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Review

Integrating membrane filtration into bioelectrochemical systems as next generation energy-efficient wastewater treatment technologies for water reclamation: A review

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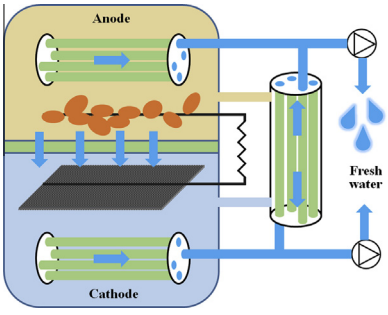
HIGHLIGHTS

- Integrating membrane filtration into BES can produce high quality effluent.
- Integration can be accomplished via internal or external configurations.
- Mutual benefits such as fouling control and energy efficiency may be achieved.
- Using filtration membrane in BES will enhance wastewater reclamation.

GRAPHICAL ABSTRACT



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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.

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 (McCarty et al., 2011). It has been reported that wastewater utilities account for approximately 1–3% of the total electricity consumption in the USA (EPA Office of Water, 2006). Meanwhile, electricity is not readily 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 (UNESCO, 2014). Wastewater contains energy potential of 17.8–28.7 kJ g^{-1} COD (chemical oxygen demand) (Heidrich et al., 2010). Energy recovery from high-strength wastewater can be accomplished by using anaerobic digestion, but anaerobic

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treatment of low-strength wastewater still faces significant challenges such as dissolved methane gas in the final effluent (Smith et al., 2013). 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 (Li et al., 2014). 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 (Lovley, 2012). 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 (Foley et al., 2010; Heidrich et al., 2013).

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 (Zhang et al., 2013), much less than the 0.4–0.8 VSS g^{-1} COD in conventional activated sludge process (Li et al., 2014), 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 (Santos et al., 2011). In addition, biomass is retained by the membrane in the reactor to improve treatment efficiency (Ozgun et al., 2013). The integrated system aims to overcome the problem of massive energy consumption by a traditional MBR, and avoid dissolved methane that occurs in 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 (Ersahin et al., 2012). 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 prevailingly 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 (Wang et al., 2012). 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 (Wang et al., 2013). 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. 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 (Liu et al., 2013; Wang et al., 2013). 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 (Wang et al., 2011). It was found that electricity generation could slow down the increase in TMP (transmembrane pressure), compared with open circuit (Liu et al., 2014). 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 (Zhang et al., 2014). 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 (Huang et al., 2014).

3. Integrating UF in BES

UF membranes with pore size smaller than 0.1 μm can reject particles larger than ~20,000 Da (Judd, 2010), 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 (Judd, 2008). 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 ion exchange membranes, installed in the anode similarly to an anaerobic MBR, or in the cathode like that in an aerobic MBR.

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