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Abstract

The ubiquitous presence of organic micropollutant (OMP) in reclaimed water and wastewater is often a major obstacle to water reuse. This book chapter reviews advanced hybrid membrane bioreactors systems of osmotic membrane bioreactor and membrane distillation bioreactors employed for OMPs removal in wastewater treatment and reclamation towards a sustainable wastewater management. Major operating parameters affecting membrane bioreactors (MBRs) for wastewater treatment and organic micropollutant removal are discussed. The difference between membrane bioreactors and hybrid advanced membrane bioreactors are presented. Latest studies for OMBRs and MDBRs in organic micropollutant removal are discussed followed by environmental assessment of these water treatment technologies by life cycle assessments of the advanced hybrid membrane bioreactor technologies are realised with case studies.

Keywords: organic micropollutnts, membrane bioreactor, osmotic membrane bioreactor, membrane distillation bioreactor, enzymatic membrane bioreactor

Chapter 23: Advanced Membrane Bioreactor hybrid systems

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23.1 Introduction

In the current century, the natural reserves of clean freshwater are depleting at an alarming rate as a consequence of an extremely high increase in demand (Stefan, 2017). The global usage of water is growing at a rate of more than twice the population growth in last 10 decades. The global population has reached almost 7.6 billion in 2017 and is projected to rise to 11.2 billion at the end of this century. In addition to the growing global population, increasing industrialization, high living standards are also contributing to the rise in water demand (Suwaileh et al., 2020, Beddington, 2011). Therefore, a severe water scarcity problem is inevitable. Without any major shifts in policy it is estimated that 2.3 billion more people than today will be living in water stressed regions with a 55% rise in water demand by 2050 (Leflaive et al., 2012). Water stressed regions are those where the annual water supply per person falls below 1700 m^3. When the water supply per person drops further to 1000 m^3, the region experiences water scarcity (Molden, 2013). However, the global water shortage problem causes serious consequences on public health and sanitation. As such 1.2 billion people are deprive of the potable water and 2.6 million people suffer from proper sanitation. In addition globally about 3,900 children die everyday due to waterborne diseases (Shannon et al., 2010, Stefan, 2017).

Global freshwater reserve is only 2.5% of the total natural water resources, whereas about 96.5% is seawater (Shiklomanov, 1993, Trenberth et al., 2007). Therefore the desalination techniques show promising option in minimizing water shortage problem. However, at present the available conventional seawater purification technologies are energy intensive and the produced water is still beyond the affordability of lower income group people (Chekli et al., 2016, Ziolkowska, 2015). Reuse of impaired water can be another potential measure to address the water scarcity issue. However, the conventional treatment of wastewater effluent to produce high quality water is also a high energy demanding process (Linares et al., 2014). Therefore an alternative technology is urgently needed to economically recover freshwater from these unconventional sources for the growing global population. As reclaimed water use is increasing, its safety attracts growing attention, particularly with respect to the health risks associated with the wide range of organic micropollutants (OMPs) found in the reclaimed water (Ma et al., 2018). However, the ubiquitous presence of OMPs in reclaimed water and wastewater is often a major obstacle to water reuse (Luo et al., 2017, Zhang et al., 2017).

23.1.1 Occurrence, fate and transport of OMPs in WWTPs and impact on human and environment

During last decade, the appearance of emerging OMPs has been detected in water resources all over the world and it has become a worldwide issue of a great importance for environmental protection strategies (Bodzek and Konieczny, 2018). This is due to its potential in causing undesirable side effects on ecosystem (Tran and Gin, 2017) and public health authorities, the whole industrial world and the agricultural sector (Hamza et al., 2016, Priac et al., 2017). OMPs are derived from either anthropogenic activities, such as industrial effluents, discharges of treated effluents from domestic and hospital effluents, agricultural runoff, septic tank or natural activities. In addition, other anthropogenic sources include landfills, inappropriately disposed wastes, surface runoff, sewer overflow and sewer leaking (Hamza et al., 2016, Tran and Gin, 2017, Pal et al., 2014). It has been shown that even conventional wastewater treatment plants (WWTP) are able to remove efficiently some

OMPs, although there is still a significant group of compounds with a recalcitrant behaviour (Alvarino et al., 2018). Actually, current WWTPs are not designed to eliminate or degrade OMPs, therefore, many of these OMPs because of their persistence some of these compounds can pass through the treatment system and enter into natural aquatic system (Asif et al., 2017b). The presence of some OMPs and their metabolites can inhibit the biological activity of microorganisms present in activated sludge and thus non-consistent and inadequate removal of OMPs by conventaional trearment (Goh et al., 2015, Morrow et al., 2018). OMP removal techniques include adsorption on activated carbon, ultraviolet disinfection, and other advanced oxidation processes such as ozonation, hydrogen peroxide. The capital and operating cost and chemical sludge disposal are some of the issues associated with such treatment (Chtourou et al., 2018). Also, membrane based processes such as MF, UF, NF, RO and most recently FO and MD are employed for OMPs removal (Pathak et al., 2020b). Further, activated sludge process when coupled with any of above mentioned membranes (most commonly MF/UF) the membrane bioreactor is promising alternative in OMP removal as it offers higher, consistent and comparatively cheaper removal. (Morrow et al., 2018, Wei et al., 2018, Calero-Díaz et al., 2017, Besha et al., 2017).

Membrane bioreactor (MBR) is An attractive alternative for wastewater reuse applications. Recently, high-retention membrane bioreactors (HRMBR) systems gaining more attention in wastewater treatment. This review examines recent developments in forward-osmosis MBR (FO-MBR) and membrane distillation bioreactor (MDBR) for OMPs removal. The MBR, OMBR and MDBR technologies comparison is presented. Finally, life cycle assessment of MBR and advanced hybrid MBRs have been discussed.

23.2 Membrane bioreactor operating conditions

MBR is a promising option in wastewater treatment as it generates pure permeate in terms of suspended solids, free of microorganisms, nutrients, OMPs, less space requirement, and reduced sludge disposal cost as compared to conventional biological treatment. Moreover, it can easily accommodate unstable flow (Wang et al., 2011, Cornelissen et al., 2008, Chtourou et al., 2018, Bui et al., 2016, Luo et al., 2014b). In the beginning activated sludge process was coupled with side stream MF/UF membrane and then after membrane was directly submerged into the mixed liquor (Huang and Lee, 2015).

The physicochemical properties of OMPs such as hydrophobicity and biosorption of OMPs, microbial activity and biodegradation, molecular weight and functional groups of OMPs, and other major operating parameters such as biomass concentration and characteristics, hydrodynamic parameters of solids retention time (SRT) and hydraulic retention time (HRT), cometabolism and influence of the redox potential, mixed liquor pH, and mixed liquor temperature affects OMPs removal in MBR (Zolfaghari et al., 2015, Hai et al., 2018, Zheng et al., 2019). The hydrophilicity and hydrophobicity is an important physicochemical property for OMP removal and hydrophobicity of an organic molecule is defined by the octanol-water partitioning coefficient (Kow) or the solid water partitioning coefficient (Kd) (Stevens-Garmon et al., 2011, Hai et al., 2018). The more hydrophilic OMP retains in water phase while more hydrophobic OMP attached to the sludge surface (Pathak et al., 2020a). Moreover as compared to negatively charged or neutral OMPs the positively charged pharmaceutical class OMPs showed more affinity towards sludge adsorption (Joss et al., 2005, Hai et al., 2018). The combined effect between biosorption and biodegradation forms another important OMPs removal mechanism realized in presence of microorganisms could achieve better OMPs removal as higher biosorption provide longer retention time and further opportunity for biodegradation to occur (Stevens-Garmon et al., 2011). Low molecular weight OMPs could not be retained by MF membranes effectively. Actually, higher molecular weight OMPs can be better retained by membrane leads to higher removals by biodegradation in MBR process. The higher molecular weight OMPs may possess more functional groups and this provides opportunities for diverse microbial communities to target selective site to commence biodegradation (Hai et al., 2018, Pathak et al., 2020a).

Higher MLSS concentration, longer SRT and smaller floc size of sludge particles are always favorable operating parameters for both sorption and biodegradation processes demonstrated by several studies (Zheng et al., 2019, Alvarino et al., 2018, Kimura et al., 2007, Verlicchi et al., 2012). As compared to activated sludge process (ASP) the MBR can retain more biomass and allow to proliferate diverse microbial communities for OMPs removal (Verlicchi et al., 2012). Hydraulic retention time (HRT) is another significant operating parameter and it can influence food to microorganism ratio (F/M ratio) and organic loading rate (OLR) in the bioreactor. Too low HRT negatively affects the biological process performance of the MBR process (Prasertkulsak et al., 2019). Moreover, in anoxic–aerobic MBRs due to the recirculation of biomass under varying redox conditions of anoxic and aerobic MBRs entirely different biological environment has been realized that helps in improved removal of OMPs (Phan et al., 2016). Mixed liquor pH and temperature are another important operational parameters that affects MBR process performance. The average 15-20 °C temperature of MBRs is suitable in cold countries and seasonal temperature variation can also affects process performance (Mert et al., 2018). However, MBR report mentions that 10-35 °C temperature fluctuation did not affect OMP removal in MBRs (Verlicchi et al., 2012).

Aerobic process takes place in presence of oxygen while anaerobic process does not require oxygen. Anaerobic process is suitable to treat high strength water and it takes long time to start-up. Anaerobic microorganisms are more sensitive to shock loads (Mutamim et al., 2013). MBR for biogas as an alternative and renewable fuel production is still an emerging concept and limited industrial applications have been seen employing AnMBR for effluent polishing (Neoh et al., 2016). It has been reported that about 98 % of raw sewage COD can be efficiently transformed into methane gas using AnMBR. The biogas produced from AnMBRs having a composition more than 80 % methane content which means it can be used as a fuel. This methane composition is more favorable than obtained through conventional anaerobic digesters that produces upto 65 % methane can be attributed to shorter HRT in AnMBRs (Guo et al., 2016, Skouteris et al., 2012). However, methane production has linear correlation with methnogenesis step which is the slow growth rate process and therefore methanogen can possibly easy to wash out (Neoh et al., 2016). Monsalvo et al. (2014) kept mesophilic conditions (30 °C) in an AnMBR as compared to the higher thermophilic range and very low 0.25 d HRT than usual HRT of 1-25 d, which are favorable for the anaerobic process. However, methane production details were missing in this report. Song et al. (2016) investigated the effects of increased salt concentration on OMPs removal in anaerobic membrane bioreactor (AnMBR). It has been reported that salt accumulation upto 15 g/L (as NaCl) adversely affected AnMBR performance in terms of methane production and hydrophilic OMPs. Authors further reported that salt accumulation had no pronounce effect on high removal of hydrophobic OMPs.

23.3 Advanced membrane bioreactor hybrid systems

The hybrid MBR can produce better quality permeate, lessen membrane fouling and thereby reduced cleaning cycles (Neoh et al., 2016). Nonetheless, hybrid MBR technology has certain drawbacks need to be resolve for commercialization. For example in osmotic membrane bioreactor, draw solution accumulates into the feed tank and due to this reverse diffusion of draw salts salinity builds up in the reactor. It leads to concentration polarization, flux decline and increases fouling propensity. In order to mitigate such issues novel membranes with less fouling propensity, and development of bacterial consortia that can withstand hypersaline condition need to be explored (Luo et al., 2014a). In the following Table 23.1 comparison are made for conventional MBRs and two major advanced hybrid MBR systems, namely osmotic membrane bioreactors (OMBR) and Membrane distillation bioreactors (MDBR) performance in wastewater treatment.

Table 23.1. Comparison for MBR, OMBR and MDBR in wastewater treatment (Barbosa et al., 2016, Mert et al., 2018, Neoh et al., 2016, Goh et al., 2015, Bharwada, 2011).

Parameters/description	**MBR**	**OMBR**	**MDBR**
Membrane type	Low-pressure MF/UF membranes are employed. (MF MWCO =1000 kDa) (UF MWCO = 10 - 100 kDa) Liquid (permeate water) inside the lumen.	Forward osmosis (FO) semi-permeable membranes are used. FO (MWCO = 0,1 - 2 kDa) Liquid (permeate water) inside the lumen.	Hydrophobic membrane distillation membrane (MD) is used. MD (MWCO < 150 Dalton Vapour phase (permeate) inside the lumen.
Removal mechanism	Size exclusion is principal removal mechanism.	Steric hindrance and electrostatic repulsion are principal removal mechanism.	Steric hindrance is the principal removal mechanism.
Pressure	Hydraulic pressure (50-70 bar) is a driving force	Natural osmotic pressure (27 bar) is a driving force.	Vapour pressure gradient (heat transfer) is driving force.
Temperature	Normally operates at ambient conditions.	Normally operates at ambient conditions.	Normally operates at high temperature (30-80° C).
Effect of operating condition on process performance	Normal operating conditions does not have a significant effect on the DO level in a bioreactor.	DO level reduces and adversely affects the microbial community due to salinity build-up in bioreactor with time.	DO level reduces and adversely affects the microbial community by thermophilic conditions.
	Hydrophilic MF or UF membranes are preferably employed. Comparatively less rejection is obtained than FO.	Hydrophilic FO membrane can achieve similar rejection as RO.	Hydrophobic MD membrane can achieve similar rejection as RO.
Flux (LMH-Litres per square meter per hour)	MF/UF MBR operates at 10-25 LMH flux.	OMBR operates at 2-10 LMH flux. Lab-scale hollow fiber FO module can achieve up to 30	MDBR operates at 2-15 LMH flux. Wetting of membrane is major concern.

		LMH initial flux during preliminary testing.	
Process performance on TOC removal	In MBR 30%-75% TOC removal efficiencies can be achieved.	In the OMBR process the FO membrane with a 98% TOC removal efficiency allows the downstream RO to operate in longer cycles.	In MDBR process, the MD membrane with a 98% TOC removal efficiency.
Process performance on P removal	In MBR removal of P can be achieved by the addition of flocculants followed by larger particle flocs filtration or rejection through the membrane.	OMBR system rejects P more cost-effectively because the removal mechanism is size exclusion without flocculation.	MDBR system rejects P more cost-effectively because the removal mechanism is size exclusion without flocculation.
Concentration and temperature polarisation and fouling	In MBR fouling is major issue and cleaning cost is high.	OMBR offers low fouling characteristics and less cleaning cost due to lack of hydraulic pressure across the membrane. Fouling is largely reversible. However, the salinity build-up is one of the major issues. CECP also adversely affects OMPs removal.	The OMBR offers ultralow fouling characteristics and less cleaning cost due to lack of hydraulic pressure across the membrane. However, temperature polarization is one of the issues.
Membrane process influence on economy	In MBR, the design has evolved to continually improve the economy of energy required for scouring, backwashing and aeration.	In OMBR, fine bubble diffusion for oxygen transfer and a longer interval between backwashing and cleaning should require less energy.	In MDBR, the waste heat source can be utilised, thus saving energy and minimise GHG emission. MD utilizes waste heat directly with a heat exchanger.
Energy consumption (kWh/m^3)	In MBRs total energy estimate is 4.20 kWh/m^3 water treated.	In OMBR total energy estimate is 2.80 kWh/m3 water treated.	Electrical energy requirement for RO would increase as feed solution salinity increases whereas MD is only minimally affected by feed solution salinity.
OMP removal	MF/UF membrane of the MBR process is commercialised. Too low hydrophilic OMP removal.	Membrane stability is major concern. CTA membrane can operate in narrow pH range and stability of membrane due to biodegradation is a	Complete rejection of inorganic salts and OMPs. Ammonia and CO_2 can seep through MD membrane.

		concern.	
Sludge/concentrate production	Less sludge yield as compared to CAS.	Concentrate disposal and relevant cost are disadvantages.	Concentrate disposal and relevant cost are disadvantages.

23.3.1 Osmotic membrane bioreactor (OMBR)

Osmotic membrane bioreactors (OMBRs) is membrane based promising technology employs in wastewater treatment and reclamation for indirect and direct potable water reuse applications (Van Huy Tran and Shon, 2020, Achilli et al., 2009, Alturki et al., 2012), that integrates semipermeable forward osmosis membrane with bioreactor (Nguyen et al., 2018, Li et al., 2016). OMBR achieves better permeate quality with less dissolve organic matters, less fouling tendency and higher reversibility of membrane fouling, high removal and rejection of organics by enhanced biodegradation, nitrogen, phosphorus and improved organic micropollutants, and low electrical utilities (Li et al., 2016, Luo et al., 2018, Alturki et al., 2013, Jin et al., 2012). Nevertheless, reverse salt flux (RSF) of draw solutes (DS) leads to salinity rise in the bioreactor adversely affects microorganisms exacerbated by deterioration in the OMBR's performance in terms of water flux and removal of organics, nutrients and OMPs (Cicek et al., 1999). In order to mitigate salinity build up operation at short SRT and simultaneous operation of MF/UF membrane has been implemented. In forward osmosis and OMBR applications cellulose triacetate (CTA FO) (Achilli et al., 2009, Cornelissen et al., 2008, Sun et al., 2016) and TFC FO (thin film composite) (Luo et al., 2017, Zhang et al., 2017, Morrow et al., 2018) are most commonly used FO membranes. In comparison to TFC FO (2-12 pH range) the CTA FO membranes are more pH sensitive means it can be operated in narrow range of pH variations (4-10) as well as more prone to bacterial attack in mixed liquor environment (Yip et al., 2010). In OMBR application membrane can be oriented either as active layer facing feed side (AL-FS) or active layer facing draw solution side (AL-DS) (Pathak et al., 2020b). AL-FS orientation is more preferred in OMBR applications based on concentration polarization and fouling propensity aspects. Osmotic process is driven by osmotic pressure difference and to achieve this inorganic (sodium chloride, magnesium chloride) and organic draw solutes (sodium acetate) are commonly used (Bowden et al., 2012). Draw solute screening and selection based on higher flux, lower RSF and fouling properties are another major area of ongoing research in forward osmosis applications (Bowden et al., 2012, Ansari et al., 2015). Organic DS could be more attractive option with regards to OMBRs due to less RSF, non-toxic to microbes in the mixed liquor. However, less flux compared to inorganic DS and higher fouling propensity on membrane surface as it serves as a food to bacteria are downsides for organic DS (Huang et al., 2018). FO membrane fouling can be alleviated by air scouring, physical cleaning, and osmotic backwashing techniques. As compared to pressurized MF/UF membranes applications FO membranes have less fouling propensity in absence of hydraulic pressure and even loose biofilm or inorganic scalant formation takes place (Pathak et al., 2018a).

Some recently published OMBR research studies for OMPs removal are summarized in shown in Table 23.2.

Table 23.2. Summary of recently published OMBR studies

FO membrane	**Draw solution**	**HRT (h)**	**SRT (d)**	**MLSS (g/l)**	**Water flux (LMH)**	**Bioreactor conductivity**	**OMP**	**Removal (%)**	**Reference**
Plate-and-frame FO membrane Hydration Technology Innovations (HTI, USA) made of cellulose triacetate (CTA)	1 M NaCl	25.25	30	--	11.88	--	CBZ 100 (µg/L)	93.27 ±3.77 %	(Yao et al., 2020)
plate-and-frame FO membrane Hydration Technology Innovations (HTI, USA) made of cellulose triacetate (CTA)	1 M NaCl	25.25	30	--	11.88		CBZ 200 (µg/L)	88.20 ±3.27 %	(Yao et al., 2020)

HTI-CTA FO membrane	075 M NaCl	30	70	3.5	7-5.5	2.5 (g/L)	Caffeine Atrazine Atenolol	94 51 100	(Pathak et al., 2018b)
Cellulose triacetate (CTA) FO membrane (obtained from Hydration Technologies Inc., Oregon, USA)	49.0 g/L NaCl	27.15	50	5.0	5.15 LMH	27.89 mS/cm	500 ng/L Sulfathiazole Sulfamethazine Trimethoprim Norfloxacin Ciprofloxacin Lomefloxacin Enrofloxacin Ofloxacin Tetracycline Oxytetracycline Chlortetracycline Roxithromycin	 98 25 80 62 10 70 100 35 40 30 80 30	(Raghavan et al., 2018)
Cellulose triacetate (CTA) forward osmosis (FO) membranes dye	1M $MgCl_2$	48	--	4.8-10.3	9.63 - 3.65	6800 ± 105 µS cm−1	Lanaset red G. GR refractory acid dye 100 mg/L	100	(Li et al., 2018)*
Cellulose triacetate (CTA) FO Hydration Technology Innovations, HTI (Albany, OR, USA) Side stream AnMBR+FO (AL-FS)	1M MAP	24	--	--	7.58	--	Caffeine Atenolol, Atrazine	95.3 99.5 96.6	(Kim et al., 2017)
Cellulose triacetate (CTA) FO Hydration Technology Innovations, HTI (Albany, OR, USA) Side stream AnMBR+FO (AL-FS)	1M DAP	24	--	--	7.35	--	Caffeine Atenolol, Atrazine	95.9 99.3 96.4	(Kim et al., 2017)
Cellulose triacetate (CTA) FO Hydration Technology Innovations, HTI (Albany, OR, USA) Side stream AnMBR+FO (AL-FS)	1M KCl	24	--	--	11.20	--	Caffeine Atenolol, Atrazine	94.1 99.5 95.1	(Kim et al., 2017)
Cellulose triacetate (CTA) FO Hydration Technology Innovations, HTI (Albany, OR, USA) Side stream AnMBR+FO (AL-DS)	1M MAP	24	--	--	7.58	--	Caffeine Atenolol, Atrazine	90.6 99.7 92.2	(Kim et al., 2017)
Cellulose triacetate (CTA) FO Hydration Technology Innovations, HTI	1M DAP	24	--	--	7.58	--	Caffeine Atenolol, Atrazine	97.5 99.2 98.0	(Kim et al., 2017)

(Albany, OR, USA) Side stream AnMBR+FO (AL-DS)									
Cellulose triacetate (CTA) FO Hydration Technology Innovations, HTI (Albany, OR, USA) Side stream AnMBR+FO (AL-DS)	1M KCl	24	--	--	7.58	--	Caffeine Atenolol, Atrazine	91.8 99.1 94.1	(Kim et al., 2017)

(Li et al., 2018)* Synthetic dye as feed solution rest of all synthetic wastewater

UF-OMBR performance was evaluated for treating oil refinery effluent and two different draw solutes sodium chloride (NaCl) and sodium acetate (CH_3COONa) for long term (505 days). UF membrane helped in salinity buildup mitigation with sodium acetate (5 times) and sodium chloride (10 times) in comparison to OMBR. However, process efficiency declined due to slow degradable or recalcitrant compounds. The raw refinery effluent indicated the presence of highly toxic and recalcitrant compounds, such as polyaromatic hydrocarbons (1413 cm^{-1}), nitrates (3277–3300 cm^{-1}), amide (1653 cm^{-1}), phenol (1248 cm^{-1}) and sulfur containing groups (609 cm^{-1}). Acetate DS is more favoured as compared to NaCl in refractory compound removal. NaCl DS achieved higher flux than acetate DS due to higher biofouling occurrence on membrane in presence of organic DS (Moser et al., 2020). Yao et al. (2020) recently examined carbamazepine (CBZ) degradation in submerged OMBR. Authors reported very high COD and ammonia removal and 88.20 %–94.45 % removal of carbamazepine (CBZ). Further, it was reported that higher carbamazepine concentration was favourable in high COD and ammonia removal. The oxidation, hydroxylation, and decarboxylation were found dominant CBZ degradation mechanism in presence of Delftia as a predominant degradation species. Raghavan et al. (2018) investigated removal of 12 antibiotic (500 ng/L) in OMBR in 40 d time span. They achieved very high removal of TOC (> 98 %) and ammonium (> 97 %). The antibiotic removal was observed from 77.7 to 99.8 %

as FO membrane achieved > 90 % rejection. The biodegradation (16.6 % to 94.4 %) was the dominant removal mechanism followed by biosorption 2 to 30 %. Certain antibiotics showed poor biodegradation such as ofloxacin, ciprofloxacin and roxithromycin. Sulfathiazole, enrofloxacin and chlortetracycline showed the highest removal via biodegradation at 94.4 %, 90.2 %, and 78.9 % respectively.

Li et al. (2018) studied performance of an anaerobic osmotic membrane bioreactor (OMBR) for the biodegradation and decolorization performance of a refractory acid dye, Lanaset red G.GR. Authors reported COD, colour and aniline rejection. COD removal by biodegradation decreased from 73 % to 65 % in 60 days. Similarly color removal by biodegradation reduced from 41 % to 30 %. However overall 99.4 ± 0.1 % COD removal and color removal (100 %) in OMBR was achieved. The reduced biodegradation efficiency could be attributed to the increased solubale microbial products (SMP) and extracellular polymeric substances(EPS) concentration and salt accumulation adversely affected bacterial community. However, at a later stage of operation, in FO permeate dye and dye intermediate molecules were observed including chromophoric groups like aniline. However, authors noticed that the toxic and oxidative intermediate Aniline rejection by CTA FO membrane was only 50 % and aniline like compounds concentration increased by 24 % within 60 days. Kim et al. (2017) assessed removal of three organic micropollutants employing side stream anaerobic membrane bioreactor (AnMBR) combined with side stream CTA-FO membrane in both cases the active layer facing feed solution (AL-FS) and active layer facing draw solution (AL-DS) mode. In AL-DS orientation severe flux decline was observed and this can be attributed to struvite thin layer formation on membrane surface when DAP was used as a DS. In both AL-FS and AL-DS mode DAP as a fertilizer DS outperformed other two fertilizer draw solution in OMPs removal. Authors concluded that the trade-off between high dilution of draw solution (i.e., high water flux and low flux decline) and high OMPs rejection (i.e., low OMPs forward flux) should be considered in fertilizer drawn forward osmosis (FDFO) design and optimization.

23.3.1 Membrane distillation bioreactor (MDBR)

Membrane distillation incorporates hydrophobic microporous membrane operates at low-temperature which involves solely transfer of water vapour from feed side to the distillate side through membrane pores. Due to gas-phase mass transfer, only volatiles could pass through and thus MD completely retains non-volatiles in feed solution (Wijekoon et al., 2014, Curcio and Drioli, 2005). More recently osmotic membrane bioreactor has been studied that integrates membrane distillation and conventional biological system in a single reactor. The direct contact membrane module submerges into the activated sludge tank (Figure 23.1(b)) (Yeo et al., 2015, Phattaranawik et al., 2008). By adjusting 30-38 °C temperature range (40 ± 10 °C optimum for thermophiles), the temperature gradient provides driving force for water vapour to pass through hydrophobic membrane of the MD process. In the submerged configuration, membrane is submerged inside the mixed liquor of the feed solution and the outer surface of hollowfiber remains in the contact with feed. Pure permeate is withdrawn from membrane is collected in the product tank (Phattaranawik et al., 2008). In side stream arrangement (Figure 23.1(a)), reactor feed is continuously pumped to membrane unit and returned to the bioreactor. During this operation at moderately high temperature water vapour has been produced from feed that passes through MD membrane to the collection tank (Neoh et al., 2016). Stricter statutory requirement in particular for OMPs removal could make MDBR as a promising option in wastewater treatment. MD membrane rejects low molecular weight cut off (MWCO) and refractory hydrophilic nature OMPs thereby increasing its organic retention time in a bioreactor (Song et al., 2018, Wijekoon et al., 2014, Yeo et al., 2015). In MDBR process heat transfers from the feed side through the hydrophobic membrane element and then to mixed liquor of the biological reactor. Hence, naturally higher mixed liquor temperature in reactor reduces water viscosity and thereby increases initial water flux through MD membrane. This also increases fouling and scouring of MD membrane that consequently adversely affects permeate quality and leads to elevated fouling and increases operating cost. Furthermore, nitrifiers are too much affected by temperature variations and rise in temperature also adversely affects nitrogen removal process (Morrow et al., 2018).

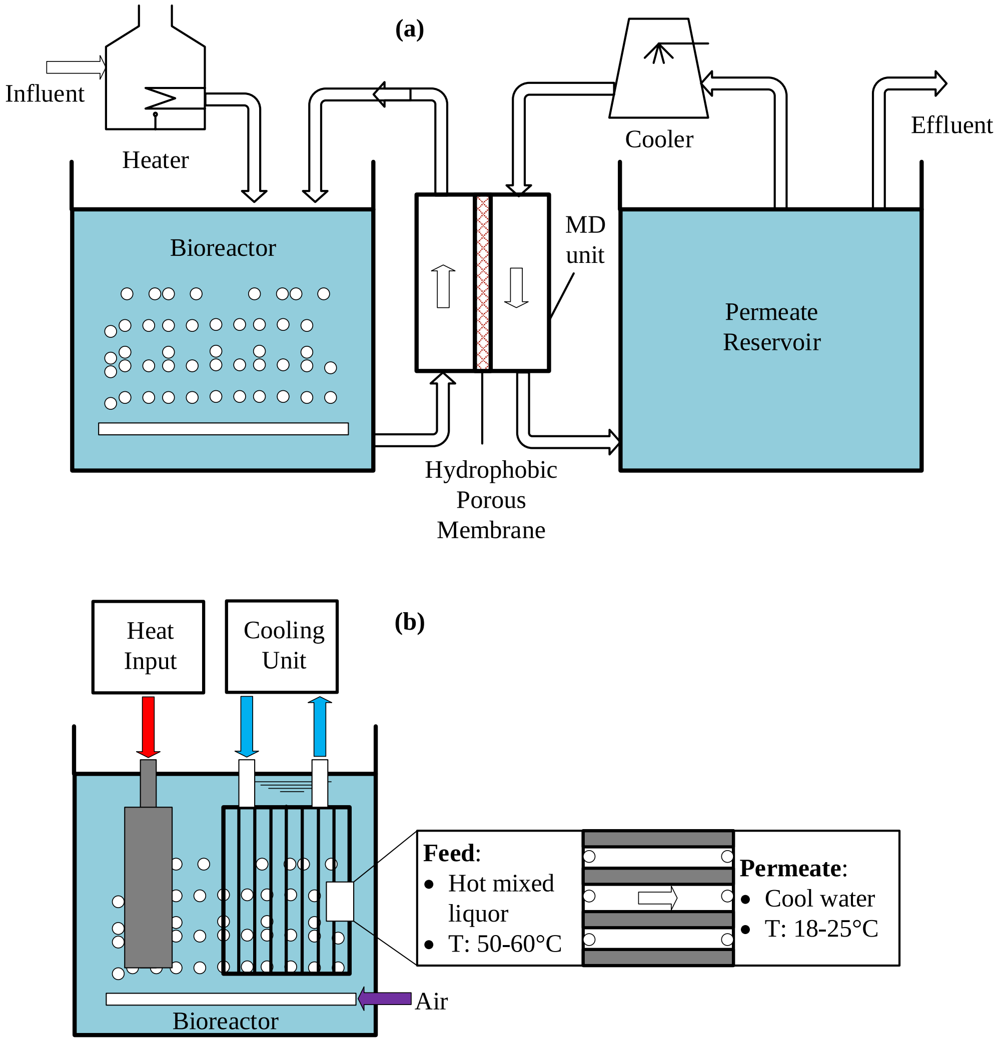

Figure 23.1. Schematic diagram of (a) side stream MDBR process (Neoh et al., 2016) and (b) submerged (Goh et al., 2015).

Table 23.3 Summary of recently published OMBR studies.

Feed solution	**MD membrane**	**Temperature**		**HRT (h)**	**SRT (d)**	**MLSS (g/L)**	**Water flux (LMH)**	**DO (mg/L)**	**OMP**	**Removal (%)**	**Reference**
		Feed °C	Permeate °C								
Synthetic wastewater	PTFE 0.22 µm	50	20-25	--	--	--			Ibuprofen	99	(Asif et al., 2017a)
									Naproxen	99	
									Ketoprofen	99	
									Diclofenac	97	
									Primidone	99	
									Carbamazepine	98	
									Salicylic acid	98	
									Metronidazole	97	
									Gemfibrozil	99	
									Amitriptyline	98	
									Triclosan	100	
									Benzophenone	97	
									Oxybenzone	97	
									Octocrylene	99	
									Fenoprop	98	
									Pentachloro-phenol	98	
									Atrazine	90	
									Propoxur	99	
									Ametryn	97	
									Clofibric acid	99	
									DEET	100	
									4-tert-butylphenol	90	
									Bisphenol A98	98	
									Estrone98	98	
									17β-estradiol99	99	
									17β-estradiol 17–Acetate100	100	
									17α -Ethinylestradiol100	100	
									Estriol (E3)100	100	
									Enterolactone99	99	
Synthetic wastewater	PTFE membrane	45	20	4 d	--	10	--	--*	Amtriptyline	99	(Song et al., 2018)
									Atrazine	74	
									Bisphenol A	85	
									Caffeine	99	
									Carazolol	97	
									Carbamazepine	90	
									Clozapine	99	
									Diazinon	99	
									Diclofenac	75	
									Diuron	99	
									Gemfibrozil	99	
									Ibuprofen	99	
									Ketoprofen	99	
									Linuron	93	
									Naproxen	97	
									Paracetamol	99	
									Phenylphenol	80	
									Primidone	99	
									Propylparaben	91	
									Simazine	79	
									Sulfamethoxazole	89	
									TCEP	92	

								Triamterene	98	
								Triclocarban	95	
								Triclosan	85	
								Trimethoprim	99	
Synthetic wastewater	PTFE side stream	40	14	9.6 d	5.3	1.2	2.8	17α-Ethinylestradiol	99	(Wijekoon et al., 2014)
								17β-Estradiol	100	
								17β-Estrodiol-17-acetate	100	
								4-Tert-butyphenol	98	
								Ametryn	99	
								Amitriptyline	99	
								Atrazine	96	
								Benzophenone	97	
								Carbamazepine	96	
								Clofibric acid	100	
								Diclofenac	95	
								Estriol	98	
								Estrone	100	
								Fenoprop	97	
								Gemfibrozil	98	
								Ibuprofen	100	
								Ketoprofen	99	
								Naproxen	100	
								Octocrylene	97	
								Oxybenzone	99	
								Pentachlorophenol	97	
								Primidone	100	
								Propoxure	100	
								Salicylic acid	96	
								Triclosan	98	
Synthetic wastewater	PTFE side stream MD	30	10			3.75	3	Sulfamethoxazole	>99%	(Asif et al., 2017b)
								Carbamazepine	>99%	
								Diclofenac	>99%	
								Oxybenzone	>99%	
								Atrazine	>99%	
Synthetic wastewater		30	10	4 d		4	3	17α–Ethinylestradiol	98	(Asif et al., 2018)
								17β–Estradiol	98	
								17β-Estradiol-17-acetate	98	
								4-tert-Butylphenol	98	
								Ametrine	94	
								Amitriptyline	99	
								Atrazine	92	
								Benzophenone	99	
								Bisphenol A	96	
								Carbamazepine	99	
								Clofibric acid	99	
								DEET	94	
								Diclofenac	96	
								Enterolactone	96	
								Estriol	97	
								Estrone	99	
								Fenoprop	99	
								Gemfibrozil	98	
								Ibuprofen	98	
								Ketoprofen	98	
								Metronidazole	98	
								Naproxen	99	
								Octocrylene	99	
								Oxybenzone	94	
								Pentachlorophenol	97	
								Primidone	99	
								Propoxur	95	
								Salicylic acid	96	
								Triclosan	97	

The enzyme laccase in presence of oxygen as a co-substrate can catalyze recalcitrant molecules including organic micropollutants. Asif et al. (2017b) evaluated performance of membrane distillation with an enzymatic bioreactor (MD-EMBR) to examine removal of phenolic and non-phenolic OMPs. This hybrid reactor achieved 90–99 % OMPs removal. The removal was correlated with electron donating group (EDG) and electron withdrawing group (EWG) of the OMPs. The OMPs having EDG demonstrated more than 90 % removal while EWG OMPs achieved 40-75 % removal. Further, addition of redox mediator and OMPs removal was studied. Violuric acid (VA) redox mediator outperformed among syringaldehyde (SA), violuric acid (VA) and 1-hydroxybenzotriazole (HBT) mediators in OMPs removal.

Wijekoon et al. (2014) evaluated performnac eof membrane distillation biorwactor (MDBR) in OMPs removal and concluded that 95 % of OMPs can removed by this process and biodegradation contributed to 70 % of OMPs removal. Actually, high temperature and salinity can adversely affect the performance of MDBR. Triclosan, fenoprop, atrazine, clofibric acid, diclofenac, and carbamazepine compound could be retained by MD membrane in the range of 42 to 94 %. The hydrophilic compounds having EWGs in their structure are more resistant to biodegradation and they were poorly degradable compounds in the range of 0 to 53 %. Song et al. (2018) examined performance of anaerobic membrane bioreactor-membrane distillation in OMPs removal. This hybrid process accomplished 75 % to 100 % removal of 26 OMPs studied. Authors notice that recalcitrant compounds such as bisphenol A, diclofenac, ibuprofen, and primidone effectively retained by MD membrane followed by further degradation in AnBR process.

3 Life cycle assessment (LCA) of hybrid MBRs

Life cycle assessment (LCA) is a significant tool to measure environmental impact of different wastewater treatment schemes to compare their performances in terms of energy, green house emission, and cost components (Krzeminski et al., 2017). However, the LCA of MBRs and advanced hybrid MBRs are limited to few studies. Ortiz et al. (2007) evaluated environmental impact analysis of different wastewater treatment schemes designed to accommodate 13200 population equivalent (P.E.). In order to find the lowest environmental load of treatment schemes authors used Simapro 5.1 software. Authors considered activated sludge process (ASP) standalone and ASP combined with advanced treatment, membrane bioreactors both side stream and submerged. LCA analysis results suggested that ASP with advanced treatment had highest environmental loads. It was apparent that side stream MBR had higher environmental load as compared to submerged MBR due to its high energy consumption in pump operation. In general, environmental impact resulting from plant operation remains higher than arising from construction, maintenance and final disposal aspects.

Further, Krzeminski et al. (2017) evaluated performances of four membrane processes namely aerobic MBR, anaerobic MBR, biofilm MBR and osmotic membrane bioreactor. Aerobic MBR can produce highest quality of permeate of direct reuse applications and able to meet stringent prescribed standards and less effect on marine and fresh water eutrophication. Nevertheless, operating costs in terms of frequent membrane cleaning and higher energy for aeration implies larger carbon emission which are higher for MBRs. In order to reduce environmental loads sludge to biogas production and use of renewable energy alternatives could be explored installing anaerobic MBRs that operates in absence of oxygen (no aeration cost). Yet, in sewage treatment plant 30-40 % methane seepage was observed that further contributed to GHG emissions. In AnMBR the COD and nutrient removal is low as compared to aerobic MBRs and it is more sensitive to shock loads and demands more skilful operations. The biofilm MBRs consumes more DO to achieve complete nitrification. It is more energy intensive and carbon foot print is also large. In recent years OMBRs has gained more attention in both academia and industrial application due to very low energy consumption, excellent effluent quality for direct and indirect reuse applications and efficient organic micropollutnat removal. OMBR exploits osmotic pressure of draw solution as a driving force hence compared to other hydraulic MF/UF membranes processes incurs very low energy consumption. OMBR can effectively remove phosphorous and ammonium but it could not remove nitrite totally. Table 23.4 below shows various MBR configuration and their anticipated environmental load.

Table 23.4 Comparison of the performance of MBR, AnMBR, BF-MBR, MABR and FO-MBR against energy demand and their impact on climate change, fresh water and marine eutrophication (Krzeminski et al., 2017).

Process type	**Energy related emissions**	**Climate change impact**	**Fresh water eutrophication**	**Marine eutrophication**
MBR	High	High	Low	Low
AnMBR	Low	High	High	High
BF-MBR	High/ medium	High/ medium	Medium	Low
FO-MBR	Medium	Medium	Low	Low/Medium

Holloway et al. (2016a) compared performance of UF-OMBR hybrid system (Figure 23.2) with advanced wastewater treatment in sewage treatment to obtain pure water for reuse application that employed activated sludge treatment combined with MF/UF membrane, reverse osmosis

(RO), and ultraviolet reactor. The UF-OMBR consisted of UF and FO membrane in bioreactor. UF produced non-potable reuse water while FO produced potable quality water.

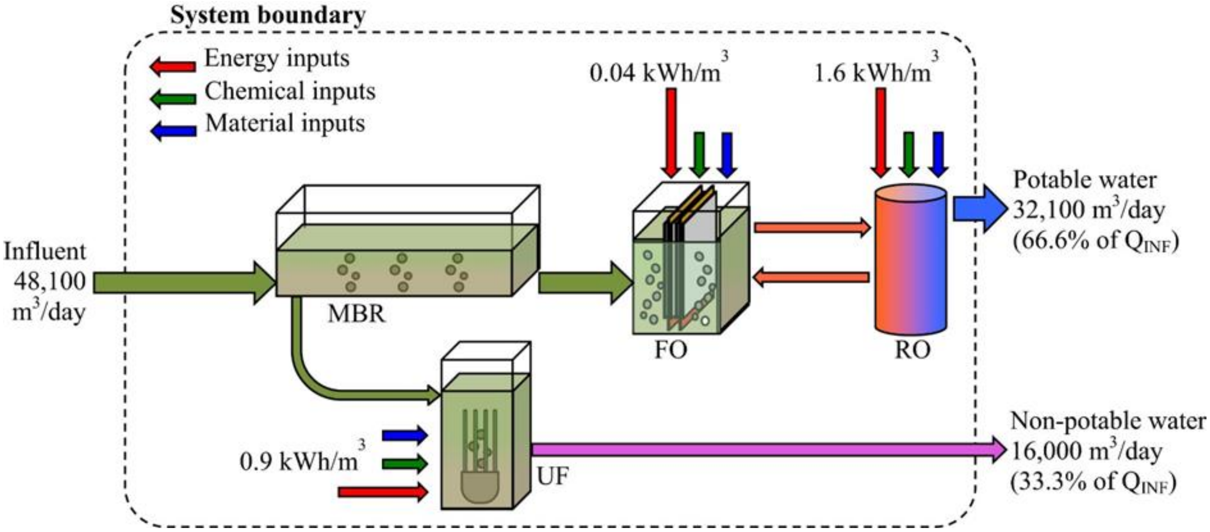

Figure 23.2. Schematic drawing of system boundary, flows, unit processes, and energy, materials, and chemical inputs used for the LCA of a UFO-MBR treatment plant. The illustrated RO power is for an RO system without energy recovery, producing an RO brine of 40 g/L NaCl. The energy usage for the MBR component (activated sludge and UF/FO membrane aeration) of the UFO-MBR is included in the UF energy (Holloway et al., 2016b).

Wastewater-Energy Sustainability Tool (WWEST), LCA program considered energy use, GHG emissions, and other environmentally relevant emissions to compare process performances. Authors compared both treatment technologies by taking into account construction cost, chemical inventory, and electricity to assess energy demand and environmental impact of both treatment schemes. The hybrid advanced treatment process outperformed UF-OMBR based on this LCA analysis. UF-OMBR exhibited higher environmental load arising from the larger footprint and lower permeability FO membranes and higher energy consumption from RO regeneration. However, UF-OMBR optimisation based on 40 g/L NaCl DS concentrations among (20, 30, 40, and 50 g/L NaCl) and demonstrated that both processes had very much similar environmental loads when higher permeability FO membranes and RO energy recovery system were implemented. This outcome further reinforces scope of OMBR in water reuse applications (Holloway et al., 2016b). Further, authors reported that UF-OMBR process could have accomplished much lower environmental impact if nitrogen/phosphorous recovery would have realised with scale up of the process. However, UF-OMBR has potential to become fourth generation advanced wastewater reclamation alternative provided FO membrane development and OMBR process optimisation will be accomplished (Holloway et al., 2016b).

Conclusion

This book chapter on advanced membrane bioreactor hybrid systems explores two recently examined advance hybrid systems of osmotic membrane bioreactor and membrane distillation bioreactor. The chapter focus on water scarcity issues and wastewater reuse alternatives followed by fate and transport of organic miropolluatnts in wastewater. A comparison table for MBR, OMBR and OMBR is presented. Recent reports on OMBR and MDBR in OMPs removal are tabulated. The life cycle assessment for MBR and advance hybrid technologies are discussed. The high permeability FO/MD membrane, scale up module and optimisation of reactor design to produce reclaimed water with nutrient recovery applications need to be explored to reduce environmental load (Blandin et al., 2018).

Table Legend

Table 23.1. Comparison for MBR, OMBR and MDBR in wastewater treatment (Barbosa et al., 2016, Mert et al., 2018, Neoh et al., 2016, Goh et al., 2015, Bharwada, 2011)

Table 23.2. Summary of recently published OMBR studies

Table 23.3 Summary of recently published MDBR studies

Table 23.4 Comparison of the performance of MBR, AnMBR, BF-MBR, MABR and FO-MBR against energy demand and their impact on climate change, fresh water and marine eutrophication (Krzeminski et al., 2017).

Figure Legend

Figure 23.1. Schematic diagram of (a) side stream MDBR process (Neoh et al., 2016) and (b) submerged (Goh et al., 2015)

Figure 23.2. Schematic drawing of system boundary, flows, unit processes, and energy, materials, and chemical inputs used for the LCA of a UFO-MBR treatment plant. The illustrated RO power is for an RO system without energy recovery, producing an RO brine of 40 g/L NaCl. The energy usage for the MBR component (activated sludge and UF/FO membrane aeration) of the UFO-MBR is included in the UF energy (Holloway et al., 2016b)

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