Integrating Membrane Filtration into Bioelectrochemical Systems as Next Generation Energy-Efficient Wastewater Treatment Technologies for Water Reclamation: a Review

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Abstract

Bioelectrochemical systems (BES) represent an energy-efficient approach for wastewater treatment, but the effluent still requires further treatment for direct discharge or reuse. Integrating membrane filtration in BES can achieve high-quality effluents with additional benefits. Three types of filtration membranes, dynamic membrane, ultrafiltration membrane and forward osmosis membrane that are grouped based on pore size, have been studied for integration in BES. The integration can be accomplished either in an internal or an external configuration. In an internal configuration, membranes can act as a separator between the electrodes, or be immersed in the anode/cathode chamber as a filtration component. The external configuration allows BES and membrane module to be operated independently. Given much progress and interest in the integration of membrane filtration into BES, this paper has reviewed the past studies, described various integration methods, discussed the advantages and limitations of each integration, and presented challenges for future development.

Keywords: bioelectrochemical systems; membrane filtration; forward osmosis; bioenergy; wastewater treatment; water reclamation.

1. Introduction

Effective treatment of wastewater can alleviate water scarcity through water reuse, but conventional treatment methods consume a large amount of energy. For example, an aerobic activated sludge process employed in domestic wastewater treatment plants requires ~ 0.6 kWh to treat 1 m^3 of wastewater [1]. It has been reported that wastewater utilities account for approximately 1-3% of the total electricity consumption in the USA [2]. Meanwhile, electricity is not available to more than 1.3 billion of the global population, and the electricity demand is estimated to further grow by 70% in the year 2035 [3]. Wastewater contains energy potential of 17.8 to 28.7 kJ per g COD (chemical oxygen demand) [4]. Energy recovery from high-strength wastewater can be accomplished by using anaerobic digestion, but anaerobic treatment of low-strength wastewater still faces significant challenges such as dissolved methane gas in the final effluent [5]. Therefore, there is an urgent need to develop energy-efficient and environmentally-friendly technologies for wastewater treatment to address both energy and water challenges.

Bioelectrochemical systems (BES) are emerging technologies that can directly harvest electrical energy in the wastewater, treat wastewater at low energy consumption, and simultaneously accomplish a variety of goals such as nutrient removal, hydrogen production, or desalination [6]. In a typical BES, exoelectrogens (electrochemically-active microorganisms) degrade organic matters (e.g. organic wastes in wastewater) and release electrons extracellularly to an anode electrode via extracellular respiration [7]. These electrons flow through an external circuit to a cathode electrode to reduce terminal electron acceptors (e.g. oxygen gas) and thus electricity is generated. Life cycle assessment and pilot studies suggest that BES may hold great promise for wastewater treatment in terms of energy efficiency and greenhouse gas effect [8, 9].

Although BES can significantly decrease production of biomass or sludge, for example, the effluent of a microbial fuel cell (MFC) contained 0.1 g volatile suspended solid (VSS) g⁻¹ COD [10], much less than the 0.4-0.8 VSS g⁻¹ COD in conventional activated sludge process [6], the effluent of BES still needs further treatment for direct discharge or reuse. To achieve high-quality effluent for potential reclamation, membrane filtration has been integrated into BES to take advantages of both BES and membrane bioreactors (MBR). Due to the relatively small pore size, the filtration process can effectively remove VSS and pathogens, thereby producing an effluent of high quality [11]. In addition, biomass is retained by the membrane in the reactor to improve treatment efficiency [12]. The integrated system aims to overcome the problem of massive energy consumption by a traditional MBR, and avoid dissolved methane that occurs with anaerobic MBR. However, it also inherits the challenges such as membrane fouling.

Given much interest and various reports about membrane integration into BES in the past few years, it is critically important to evaluate both advancement and challenges. In this paper, the research progress of integration of membrane filtration in BES has been reviewed, and major studies are summarized in Table 1. According to the pore size, the membranes used in BES are grouped into three categories: dynamic membranes (DM, >1 µm), ultrafiltration (UF, <0.1 µm), and forward osmosis (FO, <1 nm). Membrane modules can be installed either in an internal or external configuration. This review is expected to provide the current status of research in membrane integration in BES, identify the challenges for further development, and encourage more research efforts to move this technology towards practical applications for energy-efficient wastewater treatment and water reclamation.

2. Integrating DM in BES

Dynamic membranes, also known as secondary membranes, are formed through the fouling of colloidal substances in the mixed liquid *in situ* on a support material such as stainless steel (SS) mesh or non-woven cloth. Because those membranes can be easily cleaned and reformed when they are severely fouled and the inexpensive support material can be replaced with new ones, its capital cost is significantly lower than that of other membrane technologies [13]. Their large pore size can result in less fouling compared with micro/ultra-filtration membranes; however, the quality of the effluent will be worse than that from the membranes with a smaller pore size.

The formation of DM requires directly contact of the support material and the mixed liquor; therefore, when being integrated into BES, the membrane modules are prevalingly submerged (internal configuration). For example, in an MFC that had both the anode chamber and the membrane module immersed in an aerated container (cathode chamber), the anode effluent was further treated by both the cathode and the nylon-mesh supported membrane module [14]. This system achieved a comparable COD removal (89.6%) to conventional MBRs, and the material cost for the whole system was estimated to be \$ 0.3 m⁻³ yr⁻¹, which was significantly lower than previous MFCs or MBRs. To eliminate aeration and improve energy benefits, an air cathode was used and a piece of non-woven cloth served as both separator and filtration medium [15]. The optimized system achieved 88-92% of COD removal and 69-98% of ammonia removal, affected by the HRT varying between 1.6 and 14.5 h. The energy recovery of this updated system could reach 0.766 kWh m⁻³ at the HRT of 14.5 h, more than 18 times higher than its energy

consumption. However, the performance of this system cannot be critically evaluated due to the lack of a control reactor.

Conductive support materials for DM such as SS mesh and carbon felt are attractive, because of their dual functions as both membrane modules and electrodes. The enhanced catalysis for oxygen reduction was observed after biofouling, indicating that the biofilm formed on SS mesh could function simultaneously as a part of DM and a biocathode [16, 17]. A BES with such a biocathode removed more than 90% of COD and ammonia, and produced an effluent with a turbidity of 0.8 NTU [18]. It was found that electricity generation could slow down the increase in TMP (transmembrane pressure), compared with open circuit [19]. The mitigated fouling was possibly due to two reasons: 1) H_2O_2 produced during oxygen reduction could remove foulant, and 2) the electric field might be repulsive to negatively charged microbial cells. Using carbon felt to replace SS mesh generated comparable effluent quality but its better biocompatibility resulted in a 10-time increase in power density [20]. In summary, DM as filter/electrode can be an effective component that can make BES competitive to conventional treatment technologies; however, its effluent quality must be further improved, system stability should be demonstrated through a long-term study, and the dynamics of biofilm formation and the microbial ecology remains to be elucidated [21].

3. Integrating UF in BES

UF membranes with pore size smaller than $0.1\ \mu m$ can reject particles larger than ~ 20000 Daltons [22], including pathogens and viruses, thereby producing water with a high quality. Moreover, the retained biomass leads to separate solid retention time (SRT) and HRT, which is

beneficial for slow biological processes such as methanogenesis and nitrification/denitrification. A longer SRT and the consequent high concentration of mixed liquor suspended solids (MLSS) can also reduce sludge production and the size of treatment plant [23]. Applying UF in BES can presumably produce a final effluent with a much better quality than that from DM. Similar to conventional MBRs, UF can be immersed in BES (internal configuration), or operated as an external module coupled to BES.

3.1 Internal configuration

In an internal configuration, UF can be used as a separator to replace AEM/CEM, installed in the anode similarly to an anaerobic MBR, or in the cathode like that in an aerobic MBR.

3.1.1 UF membrane as a separator

UF membrane was initially integrated in MFCs to investigate its feasibility as a separator between the anode and the cathode [24]. The UF membranes with molecular cutoff weights ranging from 0.5 to 3 kDa resulted in lower current generation and Coulombic efficiency compared to ion exchange membranes, with a large proportion of energy loss unable to identify. However, contradictory results were obtained by a similar configuration in a later study [25], in which the MFC equipped with 1 kDa UF membrane produced the highest power density and had slightly lower internal resistance than the one containing proton exchange membrane. Regardless of the arguable electrochemical performance, high-quality effluent is a distinct feature of the UF-integrated BES. High rejection of total coliform (>97%) and a stable water flux of 14.1 LMH was obtained in an MFC with UF membrane as a separator, both of which could not be achieved by the MFC equipped with Nafion membrane [26].

To enhance fouling resistance, polydopamine was coated on an UF membrane and the coating led to increased hydrophobicity and more negative zeta potential, which have been reported to be beneficial to mitigate biofouling [27]. As a result, a higher power density and a lower level of extracellular polymeric substances (EPS) were observed in this MFC using modified UF membrane, but its water flux declined by 25% compared to that with untreated UF membrane. The direct contact between the anode and UF membrane achieved more noticeable resistance to living cells and EPS (reduced by 62.8% and 64.9%, respective) in comparison to a control reactor (a 5-cm space between the anode and the membrane), which seemed more viable for large-scale applications [28].

The UF membrane can also be modified to reduce the electrical resistance without affecting ultrafiltration function. For example, an conductive membrane was fabricated by coating multiwalled carbon nanotubes (MWCNTs) on a polyester nonwoven membrane base to form a membrane/biocathode assembly for MFC application (average pore size of ~65 nm) [29]. Although the bioelectrochemical performance of such an MFC was inferior to a regular MFC with Pt/C as a cathode catalyst, its permeate had a turbidity <0.1 NTU and 91% of bacterial cells removed. Katuriet al. [30] synthesized conductive hollow-fiber membranes with nickel and used in a single-chamber microbial electrolysis cell (MEC), in which aeration was eliminated and energy was recovered as H₂ and CH₄. The system removed >95% of the soluble COD and showed reduced fouling compared to a control reactor operated under an open circuit mode. Using UF membranes as a separator can significantly lower the capital cost and enhance effluent quality. However, their effects on the electrochemical process are not well understood and

remain controversial [24, 25]. Another problem is that the crossover leakage of oxygen and substrate will be detrimental to the overall BES performance [31].

3.1.2 UF membrane in the anode

Installing UF membranes in the anode of a BES is to mimic an anaerobic MBR (AnMBR), and use UF membranes mainly as a filtration component. Geet al. [32] installed an UF module consisting of hollow-fiber membranes in the anode chamber of a tubular MFC, and this membrane bioelectrochemical reactor (MBER) achieved ~90% COD removal with the effluent turbidity lower than 0.5 NTU when treating real wastewater from a primary effluent. The gap between energy consumption (0.027 kWh m^{-3}) and production (0.025 kWh m^{-3}) was diminished by shortening the HRT to 15 h. One critical problem found in this study was the severe membrane fouling indicated by a rapid TMP increase from zero to ~50 kPa in 15 days. Fluidized granular activated carbon (GAC) was therefore introduced into the anode chamber as a fouling control mechanism [33], and this modification maintained the TMP below 10 kPa with an energy neutral operation; in a control experiment where the fluidization was stopped, the TMP raised to 25 kPa in 20 days, and restarting the fluidization of GAC decreased the TMP back to 10 kPa. Having membrane modules in the anode creates the challenging for fouling control, and regular methods such as biogas flush will have minor effect because of the presence of the anode electrode and *in situ* chemical cleaning will be difficult because of microorganisms; fluidized GAC has been demonstrated to be effective for reducing fouling [34], and its role in electricity generation (as a part of the anode electrode) remains to be further explored.

3.1.3 UF membrane in the cathode

Having UF membranes in the cathode could be more effective for fouling control, because: 1) when the anode effluent is used as a catholyte, it contains a low concentration of COD that may lead to less microbial growth and thus less fouling; and 2) aeration in the cathode can serve as a fouling control method, in addition to supply of electrode acceptors. It was demonstrated in an MBER with an UF module submerged in the cathode chamber that more than 90% of the COD was removed from actual wastewater sampled from a cheese plant and the TMP remained lower than 10 kPa without cleaning [35]. The cation exchange membrane (CEM) in this MBER was later replaced by an anion exchange membrane (AEM) to enhance the removal of total inorganic nitrogen, through combined nitrification in the cathode, nitrate migration across the AEM driven by electricity generation, and detritification in the anode [36]. The coupled system removed 56.9% of the total nitrogen inorganic nitrogen, significantly higher than the 7.6% of the MBER equipped with CEM. The alleviated fouling in similar configurations could also be attributed to the lower particle zeta potential and a lower amount of soluble microbial products in the cathodes [37, 38]. Although fouling mitigation was observed in these MBERs, aeration consumes a large amount of energy, which may be not economically feasible in large-scale practice. In addition, the removal efficiency of total nitrogen was generally low, mainly because anaerobic denitrification was not effectively performed in the aerobic cathode chamber. Nitrate migration/diffusion from the cathode to the anode and electrochemical nitrate reduction on the cathode electrode should be further investigated.

3.2 External configuration

UF membrane modules can be externally linked to BES in different ways, for example having BES to enhance MBR treatment or using MBR to improve BES effluent quality. It was reported

that MFCs could act as a down-stream process to treat the excess sludge from a conventional aerobic MBR [39]. Compared to a conventional MBR, the combine system reduced the sludge yield by 5.1% and showed fouling mitigation through reducing the loose-bound extracellular polymeric substances by 22%, a major contributor to membrane fouling. In addition, the occurrence of sudden rise in TMP in the combined system was 20 days later than the conventional MBR. A fluidized bed MBR was connected to an air-cathode MFC to improve the quality of the treated effluent (MFC-AFMBR) [40]. This MFC-AFMBR removed 92.5% of the total COD, 86.2% of the soluble COD and 99.6% of the total suspended solid (TSS), all of which were distinctly higher than the individual MFC or AFMBR. Moreover, a water flux of 16 LMH was maintained without membrane cleaning during the 50-d operation. The electrical energy production ($0.0197 \text{ kWh m}^{-3}$) by the MFC along could meet the energy requirement of the pumping system ($0.0186 \text{ kWh m}^{-3}$), and when methane production was taken into account, energy benefit would be more significant. A study revealed that MFC-MBR had great potential for sustainable fermentation process with reduced environmental impacts regarding carbon emission, nutrient use, and water management (unpublished information) The external configuration can improve the flexibility of the coupled system and allow the management and operation of individual component without much influence on each other. For example, membrane cleaning can be performed without affecting the bioelectrochemical processes in BES. However, capital cost of two separate units may be higher than the combined one (internal configuration), and some mutual benefits such as oxygen and electricity-influenced anti fouling may not be shared as those with internal configuration.

4. Integrating FO membranes in BES

An FO process refers to the movement of water molecules from a low-salinity solution (feed) through a semipermeable membrane to a high-salinity solution (draw) under an osmotic pressure gradient. Because water permeation is a natural process with relatively low flux, FO is advantageous over conventional membrane technologies such as reverse osmosis, nanofiltration and ultrafiltration, in terms of fouling propensity and energy efficiency [41]. Meanwhile, the small pore size (average pore radius 0.25–0.30 nm) of FO membrane can guarantee rejection of a wide range of contaminants [42]. When wastewater is used as a feed solution and saline water (e.g. seawater) serves as a draw, clean water can be extracted by the osmotic pressure and the volume of wastewater can be greatly reduced [43]. The concentrated feed contains organic matters and nutrients that must be treated before discharge, which provides an opportunity for the synergistic linkage between FO and BES [44].

4.1 Internal configuration

The first successful integration of FO into BES was demonstrated in an MFC, in which an FO membrane was installed between the anode and cathode to replace the ion exchange membrane [45]. This osmotic MFC (OsMFC) using NaCl solution as a catholyte/draw solution generated ~25% higher electric current than a conventional MFC containing CEM, likely because of the enhanced proton transport with water flux and smaller membrane resistance. The performance of this OsMFC slightly decreased with artificial seawater (equivalent to 35 g L⁻¹ NaCl) as a draw, but was still superior to the conventional MFC, especially in water flux. Further study found that the fouling of FO membrane could enhance electricity generation, but was detrimental to water flux [46], indicating that the role of FO membrane in an OsMFC for ion and water transportation is not well understood. When being used to treat domestic wastewater, the OsMFC was able to

remove 74.8% of the soluble COD and reduce the wastewater volume by up to 72.2% depending on HRT, and the water flux reached 2.15 LMH by increasing the recirculation rate to alleviate the concentration polarization [47]. It is worth noting that the relatively low COD removal remained to be further examined because a control reactor with ion exchange membrane was not reported. An energy analysis indicated that the OsMFC could theoretically generate 0.108 kWh m⁻³ of energy, which was sufficient to drive the pumping, thereby establishing a self-sustained treatment system. To eliminate energy consumption by aeration, an air-cathode was used to replace the immersed cathode, and such an OsMFC achieved a power density 7.5% or 87.0% higher than the MFC equipped with AEM or CEM [48]. It was found that a small proportion of acetate in the anolyte migrated into the catholyte, indicating the potential limitation of current FO membrane fabrication. Recently, a novel layer-by-layer polyelectrolyte FO membrane was fabricated and resulted in a high initial water flux of 18.43 LMH in an OsMFC using 2 M NaCl as a catholyte/draw, suggesting that improving FO membrane will have significant impact on the performance of OsMFC [49]. Further studies are warranted to compare the novel FO membrane with conventional FO membranes based on cellulose triacetate or thin film composite.

FO has also been integrated into microbial electrolysis cells (MECs) for enhancing hydrogen production. It was reported that an osmotic MEC achieved 3 times higher hydrogen production compared to a conventional MEC equipped with CEM [50]. The increased hydrogen production was consistent with the enhanced cathodic efficiency, suggesting a facilitated proton transport with water flux. The researchers also hypothesized that the movement of a small amount of cations and anions across the FO membrane under a concentration gradient, known as reverse salt flux, could lower the ohmic resistance of the electrolyte and consequently facilitate electron

transfer. The osmotic MECs represent a new application for the FO-BES integration to produce high-value products, and may be expanded to microbial electrosynthesis that produce organic compounds from carbon dioxide [51].

Although FO can extract high quality water from wastewater, its diluted draw solution needs further treatment (reconcentration or removal of salts) before reclamation. Salt removal can be accomplished through integrating FO into microbial desalination cells (MDCs), which has higher energy efficiency than conventional desalination technologies such as reverse osmosis, multi-stage flash and electrodialysis [52]. This osmotic MDC (OsMDC) simultaneously realizes wastewater treatment, water extraction and desalination [53]. Although the OsMDC was advantageous in water extraction, its salt removal was outperformed by a convention MDC, likely because that Cl^- was retained in the salt chamber by the FO membrane. To overcome this limitation in salt removal, a conventional MDC was hydraulically linked to an OsMFC to enhance desalination without compromising water extraction [54]. The coupled OsMFC-MDC could remove approximately 10% more COD and 3 times more salts than a conventional MDC. It was concluded that the high-power mode (with an external resistance of $31\ \Omega$, which was equivalent to the internal resistance of the MDC) was more favorable because of the higher energy production ($0.16\ \text{kWh m}^{-3}$).

4.2 External configuration

Similar to the UF, external linkage between FO and BES has also been investigated. For example, the previously described OsMFC-MDC system exhibited the enhanced desalination and COD removal compared to conventional MDCs. A further study hydraulically coupled a tubular MDC

to an external FO module by introducing the MDC anode effluent into the FO feed chamber and then the FO feed effluent returning back to the cathode of the MDC [55]. Such a flow pattern achieved 75% COD removal, 64% volume reduction of the wastewater, and 80% conductivity reduction of the salt solution with a salt solution HRT of 24 h, all of which were superior to a standalone MDC or FO module. The TDS (total dissolved solid) decrease rate of this coupled system was $22.7 \text{ g L}^{-1} \text{ d}^{-1}$, which is among the highest reported in the literatures. The FO process contains a large amount of osmotic energy between the feed and draw [56], and this energy can be harvested by pressure retarded osmosis (PRO), in which electrical energy is generated by pressurizing the diluted draw through a hydroturbine. An external PRO module was applied to as pretreatment of an MEC and provide electrical energy to the MEC for hydrogen production, which demonstrated its feasibility and identify several major limitations for further development (unpublished information).

Ammonium-based draw solution is attractive to FO application, because of relatively easier recovery of draw solute [57]. An innovative MEC-FO system was developed to recover ammonium from wastewater in the MEC and use the recovered ammonium as a draw solute in the FO to treat the MEC effluent [58]. This system generated an ammonium solution at 0.8 M and successfully reduced the wastewater volume by 50.1% at a maximal water flux of 2.9 LMH; the final effluent after ammonia recovery contained $<1 \text{ mg L}^{-1} \text{ NH}_3$ and no COD. Including nitrogen recovery into the FO-BES integration will make the system more economical and environmental advantageous. However, at the current stage of the development, the MEC-FO system consumed 3.9 kWh m^{-3} energy, more than half of which came from the power supply,

implying the necessity of using renewable energy to drive the system and decreasing energy consumption through optimizing the operation.

5. Perspectives

The previous studies have collectively demonstrated that the integration of membrane filtration into BES creates a system that possesses the benefits of each component, and will address water energy nexus through energy efficient treatment, energy recovery, and water reclamation. To better understand this integration towards the development of effective treatment technologies, several issues/challenges must be addressed.

Energy efficiency and balance. Integrating membrane filtration introduces new factors for energy consumption such as vacuum pressure for extracting final effluent. Although several studies have demonstrated that the membrane-integrated BES could theoretically achieve energy neutral or positive [18, 33, 47], energy performance has not been widely presented in the BES studies. A new parameter, normalized energy recovery (NER), has been proposed to present energy consumption and production. NER is expressed in either kWh m^{-3} or kWh kgCOD^{-1} . Future studies should really incorporate NER in data expression, and analyze both energy consumption and recovery to establish an energy balance for the developed system.

Membrane fouling. Like conventional MBRs, membrane fouling will be a significant challenge for the BES integrated with membrane filtration. It is expected that fouling mechanisms will be mostly similar to those in conventional MBRs. However, it will be of interest to investigate the interaction between fouling and electricity generation in the BES integrated with membrane

filtration. The interaction could lie in two aspects, electricity generation alleviating membrane fouling and fouling affecting electricity production. Electricity generation could alleviate the fouling condition through stimulating the degradation of organic compounds and creating electrical field force. Moreover, the low pH in the anode due to the microbial respiration may serve as a fouling control when membranes are installed in the anode. Oxygen reduction reaction in the cathode through 2-electron process will generate reactive hydroxide radicals, which may inhibit the formation of biofouling on the membrane surface.

Mutual benefits. It is well known that membrane filtration can improve the quality of final effluent from BES. However, mutual benefits between the two remain further exploration. Several mutual benefits have been discussed in a previous review paper about integrating FO into BES [44], such as using BES to provide draw solute for FO and having FO to provide energy to drive hydrogen production in BES. In UF-BES systems, those mutual benefits have not been well identified. In addition to the benefit that BES could alleviate membrane fouling as previously discussed, membranes modified with conductivity materials can function as electrode materials, thereby benefiting BES performance. For example, an BES with conductive nickel-based hollow-fiber membranes as both filtration component and cathode electrode can recover energy in the form of biogas (CH_4 and H_2) [30]. However, energy neutrality could not be achieved in such a system because of the relatively low conversion efficiency by combustion. The membrane's ohmic resistance can be reduced by coating conductive MWCNTs or synthesizing the membrane with nickel [29, 30].

Membrane improvement. Material science of filtration membranes must be advanced to enhance the performance of filtration. For example, fouling can be mitigated by doping polymers such as polydopamine or anthraquinone/polypyrrole in the membrane [27, 59]. In a recent study, the inexpensive carbon powder was used to synthesize filtration membrane-cathode assembly, resulting in remarkable performance with respect to both wastewater treatment and energy production [60]. These studies are indicative that multi-functional membrane unit may play a critical role in the development of membrane-BES.

System scaling up. System scaling-up remains a significant challenge for BES to demonstrate the feasibility of the membrane-BES for practical application. It strongly relates to the configuration, for instance, internal or external integration of membrane modules. Scaling up the membrane-BES should take advantage of the existing efforts of scaling up BES (MFCs, MECs, and MDCs). Moreover, the successful development of MBR and BES models suggests that mathematical modeling can be a powerful tool to help optimize the reactor configuration and predict system performance [61, 62]. As one of the most critical parameters for scaling McCarty et al., 2011 better understand the limitations of the system. The cost to benefit ratio is another helpful index to compare membrane-BES with the existing technologies. That will require more research efforts with the large-scale membrane-BES with the analysis of economic feasibility and life cycle assessment.

Removal of emerging contaminants. Emerging trace contaminants such as pharmaceuticals, antibiotics and personal care products have raised increasing attention in recent years due to their potential environmental risks and adverse effects to human health [63-65]. MBR, benefiting from

the combination of biodegradation and membrane filtration, is believed to remove trace contaminants more effectively than activated sludge process do [66]. FO has also been reported to reject a variety of trace organic compounds at a pilot scale [67]. Meanwhile, a recent study demonstrated that the removal of p-fluoronitrobenzene was significantly enhanced by the cathodic reduction in a BES [68]. It is therefore expected that membrane-BES will combine the advantages of BES and MBR with great promise for the removal of emerging contaminants.

6. Conclusions

Membrane filtration can synergistically be integrated in BES as a separator between the electrodes, an internal filtration component in the anode/cathode compartment, or an external treatment process before or after BES. Such integration generates multiple benefits, including high-quality effluent, high energy efficiency, reduced capital cost, mitigated fouling and/or sustainable desalination. Challenges lie in better understanding of energy production and consumption by the coupled system, membrane fouling, identification of proper application niches, and system scaling up. BES integrated with membrane filtration will have potential to be developed as energy efficient technologies for wastewater treatment and water reclamation.

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Table 1. Summary of the studies about the membrane-integrated BES

Membrane	Pore size	Configurat ion	Carbon source	COD removal (%)	NH ₄ ⁺ -N removal (%)	Turbid ity (NTU)	Maximum power density	Reference
SS mesh	40 µm	separator/c athode	acetate	86.6-93.9	92.7- 99.6	~0.8	4.35 W m ⁻³	Wang et al. [18]
nylon mesh	74 µm	cathode		89.6		~0.8	6.0 W m ⁻³	Wang et al. [14]
pyrrole-modified polyester filter cloth		cathode	glucose	~100			2.6 mW m ⁻²	Liuet al. [16]
non-woven cloth	50 µm	cathode	acetate	87.4-91.2	69.5- 97.6	<2	7.6 W m ⁻³	Liuet al. [16]
SS mesh	48 µm	separator/c athode	acetate	81.0-92.8	95.3- 98.5	0.80	8.56 W m ⁻³	Wang et al. [17]
SS mesh	15 µm	cathode	sucrose	91.9-95.3			0.15 W m ⁻³	Liuet al. [19]
SS mesh	13 µm	cathode	glucose	96.4		2.82	0.12 W m ⁻³	Zhang et al. [20]
carbon felt				95.5		4.98	1.25 W m ⁻³	
microfiltration membrane	0.45 µm	separator	acetate				831 mW m ⁻²	Tang et al. [69]
nickel-based hollow fiber membrane	1 µm	cathode	farm wastewater	81.6			746 mW m ⁻²	
anthraquinone- disulphonate/polypyrrole composite modified polyester flat membrane	9.8 µm	cathode	acetate	>95				Katuriet al. [30]
			glucose	92.5	70.6		0.35 W m ⁻³	Xuet al. [59]
carbon filtration membrane	0.553 µm	cathode	acetate	93.7	96.2		581.5 mW m ⁻²	Zuo et al. [60]
UF membrane	0.5 kDa	separator	acetate				5 mW m ⁻²	Kim et al. [24]
	1 kDa						36 mW m ⁻²	
	3 kDa						36 mW m ⁻²	
UF membrane	1 kDa	separator	glucose	52.0			324 mW m ⁻²	Houet al. [25]
	5 kDa			60.0			138 mW m ⁻²	
	10 kDa			57.4			54 mW m ⁻²	
PVDF hollow-fiber UF membrane	0.02 µm	anode	acetate	45.3-57.8		0.41	3 W m ⁻³	Geet al. [32]
			primary effluent	86.9-90.2	9.1-50.0	0.45- 0.75	1.5 W m ⁻³	

UF membrane	1 kDa	separator	acetate	>90			53.5 mW m ⁻²	Kimet al. [26]
PVDF hollow fiber UF membrane	0.02 µm	cathode	acetate	90.4-95.4	83.0	1.0-1.2	27 W m ⁻³	Liet al. [35]
polyester nonwoven membrane base coated with MWCNTs	0.065 µm	separator/cathode	cheese plant effluent	84.4-91.9	62.2	1.8-2.4		
PVDF hollow fiber UF membrane	0.1 µm	external	domestic wastewater	97.3	97.3	<0.1	6.8 W m ⁻³	Malaebe et al. [29]
UF membrane + polyvinylidene fluoride UF membrane	30 kDa + 0.1 µm	separator + external	glucose	86.7	93.0		51 mW m ⁻²	Suet al. [39]
UF membrane + polyvinylidene fluoride UF membrane	30 kDa + 0.1 µm	separator + external	glucose	94.0	85.0	0.70	40 mW m ⁻²	Wang et al. [70]
polydopamine modified UF membrane	1 kDa	separator	glucose				60 mW m ⁻²	Wang et al. [71]
regenerated cellulose UF membrane	1 kDa	separator	glucose	93.0			159.8 mW m ⁻²	Kimet al. [27]
UF membrane	~0.01 µm	external	domestic wastewater	87.0			25.1 mW m ⁻²	Köroglu et al. [72]
PVDF hollow fiber UF membrane	0.02 µm	anode	acetate	91.6		1.00	1.8 W m ⁻³	Liet al. [33]
		anode + external	acetate	95.0		1.60		
PVDF hollow fiber UF membrane	0.1 µm	external	primary effluent	86.2			86.9 mW m ⁻²	Renet al. [40]
hollow fiber UF membrane	0.4 µm	cathode	acetate	91.6	31.7		1.16 W m ⁻³	Tian et al. [37]
regenerated cellulose UF membrane	1 kDa	separator	acetate				122.2-160.5 mW m ⁻²	Kimet al. [73]
PVDF hollow fiber UF membrane	15 kDa	cathode	acetate	91.3	99.0			Li and He [36]
			primary effluent	84.5				
PVDF hollow fiber UF membrane	0.03 µm	cathode	glucose + starch	95.1	95.2		2.18 W m ⁻³	Tian et al. [38]
FO membrane		separator	acetate				4.74 W m ⁻³	Zhang et al. [45]
FO membrane		separator	acetate					Ge and He [46]
FO membrane		separator	acetate					Zhang and He [53]
FO membrane		separator	acetate	82.5			28.2 W m ⁻³	Ge et al. [47]

cellulose triacetate FO membrane	separator	primary effluent acetate	74.8	4.5 W m ⁻³	Werneret al. [48]
			90.0	43 W m ⁻³	
chitosan [CH; polycation] + PAAc; polyanion	separator + external separator	acetate	>85%	12.45 W m ⁻³	Zhang and He [54]
			89.8	27.38 W m ⁻³	Pardeshi and Mungray [49]
cellulose triacetate FO membrane	external	glucose	60.6	81.5	Qin and He [58]
cellulose triacetate FO membrane	separator	acetate			Leeet al. [50]
cellulose triacetate FO membrane	external	acetate	~80		Yuanet al. [55]