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Review

High retention membrane bioreactors: Challenges and opportunities

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HIGHLIGHTS

- HR-MBR integrates high rejection membrane and biological treatment in a single step.
- HR-MBR is compact and can offer high treatment capacity suitable for water reuse.
- Salinity buildup, low flux, membrane stability must be addressed in future research.
- Possible directions to address these challenges were suggested.

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ABSTRACT

Extensive research has focussed on the development of novel high retention membrane bioreactor (HR-MBR) systems for wastewater reclamation in recent years. HR-MBR integrates high rejection membrane separation with conventional biological treatment in a single step. High rejection membrane separation processes currently used in HR-MBR applications include nanofiltration, forward osmosis, and membrane distillation. In these HR-MBR systems, organic contaminants can be effectively retained, prolonging their retention time in the bioreactor and thus enhancing their biodegradation. Therefore, HR-MBR can offer a reliable and elegant solution to produce high quality effluent. However, there are several technological challenges associated with the development of HR-MBR, including salinity build-up, low permeate flux, and membrane degradation. This paper provides a critical review on these challenges and potential opportunities of HR-MBR for wastewater treatment and water reclamation, and aims to guide and inform future research on HR-MBR for fast commercialisation of this innovative technology.

1. Introduction

Water reuse is an important measure to simultaneously address fresh water scarcity and environmental pollution (Shannon et al., 2008; Grant et al., 2012). Safe and reliable water reuse requires adequate removal of salts, nutrients (such as nitrogen and phosphorous), pathogenic agents, and trace organic chemicals (TrOCs) from reclaimed effluent. Amongst these contaminants, the removal of TrOCs is possibly the most challenging aspect as conventional wastewater treatment systems were not specifically designed for their removal (Schwarzenbach et al., 2006). TrOCs are continuously introduced into the sewer via household activities and industrial production. As a result, these TrOCs including pharmaceuticals, personal care products, endocrine disrupting compounds, pesticides and industrial chemicals occur ubiquitously in raw wastewater at concentrations of several μg/L or below (Ternes et al., 2004; Osorio et al., 2012; Tran et al., 2014). If not adequately removed, many of these TrOCs may have adverse impacts on human health and the ecosystem. For example, some human sex hormones can induce endocrine disrupting effect in fish at concentrations as low as 1 ng/L (Schwarzenbach et al., 2006). Thus, their widespread occurrence in wastewater does not only restrict the reuse of treated effluent, but also cause pollution of water bodies receiving effluent discharge.

Recent decades have seen the maturity of membrane bioreactor (MBR) systems as an alternative wastewater treatment technology that is superior to the conventional activated sludge (CAS) treatment processes (Hai et al., 2014). MBRs integrate low pressure membrane filtration, such as microfiltration (MF) or ultrafiltration (UF), with activated sludge treatment. Compared to CAS processes, MBRs are usually operated at higher biomass concentrations (i.e. 10–20 g/L) and longer sludge retention times (i.e. 10–30 d), resulting in better

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quality effluent and lower sludge production. For the same treatment capacity, the physical footprint of MBR is also much smaller than that of the CAS process (Hai et al., 2014).

The performance of MBR with respect to TrOC removal has been extensively investigated in recent studies (Tadkaew et al., 2011; Wijekoon et al., 2013; Luo et al., 2014). Tadkaew et al. (2011) reported that, during MBR treatment, hydrophobic TrOCs can adsorb to the biosolids, resulting in longer retention times in the bioreactor, and thereby exhibiting higher removal efficiency than the CAS process. However, some hydrophilic TrOCs such as carbamazepine and diclofenac can be similarly persistent to CAS and MBR treatment. Because TrOCs can freely permeate through MF and UF membranes, the retention time of the hydrophilic and persistent TrOCs in the bioreactor is the same as the hydraulic retention time (HRT). This is particularly important as owing to maintenance of higher MLSS concentration, compared to the CAS process, a shorter HRT is usually applied during MBR operation. Thus, the occurrence of hydrophilic and persistent TrOCs in MBR permeate necessitates a post-treatment process to ensure their removal if potable water reuse is intended. The post-treatment process mainly involves reverse osmosis or nanofiltration (Alturki et al., 2010; Nguyen et al., 2013), UV oxidation (Nguyen et al., 2013) or ozonation (Reungoat et al., 2010). While high water quality is achieved after these multiple treatment processes, they can be expensive, energy intensive and, thus can compromise the economics and environmental advantages of water reuse (Shannon et al., 2008).

Further developments of MBR have led to the emergence of a novel high retention (HR)-MBR concept. HR-MBR combines biological treatment and high retention membrane separation into a single step. The high retention membrane separation process can effectively retain TrOCs, thus prolonging their retention time in the bioreactor and potentially enhancing their biodegradation. By improving TrOC removal, HR-MBRs can offer a reliable and elegant solution for the production of high quality effluent for potable water reuse or direct effluent discharge in environmentally sensitive areas. Not surprisingly, the number of studies dedicated to the development of HR-MBR has increased rapidly in the last few years (Lay et al., 2010; Yap et al., 2012). Given the remaining technological challenges associated with the development of HR-MBR systems, including salinity build-up, low water flux, and membrane stability, many more studies are expected in the near future.

This paper provides a critical review on the challenges and potential opportunities of HR-MBR for wastewater treatment and water reclamation. The aim was also to guide and inform future research on HR-MBR to fast track the scale up and commercialization of this innovative technology.

2. HR-MBR configurations

Three HR-MBR configurations have been investigated in the literature (Fig. 1). They include nanofiltration membrane bioreactor (NF-MBR) (Choi et al., 2002), membrane distillation bioreactor (MDBR) (Phattaranawik et al., 2008) and osmotic membrane bioreactor (OMBR) (Achilli et al., 2009). In these systems, nanofiltration (NF) or reverse osmosis (RO), membrane distillation (MD) and forward osmosis (FO) are used as the high retention membrane separation process. The key differences between these systems and conventional MBRs are summarised in Table 1. Although all recent studies on HR-MBR (with the exception of a study by Chen et al. (2014)) have focused on the coupling of a high retention membrane process with an activated (aerated) biological reactor, an anaerobic reactor could be used to form an anaerobic HR-MBR (AnHR-MBR) system (Fig. 1d). Similar to conventional MBR, the membrane process in both HR-MBR and AnHR-MBR can be designed and operated in either submerged or side-stream modes.

2.1. Nanofiltration membrane bioreactor

The configuration of NF-MBR is similar to conventional MBR, but using an NF membrane or low pressure RO membrane (Fig. 1a). Given the similarity between NF and RO processes, hereafter, they will be both referred to as NF. NF membranes can effectively retain low molecular weight organic contaminants, increasing their retention time in the bioreactor for better biological degradation. Although NF is a mature process with a large number of full scale installations, it was not specifically designed for the separation of biomass. Thus, severe membrane fouling can be expected in NF-MBR applications under high hydraulic pressure. One way to reduce this is to operate at a very low permeate flux and a high cross flow velocity to minimise cake layer formation on the membrane surface. With the development of a range of NF membranes that are inexpensive, fouling resistant, chemically stable and highly permeable to water, the issue of membrane fouling could potentially be resolved in the near future (Li and Wang, 2010), allowing for NF-MBR to replace the current treatment train consisting of activated sludge treatment, MF/UF, and subsequently NF, typically used for potable water reuse applications.

2.2. Osmotic membrane bioreactor

The OMBR system combines FO with CAS treatment. FO is an osmotically driven membrane process where water transports from a feed solution across a semi-permeable FO membrane, to a draw solution (Cath et al., 2006). Commonly used draw solutes are inorganic salts with low molecular weights such as NaCl and $MgCl_2$. In a typical OMBR system (Fig. 1b), water is extracted from the mixed liquor into the draw solution by osmosis, with the FO membrane acting as a barrier to solute transport and providing effective rejection of contaminants. In most cases, a draw solute recovery process such as RO or MD is required to reconcentrate the diluted draw solution for continuous operation and to obtain the final product water for beneficial reuse (Fig. 1b). The solute recovery process can also act as an extra barrier to residual compounds that could pass through FO membranes, thereby further improving the quality of product water.

FO is still an emerging technology with limited full scale applications. Nevertheless, given its low fouling propensity (Cath et al., 2006), FO can be a good candidate for integration with biological treatment to form a HR-MBR system. In fact, the low fouling propensity of FO during OMBR operation, especially when the active layer of the membranes faces the mixed liquor, has been demonstrated in many studies (Achilli et al., 2009; Zhang et al., 2012b, 2014). This can be attributed to the absence of a hydraulic pressure and low permeate flux typically associated with this process as well as the smooth surface of the FO membranes (Yap et al., 2012). When a draw solution such as seawater is readily available and the recovery of clean water for recycling is not required, the energy consumption of OMBR can be substantially lower than that of a conventional MBR-RO hybrid system (Cornelissen et al., 2011). Even when RO is required for draw solute recovery, the high retention FO membrane can also protect the RO membrane from fouling, thereby reducing costs for membrane cleaning and replacement. Therefore, OMBR has the potential to replace the current hybrid MBR-RO system for water recycling.

2.3. Membrane distillation bioreactor

In MDBR, the MD process is utilised to separate high quality product water from the mixed liquor in a thermophilic bioreactor (Fig. 1c). MD is a thermally driven membrane process where only the vapour phase (e.g. water vapour) can be transported through the porous hydrophobic membrane. In theory, all four different