu et al. 2013a; Liu et al. 2013b). For example, in 2013, one group used conductive modified PPy membranes as cathodes in a lab-scale EMBR. Results of long-term filtration tests at an electric field strength of 0.2 V/cm suggested that the average permeate flux under the application of the electric field was about two times greater than the flux in the absence of the electric field. The total effluent volume was also decreased by 30% (Liu et al. 2013a). Liu et al. (2013) employed graphene/PPy and graphene oxide/PPy coated polyester membrane in EMBR as a cathode to induce an electric field. The electrical conductivity of the prepared membranes was improved by dopping of PPy using both Gr and graphene oxide while the graphene/PPy coated membrane had better antifouling behavior than PPy coated one, at a constant electric field strength of 1 V/cm. Electrical conductive membrane materials are the key components to the successful commercialization of future EMRs owing to their simple preparation method and lower price (Geng and Chen, 2016; Khorshidi et al. 2016; Lalia et al. 2015). But, there still remain some limitations to large-scale application of these materials in EMBR, including low resistance, high stability and low filtration precision (Huang et al. 2015). Although significant progress has been made for fouling mitigation by applying an electric field in MBRs, much more studies are still required in order to decrease the investment cost as well as further improve the properties of the membrane used for EMBRs.

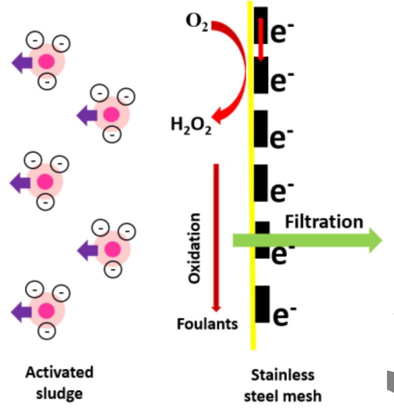

Fig. 7. Schematic representation of the contribution of in-situ produced electricity for fouling suppression in EMBR (Wang et al., 2013).

6. Future prospect

For water and wastewater treatment by using the membrane separation technology, membranes with simultaneously high permeability, selectivity, and antifouling performance are the main demands in industrial applications (Liu et al. 2015b). Membrane fouling reduces the permeability, shortens the membrane life, decreases the separation efficiency, and increases operation costs. Moreover, even at high removal efficiency of pollutants, the application of membranes is restricted by fouling (Karkooti et al. 2020). Electrically based approaches membrane filtration process has attracted significant interest in fouling mitigation. In electrofiltration technology, conductive membranes are of critical subcomponents. For instance, metal-modified polymeric membranes have successfully used in the electrofiltration process for fouling alleviation (Shakeri et al. 2019). However, the application of these membranes in electrofiltration process is restricted by their low conductivity (Li et al. 2018). On the other hand to widen the horizon of the metal modified polymeric membranes for fouling alleviation in electrofiltration process it is quite necessary to develop membranes with increased conductivity. For better understanding and investigation of the efficient conductive membranes for electrofiltration process it is necessary to study in details the membrane material, operation cost, long-term performance, conductivity, and effect of morphology and membrane structure on separation efficiency. Recently, the introduction of electricity to EMBR for fouling mitigation has gained increasing interest among researchers. It is proved that the conductive membranes are the key components to the successful commercialization of future EMRs (Geng and Chen, 2016). The extensive application of these membranes in EMBR for industrial wastewater treatment will depend on higher antifouling resistance, stability, and cost-effectiveness (Huang et al. 2015). Although significant progress has been made for fouling mitigation by applying an electric field in MBRs, much more studies are still required in order to decrease the investment cost as well as further improve the properties of the membrane used for EMBRs.

7. Conclusions

As water resources become scarcer and more polluted, the development of new water treatment methods is needed to make available, safe, and clean water supply. Membrane-based filtration technology has the compatibility to address this requirement in an efficient way. Numerous research papers have shown that the susceptibility of the membrane materials to fouling hinders the real-time application of membranes. As seen from the presented review, a large number of studies have been done to increase the negative charge of the membrane surface with the aim of fouling mitigation. An increase in surface negative charge of the membrane can be provoked by external electric field or usage of negatively charged material for membrane preparation. The mechanism of fouling reduction in electrofiltration can be divided into three main types. First, since most of the foulants are generally negative in charge, it would be feasible to reduce membrane fouling via introducing the external electric field. In other words, as the electric field is applied, the electrostatic repulsion force between the negatively charged foulants and membrane surface is increased. Second, introducing an electric field into the membrane puts electrophoresis away from the surface of the membrane leading to hindering the deposition of extracellular polymeric substances (EPS) and sludge particles on the membrane surface. Third, in the electrocoagulation process, by electrolytic oxidation of sacrificial anodic electrode, several positively charged coagulates react with negatively charged foulants and neutralize them, therefore decreasing the accumulation of foulants on the membrane surface. As evidenced from the discussion, the conductive membrane can efficiently prevent membrane fouling as well. Different conductive membranes were tested in EMBR, and the privileges in their using (conductive membranes coupled with the application of electric field) were also discussed with special emphasis to the helpful.

Aknowledgment

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Nomenclature

CNTs	Carboxylated carbon nanotubes
DBSA	Dodecylbenzene sulfonic acid
EMBR	Electro-membrane bioreactor
EPS	Extra-cellular polymeric substance
FRR	Flux recovery ratio
FO	Forward osmosis
GO	Graphene oxide
LIG	Laser-induced graphene
MBR	Membrane bioreactors
PA	Polyamide
PANI	Polyaniline
PDAAQ	Poly(1,5-diaminoanthraquinone)
PDA	Polydopamine
PES	Polyethersulfone
PPy	Polypyrrole
PVDF	Polyvinylidene fluoride
PWF	Pure water flux
rGO	Reduced graphene oxide
SDBS	Sodium dodecyl benzene sulfonate
UF	Ultrafiltration

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