Understanding the mechanisms of trace organic contaminant removal by high retention membrane bioreactors: A critical review

Muhammad B. Asif [a], Ashley J. Ansari [a], Shiao-Shing Chen [b], Long D. Nghiem [a,c], William E. Price [d], Faisal I. Hai [a]*

[a] Strategic Water Infrastructure Lab, School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia.

[b] Institute of Environmental Engineering and Management, National Taipei University of Technology, Taipei 10608, Taiwan.

[c] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia

[d] Strategic Water Infrastructure Lab, School of Chemistry, University of Wollongong, Wollongong, NSW 2522, Australia.

***Corresponding author:** Faisal I. Hai (E-mail: faisal@uow.edu.au; Tel: +61 2 42213054)

Abstract:

High retention membrane bioreactors (HR-MBR) combine a high retention membrane separation process such as membrane distillation, forward osmosis or nanofiltration with a conventional activated sludge (CAS) process. Depending on the physicochemical properties of the trace organic contaminants (TrOCs) as well as the selected high retention membrane process, HR-MBR can achieve effective removal (80-99%) of a broad spectrum of TrOCs. An in-depth assessment of the available literature on HR-MBR performance suggests that compared to CAS and conventional MBRs (using micro- or ultrafiltration membrane), aqueous phase removal of TrOCs in HR-MBR is significantly better. Conceptually, longer retention time may significantly improve TrOC biodegradation, but there are insufficient data in the literature to evaluate the extent of TrOC biodegradation-improvement by HR-MBR. The accumulation of hardly biodegradable TrOCs within the bioreactor of an HR-MBR system may complicate further treatment and beneficial reuse of sludge. In addition to TrOCs, accumulation of salts gradually increases the salinity in bioreactor and can adversely affect microbial activities. Strategies to mitigate these limitations are discussed. A qualitative framework is proposed to predict the contribution of the different key mechanisms of TrOC removal (*i.e.*, membrane retention, biodegradation and sorption) in HR-MBR.

Keywords: High retention membrane bioreactors; trace organic contaminants; removal mechanisms; predictive framework; membrane distillation (MD), forward osmosis (FO); nanofiltration (NF)

Introduction

Wastewater treatment and reuse are important strategies to mitigate pollution and water scarcity (Tang et al. 2018) . For safe water reuse applications, effective removal of a wide range of pollutants including bulk organics, salts, nutrients and trace organic contaminants (TrOCs) is essential. Among these pollutants, the effective removal of TrOCs such as pharmaceuticals, pesticides, steroid hormones, industrial chemicals and ingredients of personal care products is one of the most challenging aspects of wastewater treatment and reuse as conventional activated sludge (CAS) based wastewater treatment plants were not designed for their removal (Hai et al. 2014b, Radjenović et al. 2009). Since TrOCs are potentially harmful to the aquatic ecosystems and human health (Alexander et al. 2012, Asif et al. 2018c, Hai et al. 2018, Schwarzenbach et al. 2006), development of a wastewater treatment process for effective removal of TrOCs has gained significant interest in the recent years.

Membrane bioreactors (MBR) have been extensively studied over the last decade due to their potential of producing high quality effluent that may be suitable for water reuse applications (Bouju et al. 2008, Hai et al. 2014a, Hai et al. 2014c, Melin et al. 2006). In conventional MBR, activated sludge is responsible for the degradation of the pollutants such as bulk organics, nutrients and TrOCs, while micro- or ultrafiltration (MF/UF) based membrane separation process effectively retains the activated sludge within the bioreactor (Hai et al. 2011b, Jegatheesan &Visvanathan 2014, Reif et al. 2008). Conventional MBR can achieve efficient aqueous phase removal of bulk organics from wastewater (Judd 2014, Judd 2016, Radjenović et al. 2008a). However, the ineffectiveness of conventional MBRs for the removal of certain groups of TrOCs is a significant concern. For effective removal of TrOCs, high retention membrane separation processes such as nanofiltration (NF)/reverse osmosis (Alturki et al. 2010, Wang et al. 2015) and membrane distillation (Jacob et al. 2015, Song et al. 2018a, Wijekoon et al. 2014a) have been combined with conventional MBRs as a post-treatment step. To avoid an additional high retention membrane separation process, the high retention (HR)-MBRs have been developed which can achieve TrOC retention by membrane and subsequent biodegradation in a single step for the production of high quality effluent suitable for water reuse applications (Luo et al. 2014).

HR-MBR combines the high retention membranes such as nanofiltration (NF), forward osmosis (FO) or membrane distillation (MD) with an activated sludge process. Available studies report that HR-MBR provides effective removal of a wide range of TrOCs and can produce high quality TrOC-free effluent stream (Luo et al. 2017b, Wijekoon et al. 2014b). One of the underlying rationales for the development of HR-MBR was that the effective retention of pollutants within the bioreactor may facilitate biodegradation due to the prolonged contact time between the activated sludge and TrOCs. Despite the effective TrOC retention by the high retention membranes (Luo et al. 2017b, Wang 2013), degradation of TrOCs by activated sludge within the bioreactor has not been reported to consistently improve (Luo et al. 2017b, Wijekoon et al. 2014b). This is because the degradation of TrOCs by the activated sludge depends on their intrinsic biodegradability that is governed by their physicochemical properties such as chemical structure and hydrophobicity (Hai et al. 2014b).

A few excellent reviews on the main features, overall performance and technological constraints of HR-MBR have been published recently (Blandin et al. 2018, Luo et al. 2014, Song et al. 2018b, Yeo et al. 2015). However, removal of TrOCs by HR-MBR and factors affecting the removal of TrOCs by the activated sludge in HR-MBR have not been critically reviewed and discussed. This review aims to critically analyze the removal of TrOCs by the high retention membranes and activated sludge in HR-MBR. In addition, mechanisms of TrOC removal by HR-MBR are systematically elucidated. Based on the contribution of each mechanism of TrOC removal, a qualitative predictive framework is proposed. Finally, future research directions are identified and discussed.

HR-MBR configurations

In addition to the use of high retention membranes that allows effective retention of pollutants including TrOCs, HR-MBRs may have different features compared to the conventional MBR configuration (Figure 1a). Three configurations of HR-MBR, namely membrane distillation (MD)-MBR (Figure 1b), forward osmosis (FO)-MBR (Figure 1c) and nanofiltration (NF)-MBR (Figure 1d) have been investigated to-date (Luo et al. 2017b, Phan et al. 2016b, Wijekoon et al. 2014b).

[Figure 1]

Mechanisms of TrOC removal by HR-MBR include: (i) membrane retention; (ii) biodegradation; (iii) sorption; (iv) air stripping/volatilization; and (v) photolysis (Hai et al. 2014b, Pomiès et al. 2013, Verlicchi et al. 2012). Removal of TrOCs by volatilization depends on the Henry's constant (H), which is the ratio of the concentration of a target pollutant in air to its concentration in wastewater. It has been reported that the removal of target pollutants *via* volatilization can be significant (5-10%) if their H values are higher than 0.005 (Joss et al. 2006, Park et al. 2017, Stevens-Garmon et al. 2011). Since the values of H for TrOCs generally fall in the range of 10^{-6} to 10^{-10}, TrOC removal in HR-MBR *via* volatilization is insignificant. Similarly, contribution of photolysis is negligible due to the high mixed liquor suspended solids (MLSS) concentration in the bioreactor (Trinh et al. 2016, Wijekoon et al. 2014b). Hence, biodegradation, sorption and membrane retention mechanisms primarily contribute in varying extent for TrOC removal by HR-MBR as discussed in the following sub-sections.

Mechanisms of TrOC removal by high retention membranes

Retention by high retention membrane appears to be the most dominant mechanism for removal of TrOCs that are resistant to degradation by the activated sludge. Therefore, understanding the mechanisms of TrOC removal by MD, NF and FO membranes is vital. TrOC retention/removal by high retention membranes depends on: (i) the type of high retention membrane; (ii) influent characteristics; and (iii) operating conditions (Table 1). TrOC retention by NF and FO membranes has been reported to be influenced by a number of factors (Table 1) such as physicochemical properties (*e.g.*, hydrophobicity, charge and molecular weight) of TrOCs, operating parameters and membrane properties as explained below (Bellona et al. 2004, Hau et al. 2014, Nghiem &Coleman 2008, Nghiem et al. 2005). On the other hand, TrOC retention by MD membranes depends on the volatility (pK_H) and hydrophobicity (log D) of pollutants (Luo et al. 2014, Wijekoon et al. 2014a), thereby making TrOC retention by MD membrane simpler as compared to NF and FO membranes. In a stand-alone MD process, 'pK_H/log D' ratio of less than 2.5 corresponds to ineffective TrOCs retention (50-70%), while TrOCs with a high pK_H/log D ratio (>2.5) are effectively retained (90-99%) by MD membranes (Wijekoon et al. 2014a)

[Table 1]

Mechanisms of TrOC retention by NF and FO membrane consist of: (i) the net sorption of a solute on the membrane surface; (ii) the transport of solute inside the membrane; and (iii) the sieving property of the membrane (Coday et al. 2014, Luo et al. 2014, Nghiem et al. 2006). Influence of other factors including hydrophobicity and charge repulsion on sorption and solute transport has also been observed (Agenson et al. 2003, Taheran et al. 2016). In general, size exclusion mechanism is responsible for the retention of non-ionic and hydrophilic (log D <3) TrOCs, and the extent of retention depends on the molecular weight cut-off (MWCO) of membranes. For example, a tight NF membrane (MWCO <200 g/mole) achieved 97% retention of carbamazepine (log D = 1.89) from a filtered lake water containing a mixture of 22 TrOCs, while only 50% removal was observed by a loose NF membrane (MWCO >300 g/mole) (Comerton et al. 2008). In another study by Xie et al. (2012b), retention of carbamazepine by a cellulose triacetate FO membrane remained in between 80 and 90% at different pH values (*i.e.,* 3.5-7.5). Similarly, carbamazepine retention by cellulose triacetate and thin film composite polyamide FO membranes was reported to be 90-95% (Jin et al. 2012). Effective retention (80-99%) of other hydrophilic TrOCs such as metronidazole (log D = -0.14), clofibric acid (log D = -1.06) and N, N-Diethyl-meta-toluamide (DEET, log D = 2.42) by NF and FO membranes has been reported (Alturki et al. 2010, Cath et al. 2010, Linares et al. 2011, Valladares et al. 2011, Verliefde et al. 2009). Hydrophobic TrOCs (log D >3) such as steroid hormones, bisphenol A and 4-tert-octylphenol have also been reported to be effectively retained (>80%) by both NF and FO membranes (Alturki et al. 2013, Nghiem &Coleman 2008, Verliefde et al. 2009). Notably, hydrophobicity of TrOCs can influence their retention because hydrophobic TrOCs can adsorb onto the membrane surface, thus initially resulting in their effective retention. However, as the filtration continues, their retention may reduce due to their subsequent diffusion into the permeate (Nghiem &Coleman 2008, Verliefde et al. 2009). Compared to hydrophilic TrOCs, hydrophobic TrOCs, regardless of their size, can diffuse into the permeate to attain an equilibrium between the concentration of hydrophobic TrOCs on/near the membrane surface and the permeate. This gradually reduces the extent of TrOC retention by the NF and the FO membranes (Hu et al. 2007, Verliefde et al. 2007, Xie et al. 2012a). Once an equilibrium between the concentration of TrOCs on/near membrane surface and permeate is established, the role of adsorption in TrOC retention diminishes, and charge repulsion and size exclusion mechanisms govern the retention of TrOCs by NF and FO membranes (Coday et al. 2014, Yoon et al. 2006).

NF and FO membranes are negatively charged at pH=7 owing to the protonation of their functional groups (Coday et al. 2014, Comerton et al. 2008). Hence, membrane surface charge and its interaction with charged TrOCs such as diclofenac, naproxen and ibuprofen will govern the extent of their retention. Poor rejection of positively charged hydrophobic TrOCs such as steroid hormones by NF/FO membrane can be attributed to the attraction between positively charged TrOCs and negatively charged membrane surface. This consequently increases the concentration of solute at the surface of membrane, thus increasing their diffusion into permeate. On the other hand, effective retention of negatively charged hydrophilic TrOCs is due to the charge repulsion mechanism, which keeps TrOCs away from the membrane surface (Kimura et al. 2004, Radjenović et al. 2008b, Verliefde et al. 2007). Notably, the transformation of neutral TrOCs to negatively charged TrOCs at $pH>pK_a$ can improve their retention by NF and the FO membranes. For example, an increase of 50 and 65% in the retention of sulfamethoxazole ($pK_a = 5.6$) and ibuprofen ($pK_a = 4.47$), respectively, by a thin film composite NF membrane was observed when the feed pH was changed from 5 to 10 (Nghiem et al. 2006). In another study, retention of ibuprofen ($pK_a = 4.47$) and naproxen ($pK_a = 4.2$) by an FO membrane was observed to be increased by 10-15% due to the increase in the pH of feed from 6 to 8 (*i.e.,* $pH>pK_a$) (Jin et al. 2012). Based on the discussion regarding the factors affecting the retention of TrOCs by NF and FO membrane, a qualitative predictive framework is presented in Figure 2.

[Figure 2]

Aqueous phase removal of TrOCs by HR-MBR

As mentioned before, three configurations of HR-MBR, namely membrane distillation bioreactor (MDBR), forward osmosis (FO-MBR) and nanofiltration (NF-MBR) have been investigated to-date (Fernandez-Fontaina et al. 2012, Luo et al. 2017b, Phan et al. 2016b, Wijekoon et al. 2014b). Depending on the physicochemical properties of TrOCs and the type of HR-MBR configuration, removal of TrOCs by HR-MBRs can range between 90-99% (Table 2).

[Table 2]

The advantage of an integrated biodegradation and membrane separation process is that HR-MBR can achieve better TrOC removal as compared to the standalone HR-membrane. For instance, Wijekoon et al. (2014a) studied the rejection of a mixture of 30 TrOCs by a standalone MD process, and observed partial retention (50-70%) of a few volatile TrOCs (pK_H <9) such as 4-tert-octylphenol (pK_H= 5.06), benzophenone (pK_H= 5.88) and amitriptyline (pK_H= 8.18). On other hand, when the performance of MDBR was studied for the removal of a mixture of 30 TrOCs, effective removal (95-99%) was achieved by MDBR for all the selected 30 TrOCs including those partially removed by the standalone MD process (Wijekoon et al. 2014a, Wijekoon et al. 2014b).

Compared to ineffective or unstable removal of a few hydrophobic TrOCs such as bisphenol A (40-80%), oxybenzone (70-75%), estrone (80%), and 17α – ethynylestradiol (70-90%) by a standalone FO process (Coday et al. 2014), FO-MBR has been reported to achieve above 99% removal for hydrophobic TrOCs (Luo et al. 2015b, Luo et al. 2017b). Better performance of MDBR and FO-MBR for TrOC removal as compared to the standalone MD and FO process can be attributed to the efficient degradation of volatile and hydrophobic TrOCs such as 4-tert-octylphenol, benzophenone, triclosan, bisphenol A and oxybenzone by the activated sludge (Holloway et al. 2014, Luo et al. 2015b, Wijekoon et al. 2014b).

Both MDBR and FO-MBR was reported to achieve effective removal of a range of TrOCs (Table 2) (Li et al. 2018, Luo et al. 2014). Indeed, a comparison of the aqueous phase removal of TrOCs by CAS, conventional MBR and HR-MBR reveals that median TrOC removal by HR-MBR is almost 90%, while median values for CAS and MBR are approximately 60 and 65%, respectively (Figure 3).

[Figure 3]

Factors affecting TrOC removal by activated sludge in HR-MBR

Effect of TrOC molecular structure

Degradation of TrOCs by activated sludge depends on their intrinsic biodegradability and sorption potential. The extent of TrOC degradation can vary depending on the chemical structure of the target compound (Luo et al. 2015b, Tadkaew et al. 2011). In general, simple structured TrOCs without branched/multi chain alkyl groups are readily biodegraded compared to structurally complex TrOCs due to their resistance to microbial degradation. Similar to conventional MBR, TrOCs containing strong electron withdrawing functional groups (EWG) such as carboxyl, halogen and amide are resistant to biodegradation, and their degradation is also poor and/or unstable in HR-MBR (Phan et al. 2016b, Wijekoon et al. 2014b). For instance, atrazine, carbamazepine and diclofenac are resistant to biodegradation due to the presence of EWGs (*i.e.*, halogen and amide) in their structures (Nguyen et al. 2013a, Tadkaew et al. 2011).

Based on their biodegradation, TrOCs can be divided into three categories: (i) low or unstable removal (5-30%) for TrOCs containing strong EWGs such as atrazine, carbamazepine and primidone; (ii) consistently high removal (80-90%) of hydrophobic TrOCs containing electron donating groups (EDGs) such as steroid hormones; and (iii) poor to moderate removal (30-80%) of hydrophilic TrOC containing both EWGs and EDGs (Luo et al. 2017a, Phan et al. 2016b, Wijekoon et al. 2014b). Limited degradation of some TrOCs by the activated sludge highlights the significance of high retention membranes in effective TrOC removal for producing a high quality effluent. Specific groups of TrOCs that are poorly degraded by the activated sludge accumulate within the bioreactor of HR-MBR.

Effect of TrOC sorption on activated sludge

Hydrophobic TrOCs (log D>3) can adsorb onto the activated sludge by following mechanisms: (i) chemical binding to bacterial proteins and nucleic acids; (ii) sorption onto polysaccharide structures outside the bacterial cell; (iii) adsorption onto bacterial lipid structure (Semblante et al. 2015). With a few exceptions, HR-MBR can achieve as high as 99% removal of hydrophobic TrOCs *via* biodegradation and sorption (Holloway et al. 2014, Wijekoon et al. 2014b). Additionally, non-hydrophobic interactions such as hydrogen bonding, electrostatic interactions and ion exchange can also instigate sorption of hydrophilic TrOCs onto activated sludge. For instance, Wijekoon et al. (2014b) observed that sorption significantly contributed to the removal of a hydrophilic TrOC salicylic acid (log D = -1.22).

Sorption on activated sludge contributes to improvement of overall aqueous phase removal of TrOCs in conventional MBRs (Lay et al. 2012, Mascolo et al. 2010, Phan et al. 2015a, Phan et al. 2015b, Stevens-Garmon et al. 2011). For instance, halogenated TrOCs are widely reported to be persistent to microbial degradation. However, the increase in halogen-content increases the hydrophobicity of halogenated TrOCs (Hai et al. 2011a). Thus efficient removal of halogenated TrOCs, particularly of triclosan, have been reported to be achieved by even conventional

MBRs due to its sorption onto activated sludge (Hai et al. 2014b, Tadkaew et al. 2011, Wijekoon et al. 2013). Although sorption also contributes to the removal of TrOCs within the bioreactor of HR-MBRs, the overall TrOC removal by HR-MBR is less dependent on sorption because of the high retention membranes which can retain even the TrOCs demonstrating low sorption on sludge.

Following sorption onto the activated sludge, the extent of TrOCs degradation depends on their intrinsic biodegradability (Hai et al. 2014b). For instance, Wijekoon et al. (2014b) observed higher concentrations of two highly hydrophobic TrOCs, namely triclosan and octocrylene in the sludge samples of an MDBR as compared to other hydrophobic TrOCs such as bisphenol A and steroid hormones. This is because of the presence of strong EWGs in the molecular structure of triclosan and octocrylene *i.e.*, halogen and carbonyl, respectively (Hai et al. 2014b, Tadkaew et al. 2011).

Effect of mixed liquor suspended solids concentration

Conceptually, mixed liquor suspended solid (MLSS) concentration may affect the removal of TrOCs in a biological process by influencing the rate of biodegradation. However, biodegradation also depends on TrOC physicochemical properties and diversity of microbial communities (Phan et al. 2014, Phan et al. 2016a, Trinh et al. 2012). Indeed biodegradation of TrOCs containing EDGs in their molecular structure (*i.e.*, easily biodegradable) has been reported to be 80-99% in conventional MBRs at the tested MLSS concentrations ranging from 2-15 g/L (He et al. 2013, Sui et al. 2011, Tadkaew et al. 2010, Tambosi et al. 2010). Similarly, effective degradation (90-99%) of TrOCs containing EDGs such as naproxen, ketoprofen, bisphenol A and t-octylphenol has been achieved in NF-MBR, FO-MBR and MDBR over MLSS concentrations of 2-5 g/L (Luo et al. 2017b, Phan et al. 2016b, Wijekoon et al. 2014b). Holloway et al. (2014) also achieved 95-99% degradation of TrOCs containing strong EDGs such as naproxen, oxybenzone, ibuprofen and caffeine by operating an FO-MBR at a MLSS concentration of 3-4 g/L.

Degradation of hydrophilic TrOCs containing EWGs in conventional MBR has been reported to be poor irrespective of operating MLSS concentrations (Clara et al. 2005, Kim et al. 2007, Li et al. 2011, Trinh et al. 2012, Xue et al. 2010). Similarly, poor and unstable degradation (15-40%) by the activated sludge in HR-MBR has been reported for hydrophilic TrOCs containing EWGs such as carbamazepine, DEET and atrazine (Luo et al. 2015b, Phan et al. 2016b).

Effect of solids retention time

Solids retention time (SRT) governs the microbial makeup of a bioreactor. Conceptually, long SRT may improve the extent of TrOC removal by providing adequate time for the development of special TrOC degrading microbial communities (Feki et al. 2009, Maeng et al. 2013, Phan et al. 2014). Indeed, biodegradation of a few resistant TrOCs such as sulfamethoxazole, diclofenac, mefenamic acid and carbamazepine improved significantly following an increase in the SRT of conventional MBR (Figure 4). The biodegradation of resistant TrOCs containing strong EWGs varied depending on the type of HR-MBR configuration. For instance, FO-MBR (SRT = 20 days) achieved better degradation of carbamazepine, atrazine, clofibric acid, fenoprop and diclofenac as compared to MDBR (SRT = 88 days) (Luo et al. 2017b, Phan et al. 2016b, Wijekoon et al. 2014b). Disrupted metabolic activities associated with the treatment in thermophilic conditions may have resulted in less effective degradation of resistant TrOCs by MDBR (Tran et al. 2013, Wijekoon et al. 2014b). However, a systematic study is necessary to determine the actual reasons of these observations.

As expected, no improvement was observed in the degradation of easily biodegradable TrOCs containing EDGs such as naproxen, ketoprofen and ibuprofen by increasing the SRT of a conventional MBR beyond 15 days (Kimura et al. 2007, Radjenovic et al. 2007, Tambosi et al. 2010, Wijekoon et al. 2013). Similarly, no observable effect of SRT on the degradation of TrOCs such as naproxen, ketoprofen, ibuprofen, bisphenol A and 4-tert-octylphenol has been reported in HR-MBRs over a wide range of SRTs (Holloway et al. 2014, Lay et al. 2010, Phan et al. 2016b, Wijekoon et al. 2014b).

[Figure 4]

Effect of operating temperature

To date lab-scale FO- and NF-MBRs have been operated at the room temperature *i.e.,* 18-21 ºC, while the operating temperature of MDBR falls in the thermophilic range *i.e.,* 40-60 ºC (Goh et al. 2013, Holloway et al. 2015, Phan et al. 2016b, Wijekoon et al. 2014b). As noted in the previous section, relatively less degradation of a few hydrophilic TrOCs such as carbamazepine, atrazine, clofibric acid, fenoprop and diclofenac has been observed in MDBR as compared to FO-MBR (Luo et al. 2017b, Wijekoon et al. 2014b). This can be attributed to the higher operating temperature of MDBR which can disrupt microbial activities. Particularly, high operating temperature (>35 ºC) can affect TrOC degradation by reducing the abundance of nitrifying bacteria (Gao et al. 2013, Shore et al. 2012, Zhang et al. 2009). In conventional MBR, improvement in TrOC removal has been reported to concur with the achievement of efficient nitrification (Estrada-Arriaga &Mijaylova 2011). To provide further insight into this aspect, the effect of thermophilic conditions on the microbial diversity and TrOC removal in various formats of HR-MBR should be further investigated.

Fate of TrOCs in HR-MBR

Effective retention of TrOCs (90-99%) within the bioreactor of HR-MBR by the high retention membranes may facilitate their biodegradation due to the prolonged contact time between the activated sludge and TrOCs. Indeed, comparing data from independent studies, degradation of some TrOCs seems to be more stable in HR-MBR as compared to conventional MBR and CAS (Figure 5). The degradation improvement for these TrOCs in HR-MBR is discernible, however, not very high. An assessment of the relative contribution of different mechanisms of TrOC removal suggests that membrane retention and biodegradation govern the effectiveness of treatment by HR-MBR (Figure 6). According to the available literature, TrOC removal in HR-MBR *via* sorption onto activated sludge ranges between 1-10% and 2-30% for hydrophilic and hydrophobic TrOCs, respectively.

[Figure 5]

[Figure 6]

The fate of TrOCs during wastewater treatment by HR-MBR is governed by the TrOC physicochemical properties (*e.g.,* chemical structure and hydrophobicity), which influence their biodegradation. The hardly biodegradable TrOCs will not appear in the treated effluent because of the extra barrier provided by the high retention membranes. However, when not subsequently biodegraded, their accumulation on sludge would complicate sludge disposal and reuse. Based on the contribution of each mechanism of TrOC removal, a qualitative framework for the removal of TrOCs in HR-MBR is proposed in Figure 7.

[Figure 7]

Effect of salt and TrOC accumulation

HR-MBRs produce high quality effluent by retaining organic and inorganic impurities (Luo et al. 2017b, Wijekoon et al. 2014b). Complete retention of inorganic impurities results in the accumulation of salts within the bioreactor. In addition, reverse salt flux in FO-MBR also contributes to salinity buildup. The effect of salinity build-up in bioreactor has been investigated in FO-MBR (Wang et al. 2014, Zhang et al. 2017). Salinity build-up affects physical and biochemical characteristics of the biomass. For instance, increase in the concentration of extracellular polymeric substances (EPS) and soluble microbial products (SMP) has been observed following an increase in salt concentration (Luo et al. 2015a, Qiu &Ting 2013). Moreover, increase in SMP and EPS concentration can instigate membrane fouling that can affect TrOC removal by high retention membranes (Coday et al. 2014, Lay et al. 2010).

In a recent study, Luo et al. (2017b) observed a reduction in mixed liquor volatile suspended solid (MLVSS) concentration during the first two weeks of FO-MBR operation during the treatment of synthetic wastewater containing a mixture of 30 TrOCs. In addition, they reported reduced bacterial diversity during the first 20 days of FO-MBR operation (Luo et al. 2017b). They attributed the reduction in MLVSS concentration and bacterial diversity to salinity buildup in the bioreactor. Despite the adverse effects of salinity build-up on microbial activity, no effect on overall TrOC removal was observed because the high retention membrane effectively retained TrOCs within the bioreactor (Luo et al. 2015b, Wijekoon et al. 2014b).

Delgado et al. (2010) observed an increase in the endogenous respiration rates of the activated sludge collected from a conventional MBR following its exposure to carbamazepine at a concentration of 1 µg/L, probably because microbes require more maintenance energy in order to acclimatize to the stress induced by a chemical. Similarly, specific oxygen uptake rate of the activated sludge in a bioreactor was reduced by 19, 39 and 40%, when exposed to carbamazepine, ketoprofen and naproxen each at 10 µM concentration (Wang et al. 2008). Accumulation of resistant TrOCs in the bioreactor can adversely affect microbial activity, and, hence TrOC removal. However, these aspects are yet to be systematically studied.

The problem of TrOC and salt accumulation can be solved by integrating an additional ultrafiltration (UF) or microfiltration (MF) membrane with the bioreactor of HR-MBR and periodically purging liquid media through the UF/MF membrane. In a study by Holloway et al. (2015), performance of FO-MBR with and without an additional UF membrane was studied. They observed that the flux of an integrated UF+FO-MBR system remained almost constant at ~7 L/m^2 h for 4 months, while the flux of the FO-MBR without UF membrane reduced from 6 to less than 2 L/m^2 h within two months (Holloway et al. 2015). In another study, a stable operation (flux and MLSS concentration) of an FO-MBR following the integration of MF membrane was achieved for two months, but the performance was not compared to a 'control' FO-MBR (Luo et al. 2015b). The issue of reverse salt flux in FO-MBR can be solved by using organic draw solutes instead of low molecular weight inorganic salts. Organic draw solutes are biodegradable, and hence will not cause salinity buildup in FO-MBR (Bowden et al. 2012, Hau et al. 2014, Nawaz et al. 2013).

Future research

All available HR-MBR studies presented in this review employed synthetic wastewater. Real wastewater is complex and contains a wide range of pollutants that can potentially interfere with the TrOC removal performance of HR-MBR. For instance, Mascolo et al. (2010) observed during the biological treatment of pharmaceutical wastewater that the extent of biodegradation of a target compound can vary in presence of different pollutants such as wastewater derived solvents or even the co-existence of other biodegradable compounds in wastewater (Mascolo et al. 2010). Hence, it is important to evaluate the performance of HR-MBR for the treatment of real wastewater.

To improve the degradation of TrOCs in HR-MBR, other microbes with better TrOC degradation capacity than conventional activated sludge can be introduced. In this context, white-rot fungi and their extracellular enzymes (Hai et al. 2006) are worth-noting. White-rot fungi and their enzymes have been reported to achieve effective degradation of TrOCs that are resistant to activated sludge based treatment process (Asif et al. 2017a, Asif et al.

2018b, Yang et al. 2013). In a study by Nguyen et al. (2013b), addition of whole-cell white-rot fungi in conventional bacteria-dominated MBR significantly improved the degradation of three pharmaceuticals and three pesticides. Furthermore, coupling of an MD system to an enzymatic bioreactor achieved better TrOC degradation as compared to a previously developed ultrafiltration based enzymatic membrane bioreactor (Asif et al. 2018a, Asif et al. 2018b, Asif et al. 2017b, Nguyen et al. 2015, Nguyen et al. 2014), indicating the benefit of combining white-rot fungal enzyme system with high retention membranes.

The metabolites formed during treatment of TrOCs by advanced oxidation processes (AOPs) may be more amenable to degradation by activated sludge (Prado et al. 2017, Reungoat et al. 2010, Wang &Wang 2017). Thus AOPs such as ozonation and photocatalysis can be integrated with the bioreactor of HR-MBR for improving TrOC degradation. Laera et al. (2011) studied the performance of an integrated conventional MBR- UV/TiO_2 system for the treatment of pharmaceutical industry wastewater. Carbamazepine is highly resistant to degradation by the conventional activated sludge (Laera et al. 2011, Wijekoon et al. 2014b), but Laera et al. (2011) achieved above 95% removal of carbamazepine with this combination. In another study, an integrated CAS- gamma radiation system was reported to achieve up to 80% removal of carbamazepine from municipal wastewater (Wang &Wang 2017). Improved biodegradation is important as it can simplify the sludge treatment process. However, the cost associated with the application of AOPs needs to be carefully considered.

Size exclusion, diffusion and charge repulsion govern the retention of TrOCs in NF and FO based HR-MBR. Since TrOC properties (*e.g.* steric hindrance and polarity) depends on pH and feed characteristics, it is critical to investigate the effect of different feed characteristics on the retention of TrOCs by high retention membranes (Agenson &Urase 2007, Chon et al. 2012, Coday et al. 2014, Valladares et al. 2011). There is also a need to develop a technique to categorize different wastewater streams based on the type of TrOCs in order to facilitate the understanding of membrane retention mechanisms. TrOC retention by the high retention membranes needs to be assessed for longer operating period because short term operation with small bioreactor size may result in inaccurate estimation of TrOC retention.

High strength wastewater with elevated concentrations of soluble microbial product and extracellular polymeric substance can cause rapid membrane fouling. Membrane fouling can affect TrOC retention by high retention membranes (Coday et al. 2014, Taheran et al. 2016). Due to the interaction with the carboxylic and hydroxyl functional groups of the organic matter in wastewater, the negative charge on the surface of FO and NF membranes can increase following the formation of a fouling layer, consequently improving the retention of negatively charged TrOCs such as naproxen, ketoprofen and diclofenac *via* charge repulsion (Murray et al. 2010, Valladares et al. 2011, Xie et al. 2013). On the other hand, fouling layer may increase the effective MWCO size of the membranes, resulting in slightly poor retention (5-10%) of hydrophilic nonionic TrOCs, *e.g.* carbamazepine, clofibric acid and sulfamethoxazole, and hydrophobic TrOCs, *e.g.* oxybenzone and bisphenol A (Coday et al. 2014, Valladares et al. 2011). Hence, the impact of membrane fouling on TrOC retention in HR-MBRs needs to be investigated. Finally, HR-MBRs can produce high quality effluent by providing complete retention of TrOCs and salts. Sludge produced by HR-MBR is saline and potentially toxic. Hence, it is vital to assess further treatment and reuse of sludge withdrawn from HR-MBRs.

Performance of pilot- and full -scale nanofiltration/reverse osmosis, membrane distillation or forward osmosis systems has been assessed for desalination (Guillen-Burrieza et al. 2014, Hancock et al. 2013), resource recovery (Dow et al. 2016, Martinetti et al. 2009, Wang et al. 2016) and wastewater treatment (Altaee &Hilal 2014, Campagna et al. 2013, Ong et al. 2014). However, a few technological challenges such as salinity build-up, membrane stability and low permeate flux should be addressed for the scale up and commercial applications of HR-MBR for wastewater treatment. These challenges have been reviewed comprehensively by Luo et al. (2014) and Blandin et al. (2018).

Conclusion

Trace organic contaminants (TrOCs) such as pharmaceuticals, pesticides, industrial chemicals and steroid hormones are commonly detected in wastewater and wastewater-impacted water bodies. Ineffective removal of TrOCs by the wastewater treatment processes such as conventional activated sludge (CAS) and membrane bioreactors (MBR) triggered the development of high retention MBR (HR-MBR). HR-MBR couples a high retention membrane separation process (*e.g.*, membrane distillation, forward osmosis or nanofiltration) to an activated sludge bioreactor. In lab-scale studies, HR-MBRs have demonstrated promising results with more effective TrOC removal (80-99%) compared to CAS and MBR. TrOC biodegradation by activated sludge depends on a number of factors. Comparing data from independent studies, degradation of some TrOCs seems to be more stable in HR-MBR as compared to conventional MBR and CAS. The degradation-improvement for these TrOCs in HR-MBR is discernible, however, not very high. The hardly biodegradable TrOCs do not appear in the effluent of HR-MBR because of the extra barrier provided by the high retention membranes. However, when not subsequently biodegraded, their accumulation on sludge might complicate sludge disposal and reuse. In this context, bioaugmentation of activated sludge with white-rot fungi that have demonstrated better TrOC degradation capability as compared to activated sludge can be further explored.

Acknowledgement: This research has been conducted with the support of the Australian Government Research Training Program Scholarship. This study was partially funded by the GeoQuEST Research Centre, University of Wollongong, Australia.

References

Agenson KO, Oh J-I, Urase T (2003): Retention of a wide variety of organic pollutants by different nanofiltration/reverse osmosis membranes: controlling parameters of process. Journal of Membrane Science 225, 91-103

Agenson KO, Urase T (2007): Change in membrane performance due to organic fouling in nanofiltration (NF)/reverse osmosis (RO) applications. Separation and Purification Technology 55, 147-156

Alexander JT, Hai FI, Al-aboud TM (2012): Chemical coagulation-based processes for trace organic contaminant removal: Current state and future potential. Journal of Environmental Management 111, 195-207

Altaee A, Hilal N (2014): Dual-stage forward osmosis/pressure retarded osmosis process for hypersaline solutions and fracking wastewater treatment. Desalination 350, 79-85

Alturki A, McDonald J, Khan SJ, Hai FI, Price WE, Nghiem LD (2012): Performance of a novel osmotic membrane bioreactor (OMBR) system: Flux stability and removal of trace organics. Bioresource Technology 113, 201-206

Alturki AA, Tadkaew N, McDonald JA, Khan SJ, Price WE, Nghiem LD (2010): Combining MBR and NF/RO membrane filtration for the removal of trace organics in indirect potable water reuse applications. Journal of Membrane Science 365, 206-215

Alturki AA, McDonald JA, Khan SJ, Price WE, Nghiem LD, Elimelech M (2013): Removal of trace organic contaminants by the forward osmosis process. Separation and Purification Technology 103, 258-266

Asif MB, Hai FI, Hou J, Price WE, Nghiem LD (2017a): Impact of wastewater derived dissolved interfering compounds on growth, enzymatic activity and trace organic contaminant removal of white rot fungi – A critical review. Journal of Environmental Management 201, 89-109

Asif MB, Hai FI, Kang J, Van De Merwe JP, Leusch FD, Yamamoto K, Price WE, Nghiem LD (2017b): Degradation of Trace Organic Contaminants by a Membrane Distillation—Enzymatic Bioreactor. Appl. Sci. 7, 879

Asif MB, Hai FI, Dhar BR, Ngo HH, Guo W, Jegatheesan V, Price WE, Nghiem LD, Yamamoto K (2018a): Impact of simultaneous retention of micropollutants and laccase on micropollutant degradation in enzymatic membrane bioreactor. Bioresource Technology 267, 473-480

Asif MB, Hai FI, Kang J, Van De Merwe JP, Leusch FD, Price WE, Nghiem LD (2018b): Biocatalytic degradation of pharmaceuticals, personal care products, industrial chemicals, steroid hormones and pesticides in a membrane distillation-enzymatic bioreactor. Bioresource Technology 247, 528-536

Asif MB, Hai FI, Price WE, Nghiem LD (2018c): Impact of Pharmaceutically Active Compounds in Marine Environment on Aquaculture. In: Hai FI, Visvanathan C , Boopathy R (Editors), Sustainable Aquaculture. Springer, Berlin, Germany, pp. 265-299. (ISBN: 9783319732565)

Bellona C, Drewes JE, Xu P, Amy G (2004): Factors affecting the rejection of organic solutes during NF/RO treatment—a literature review. Water Research 38, 2795-2809

Blandin G, Le-Clech P, Cornelissen E, Verliefde AR, Comas J, Rodriguez-Roda I (2018): Can osmotic membrane bioreactor be a realistic solution for water reuse? npj Clean Water 1, 7

Bouju H, Buttiglieri G, Malpei F (2008): Perspectives of persistent organic pollutants (POPS) removal in an MBR pilot plant. Desalination 224, 1-6

Bowden KS, Achilli A, Childress AE (2012): Organic ionic salt draw solutions for osmotic membrane bioreactors. Bioresource Technology 122, 207-216

Campagna M, Çakmakcı M, Yaman FB, Özkaya B (2013): Molecular weight distribution of a full-scale landfill leachate treatment by membrane bioreactor and nanofiltration membrane. Waste management 33, 866-870

Cath TY, Hancock NT, Lundin CD, Hoppe-Jones C, Drewes JE (2010): A multi-barrier osmotic dilution process for simultaneous desalination and purification of impaired water. Journal of Membrane Science 362, 417-426

Chon K, KyongShon H, Cho J (2012): Membrane bioreactor and nanofiltration hybrid system for reclamation of municipal wastewater: removal of nutrients, organic matter and micropollutants. Bioresource technology 122, 181-188

Clara M, Strenn B, Gans O, Martinez E, Kreuzinger N, Kroiss H (2005): Removal of selected pharmaceuticals, fragrances and endocrine disrupting compounds in a membrane bioreactor and conventional wastewater treatment plants. Water research 39, 4797-4807

Coday BD, Yaffe BGM, Xu P, Cath TY (2014): Rejection of Trace Organic Compounds by Forward Osmosis Membranes: A Literature Review. Environmental Science & Technology 48, 3612-3624

Comerton AM, Andrews RC, Bagley DM, Hao C (2008): The rejection of endocrine disrupting and pharmaceutically active compounds by NF and RO membranes as a function of compound and water matrix properties. Journal of Membrane Science 313, 323-335

Delgado LF, Faucet-Marquis V, Schetrite S, Pfohl-Leszkowicz A, Paranthoen S, Albasi C (2010): Effect of cytostatic drugs on the sludge and on the mixed liquor characteristics of a cross-flow membrane bioreactor: Consequence on the process. Journal of membrane science 347, 165-173

Dow N, Gray S, Zhang J, Ostarcevic E, Liubinas A, Atherton P, Roeszler G, Gibbs A, Duke M (2016): Pilot trial of membrane distillation driven by low grade waste heat: Membrane fouling and energy assessment. Desalination 391, 30-42

Estrada-Arriaga EB, Mijaylova PN (2011): Influence of operational parameters (sludge retention time and hydraulic residence time) on the removal of estrogens by membrane bioreactor. Environmental Science and Pollution Research 18, 1121-1128

Feki F, Aloui F, Feki M, Sayadi S (2009): Electrochemical oxidation post-treatment of landfill leachates treated with membrane bioreactor. Chemosphere 75, 256-260

Fernandez-Fontaina E, Omil F, Lema JM, Carballa M (2012): Influence of nitrifying conditions on the biodegradation and sorption of emerging micropollutants. Water Research 46, 5434-5444

Gao D-W, Wen Z-D, Li B, Liang H (2013): Membrane fouling related to microbial community and extracellular polymeric substances at different temperatures. Bioresource Technology 143, 172-177

Goh S, Zhang J, Liu Y, Fane AG (2013): Fouling and wetting in membrane distillation (MD) and MD-bioreactor (MDBR) for wastewater reclamation. Desalination 323, 39-47

Guillen-Burrieza E, Ruiz-Aguirre A, Zaragoza G, Arafat HA (2014): Membrane fouling and cleaning in long term plant-scale membrane distillation operations. Journal of Membrane Science 468, 360-372

Hai F, Riley T, Shawkat S, Magram S, Yamamoto K (2014a): Removal of Pathogens by Membrane Bioreactors: A Review of the Mechanisms, Influencing Factors and Reduction in Chemical Disinfectant Dosing. Water 6, 3603

Hai FI, Yamamoto K, Fukushi K (2006): Development of a submerged membrane fungi reactor for textile wastewater treatment. Desalination 192, 315-322

Hai FI, Tadkaew N, McDonald JA, Khan SJ, Nghiem LD (2011a): Is halogen content the most important factor in the removal of halogenated trace organics by MBR treatment? Bioresource Technology 102, 6299-6303

Hai FI, Yamamoto K, Lee C-H (2011b): Membrane Biological Reactors. In: Wilderer P (Editor), Treatise on Water Science. Elsevier, New York, pp. 571-613. (ISBN: 9780444531995)

Hai FI, Nghiem LD, Khan SJ, Price WE, Yamamoto K (2014b): Wastewater reuse: Removal of emerging trace organic contaminants. In: Hai FI, Yamamoto K , Lee CH (Editors), Membrane Biological Reactors. IWA publishing, London, United Kingdom

Hai FI, Yamamoto K, Lee CH (2014c): Membrane Biological Reactors: Theory, Modeling, Design, Management and Applications to Wastewater Reuse. IWA Publishing, London

Hai FI, Yang S, Asif MB, Sencadas V, Shawkat S, Sanderson-Smith M, Gorman J, Xu Z-Q, Yamamoto K (2018): Carbamazepine as a Possible Anthropogenic Marker in Water: Occurrences, Toxicological Effects, Regulations and Removal by Wastewater Treatment Technologies. Water 10, 107

Hancock NT, Xu P, Roby MJ, Gomez JD, Cath TY (2013): Towards direct potable reuse with forward osmosis: Technical assessment of long-term process performance at the pilot scale. Journal of Membrane Science 445, 34-46

Hau NT, Chen S-S, Nguyen NC, Huang KZ, Ngo HH, Guo W (2014): Exploration of EDTA sodium salt as novel draw solution in forward osmosis process for dewatering of high nutrient sludge. Journal of Membrane Science 455, 305-311

He Y-j, Chen W, Zheng X-y, Wang X-n, Huang X (2013): Fate and removal of typical pharmaceuticals and personal care products by three different treatment processes. Science of The Total Environment 447, 248-254

Holloway RW, Regnery J, Nghiem LD, Cath TY (2014): Removal of Trace Organic Chemicals and Performance of a Novel Hybrid Ultrafiltration-Osmotic Membrane Bioreactor. Environmental Science & Technology 48, 10859-10868

Holloway RW, Wait AS, Fernandes da Silva A, Herron J, Schutter MD, Lampi K, Cath TY (2015): Long-term pilot scale investigation of novel hybrid ultrafiltration-osmotic membrane bioreactors. Desalination 363, 64-74

Hu J, Jin X, Ong S (2007): Rejection of estrone by nanofiltration: Influence of solution chemistry. Journal of Membrane Science 302, 188-196

Jacob P, Phungsai P, Fukushi K, Visvanathan C (2015): Direct contact membrane distillation for anaerobic effluent treatment. Journal of Membrane Science 475, 330-339

Jegatheesan V, Visvanathan C (2014): Process fundamentals: From conventional biological wastewater treatment to MBR. In: Hai FI, Yamamoto K , Lee CH (Editors), Membrane Biological Reactors: Theory, Modeling, Design, Management and Applications to Wastewater Reuse. IWA Publishing, London, pp. 29-54. (ISBN: 9781780400655)

Jin X, Shan J, Wang C, Wei J, Tang CY (2012): Rejection of pharmaceuticals by forward osmosis membranes. Journal of Hazardous Materials 227–228, 55-61

Joss A, Zabczynski S, Göbel A, Hoffmann B, Löffler D, McArdell CS, Ternes TA, Thomsen A, Siegrist H (2006): Biological degradation of pharmaceuticals in municipal wastewater treatment: Proposing a classification scheme. Water Research 40, 1686-1696

Judd S (2014): Industrial MBRs: membrane bioreactors for industrial wastewater treatment. IWA Publishing, London, 160. (ISBN: 9781780407036) pp

Judd S (2016): The status of industrial and municipal effluent treatment with membrane bioreactor technology. Chemical Engineering Journal 305, 37-45

Kim SD, Cho J, Kim IS, Vanderford BJ, Snyder SA (2007): Occurrence and removal of pharmaceuticals and endocrine disruptors in South Korean surface, drinking, and waste waters. Water Research 41, 1013-1021

Kimura K, Toshima S, Amy G, Watanabe Y (2004): Rejection of neutral endocrine disrupting compounds (EDCs) and pharmaceutical active compounds (PhACs) by RO membranes. Journal of Membrane Science 245, 71-78

Kimura K, Hara H, Watanabe Y (2007): Elimination of Selected Acidic Pharmaceuticals from Municipal Wastewater by an Activated Sludge System and Membrane Bioreactors. Environmental Science & Technology 41, 3708-3714

Laera G, Chong M, Jin B, Lopez A (2011): An integrated MBR–TiO2 photocatalysis process for the removal of Carbamazepine from simulated pharmaceutical industrial effluent. Bioresource technology 102, 7012-7015

Lay WCL, Liu Y, Fane AG (2010): Impacts of salinity on the performance of high retention membrane bioreactors for water reclamation: A review. Water Research 44, 21-40

Lay WCL, Zhang Q, Zhang J, McDougald D, Tang C, Wang R, Liu Y, Fane AG (2012): Effect of Pharmaceuticals on the Performance of a Novel Osmotic Membrane Bioreactor (OMBR). Separation Science and Technology 47, 543-554

Li X, Hai FI, Tadkaew N, Gilbertson S, Nghiem LD (2011): Strategies to enhance the removal of the persistent pharmaceutically active compound carbamazepine by membrane bioreactors. Desalination and Water Treatment 34, 402-407

Li Y, Zhang B, Li G, Luo W (2018): Osmotic Membrane Bioreactor and Its Hybrid Systems for Wastewater Reuse and Resource Recovery: Advances, Challenges, and Future Directions. Current Pollution Reports 4, 23-34

Linares RV, Yangali-Quintanilla V, Li Z, Amy G (2011): Rejection of micropollutants by clean and fouled forward osmosis membrane. Water research 45, 6737-6744

Luo W, Hai FI, Price WE, Guo W, Ngo HH, Yamamoto K, Nghiem LD (2014): High retention membrane bioreactors: Challenges and opportunities. Bioresource Technology 167, 539-546

Luo W, Hai FI, Kang J, Price WE, Guo W, Ngo HH, Yamamoto K, Nghiem LD (2015a): Effects of salinity build-up on biomass characteristics and trace organic chemical removal: Implications on the development of high retention membrane bioreactors. Bioresource technology 177, 274-281

Luo W, Hai FI, Kang J, Price WE, Nghiem LD, Elimelech M (2015b): The role of forward osmosis and microfiltration in an integrated osmotic-microfiltration membrane bioreactor system. Chemosphere 136, 125-132

Luo W, Phan HV, Li G, Hai FI, Price WE, Elimelech M, Nghiem LD (2017a): An Osmotic Membrane Bioreactor–Membrane Distillation System for Simultaneous Wastewater Reuse and Seawater Desalination: Performance and Implications. Environmental science & technology 51, 14311-14320

Luo W, Phan HV, Xie M, Hai FI, Price WE, Elimelech M, Nghiem LD (2017b): Osmotic versus conventional membrane bioreactors integrated with reverse osmosis for water reuse: Biological stability, membrane fouling, and contaminant removal. Water Research 109, 122-134

Maeng SK, Choi BG, Lee KT, Song KG (2013): Influences of solid retention time, nitrification and microbial activity on the attenuation of pharmaceuticals and estrogens in membrane bioreactors. Water research 47, 3151-3162

Martinetti CR, Childress AE, Cath TY (2009): High recovery of concentrated RO brines using forward osmosis and membrane distillation. Journal of membrane science 331, 31-39

Mascolo G, Balest L, Cassano D, Laera G, Lopez A, Pollice A, Salerno C (2010): Biodegradability of pharmaceutical industrial wastewater and formation of recalcitrant organic compounds during aerobic biological treatment. Bioresource technology 101, 2585-2591

Melin T, Jefferson B, Bixio D, Thoeye C, De Wilde W, De Koning J, van der Graaf J, Wintgens T (2006): Membrane bioreactor technology for wastewater treatment and reuse. Desalination 187, 271-282

Murray KE, Thomas SM, Bodour AA (2010): Prioritizing research for trace pollutants and emerging contaminants in the freshwater environment. Environmental Pollution 158, 3462-3471

Nawaz MS, Gadelha G, Khan SJ, Hankins N (2013): Microbial toxicity effects of reverse transported draw solute in the forward osmosis membrane bioreactor (FO-MBR). Journal of Membrane Science 429, 323-329

Nghiem LD, Schäfer AI, Elimelech M (2005): Nanofiltration of hormone mimicking trace organic contaminants. Separation Science and Technology 40, 2633-2649

Nghiem LD, Schäfer AI, Elimelech M (2006): Role of electrostatic interactions in the retention of pharmaceutically active contaminants by a loose nanofiltration membrane. Journal of Membrane Science 286, 52-59

Nghiem LD, Coleman PJ (2008): NF/RO filtration of the hydrophobic ionogenic compound triclosan: Transport mechanisms and the influence of membrane fouling. Separation and Purification Technology 62, 709-716

Nguyen LN, Hai FI, Kang J, Price WE, Nghiem LD (2013a): Removal of emerging trace organic contaminants by MBR-based hybrid treatment processes. International Biodeterioration & Biodegradation 85, 474-482

Nguyen LN, Hai FI, Yang S, Kang J, Leusch FDL, Roddick F, Price WE, Nghiem LD (2013b): Removal of trace organic contaminants by an MBR comprising a mixed culture of bacteria and white-rot fungi. Bioresource Technology 148, 234-241

Nguyen LN, Hai FI, Price WE, Leusch FDL, Roddick F, McAdam EJ, Magram SF, Nghiem LD (2014): Continuous biotransformation of bisphenol a and diclofenac bylaccase in an enzymatic membrane reactor. International Biodeterioration and Biodegradation 95, 25-32

Nguyen LN, Hai FI, Price WE, Kang J, Leusch FD, Roddick F, van de Merwe JP, Magram SF, Nghiem LD (2015): Degradation of a broad spectrum of trace organic contaminants by an enzymatic membrane reactor: complementary role of membrane retention and enzymatic degradation. International Biodeterioration & Biodegradation 99, 115-122

Ong YK, Li FY, Sun S-P, Zhao B-W, Liang C-Z, Chung T-S (2014): Nanofiltration hollow fiber membranes for textile wastewater treatment: Lab-scale and pilot-scale studies. Chemical engineering science 114, 51-57

Park J, Yamashita N, Park C, Shimono T, Takeuchi DM, Tanaka H (2017): Removal characteristics of pharmaceuticals and personal care products: Comparison between membrane bioreactor and various biological treatment processes. Chemosphere 179, 347-358

Phan HV, Hai FI, Kang J, Dam HK, Zhang R, Price WE, Broeckmann A, Nghiem LD (2014): Simultaneous nitrification/denitrification and trace organic contaminant (TrOC) removal by an anoxic–aerobic membrane bioreactor (MBR). Bioresource technology 165, 96-104

Phan HV, Hai FI, McDonald JA, Khan SJ, van de Merwe JP, Leusch FDL, Zhang R, Price WE, Broeckmann A, Nghiem LD (2015a): Impact of hazardous events on the removal of nutrients and trace organic contaminants by an anoxic–aerobic membrane bioreactor receiving real wastewater. Bioresource Technology 192, 192-201

Phan HV, Hai FI, McDonald JA, Khan SJ, Zhang R, Price WE, Broeckmann A, Nghiem LD (2015b): Nutrient and trace organic contaminant removal from wastewater of a resort town: Comparison between a pilot and a full scale membrane bioreactor. International Biodeterioration and Biodegradation 102, 40-48

Phan HV, Hai FI, Zhang R, Kang J, Price WE, Nghiem LD (2016a): Bacterial community dynamics in an anoxic-aerobic membrane bioreactor - Impact on nutrient and trace organic contaminant removal. International Biodeterioration and Biodegradation 109, 61-72

Phan HV, McDonald JA, Hai FI, Price WE, Khan SJ, Fujioka T, Nghiem LD (2016b): Biological performance and trace organic contaminant removal by a side-stream ceramic nanofiltration membrane bioreactor. International Biodeterioration & Biodegradation 113, 49-56

Pomiès M, Choubert J-M, Wisniewski C, Coquery M (2013): Modelling of micropollutant removal in biological wastewater treatments: a review. Science of the Total Environment 443, 733-748

Prado M, Borea L, Cesaro A, Liu H, Naddeo V, Belgiorno V, Ballesteros Jr F (2017): Removal of emerging contaminant and fouling control in membrane bioreactors by combined ozonation and sonolysis. International Biodeterioration & Biodegradation 119, 577-586

Qiu G, Ting Y-P (2013): Osmotic membrane bioreactor for wastewater treatment and the effect of salt accumulation on system performance and microbial community dynamics. Bioresource Technology 150, 287-297

Radjenovic J, Petrovic M, Barceló D (2007): Analysis of pharmaceuticals in wastewater and removal using a membrane bioreactor. Analytical and Bioanalytical Chemistry 387, 1365-1377

Radjenović J, Matošić M, Mijatović I, Petrović M, Barceló D (2008a): Membrane bioreactor (MBR) as an advanced wastewater treatment technology. In: Barceló D , Petrovic M (Editors), Emerging Contaminants from Industrial and Municipal Waste. Springer, pp. 37-101

Radjenović J, Petrović M, Ventura F, Barceló D (2008b): Rejection of pharmaceuticals in nanofiltration and reverse osmosis membrane drinking water treatment. Water Research 42, 3601-3610

Radjenović J, Petrović M, Barceló D (2009): Fate and distribution of pharmaceuticals in wastewater and sewage sludge of the conventional activated sludge (CAS) and advanced membrane bioreactor (MBR) treatment. Water Research 43, 831-841

Reif R, Suárez S, Omil F, Lema J (2008): Fate of pharmaceuticals and cosmetic ingredients during the operation of a MBR treating sewage. Desalination 221, 511-517

Reungoat J, Macova M, Escher B, Carswell S, Mueller J, Keller J (2010): Removal of micropollutants and reduction of biological activity in a full scale reclamation plant using ozonation and activated carbon filtration. Water research 44, 625-637

Schwarzenbach RP, Escher BI, Fenner K, Hofstetter TB, Johnson CA, von Gunten U, Wehrli B (2006): The Challenge of Micropollutants in Aquatic Systems. Science 313, 1072-1077

Semblante GU, Hai FI, Huang X, Ball AS, Price WE, Nghiem LD (2015): Trace organic contaminants in biosolids: Impact of conventional wastewater and sludge processing technologies and emerging alternatives. Journal of Hazardous Materials 300, 1-17

Shannon MA, Bohn PW, Elimelech M, Georgiadis JG, Marinas BJ, Mayes AM (2008): Science and technology for water purification in the coming decades. Nature 452, 301

Shore JL, M'Coy WS, Gunsch CK, Deshusses MA (2012): Application of a moving bed biofilm reactor for tertiary ammonia treatment in high temperature industrial wastewater. Bioresource technology 112, 51-60

Song X, Luo W, McDonald J, Khan SJ, Hai FI, Price WE, Nghiem LD (2018a): An anaerobic membrane bioreactor–membrane distillation hybrid system for energy recovery and water reuse: Removal performance of organic carbon, nutrients, and trace organic contaminants. Science of The Total Environment 628, 358-365

Song X, Xie M, Li Y, Li G, Luo W (2018b): Salinity build-up in osmotic membrane bioreactors: Causes, impacts, and potential cures. Bioresource technology

Stevens-Garmon J, Drewes JE, Khan SJ, McDonald JA, Dickenson ERV (2011): Sorption of emerging trace organic compounds onto wastewater sludge solids. Water Research 45, 3417-3426

Sui Q, Huang J, Deng S, Chen W, Yu G (2011): Seasonal variation in the occurrence and removal of pharmaceuticals and personal care products in different biological wastewater treatment processes. Environmental science & technology 45, 3341-3348

Tadkaew N, Sivakumar M, Khan SJ, McDonald JA, Nghiem LD (2010): Effect of mixed liquor pH on the removal of trace organic contaminants in a membrane bioreactor. Bioresource technology 101, 1494-1500

Tadkaew N, Hai FI, McDonald JA, Khan SJ, Nghiem LD (2011): Removal of trace organics by MBR treatment: The role of molecular properties. Water Research 45, 2439-2451

Taheran M, Brar SK, Verma M, Surampalli RY, Zhang TC, Valéro JR (2016): Membrane processes for removal of pharmaceutically active compounds (PhACs) from water and wastewaters. Science of The Total Environment 547, 60-77

Tambosi JL, de Sena RF, Favier M, Gebhardt W, José HJ, Schröder HF, Moreira RdFPM (2010): Removal of pharmaceutical compounds in membrane bioreactors (MBR) applying submerged membranes. Desalination 261, 148-156

Tang CY, Yang Z, Guo H, Wen JJ, Nghiem LD, Cornelissen E (2018): Potable Water Reuse through Advanced Membrane Technology. Environmental Science & Technology DOI: 10.1021/acs.est.8b00562

Tran NH, Urase T, Ngo HH, Hu J, Ong SL (2013): Insight into metabolic and cometabolic activities of autotrophic and heterotrophic microorganisms in the biodegradation of emerging trace organic contaminants. Bioresource technology 146, 721-731

Trinh T, Van Den Akker B, Stuetz R, Coleman H, Le-Clech P, Khan S (2012): Removal of trace organic chemical contaminants by a membrane bioreactor. Water Science and Technology 66, 1856-1863

Trinh T, van den Akker B, Coleman HM, Stuetz RM, Drewes JE, Le-Clech P, Khan SJ (2016): Seasonal variations in fate and removal of trace organic chemical contaminants while operating a full-scale membrane bioreactor. Science of The Total Environment 550, 176-183

Valladares LR, Yangali-Quintanilla V, Li Z, Amy G (2011): Rejection of micropollutants by clean and fouled forward osmosis membrane. Water Research 45, 6737-6744

Verlicchi P, Al Aukidy M, Zambello E (2012): Occurrence of pharmaceutical compounds in urban wastewater: removal, mass load and environmental risk after a secondary treatment—a review. Science of the total environment 429, 123-155

Verliefde AR, Cornelissen ER, Heijman S, Petrinic I, Luxbacher T, Amy G, Van der Bruggen B, Van Dijk J (2009): Influence of membrane fouling by (pretreated) surface water on rejection of pharmaceutically active compounds (PhACs) by nanofiltration membranes. Journal of Membrane Science 330, 90-103

Verliefde ARD, Heijman SGJ, Cornelissen ER, Amy G, Van der Bruggen B, van Dijk JC (2007): Influence of electrostatic interactions on the rejection with NF and assessment of the removal efficiency during NF/GAC treatment of pharmaceutically active compounds in surface water. Water Research 41, 3227-3240

Wang J, Li K, Wei Y, Cheng Y, Wei D, Li M (2015): Performance and fate of organics in a pilot MBR–NF for treating antibiotic production wastewater with recycling NF concentrate. Chemosphere 121, 92-100

Wang N 2013: Removal of Organic Micropollutants by Aerobic Activated Sludge, King Abdullah University of Science and Technology, Kingdom of Saudi Arabia (Accessed on 20.04.2018 from http://repository.kaust.edu.sa/kaust/bitstream/10754/295059/1/ThesisNanWang.pdf)

Wang S, Holzem RM, Gunsch CK (2008): Effects of pharmaceutically active compounds on a mixed microbial community originating from a municipal wastewater treatment plant. Environmental science & technology 42, 1091-1095

Wang S, Wang J (2017): Carbamazepine degradation by gamma irradiation coupled to biological treatment. Journal of hazardous materials 321, 639-646

Wang X, Chen Y, Yuan B, Li X, Ren Y (2014): Impacts of sludge retention time on sludge characteristics and membrane fouling in a submerged osmotic membrane bioreactor. Bioresource Technology 161, 340-347

Wang Z, Zheng J, Tang J, Wang X, Wu Z (2016): A pilot-scale forward osmosis membrane system for concentrating low-strength municipal wastewater: performance and implications. Scientific reports 6, 21653

Wijekoon KC, Hai FI, Kang J, Price WE, Guo W, Ngo HH, Nghiem LD (2013): The fate of pharmaceuticals, steroid hormones, phytoestrogens, UV-filters and pesticides during MBR treatment. Bioresource Technology 144, 247-254

Wijekoon KC, Hai FI, Kang J, Price WE, Cath TY, Nghiem LD (2014a): Rejection and fate of trace organic compounds (TrOCs) during membrane distillation. Journal of Membrane Science 453, 636-642

Wijekoon KC, Hai FI, Kang J, Price WE, Guo W, Ngo HH, Cath TY, Nghiem LD (2014b): A novel membrane distillation–thermophilic bioreactor system: Biological stability and trace organic compound removal. Bioresource Technology 159, 334-341

Xie M, Nghiem LD, Price WE, Elimelech M (2012a): Comparison of the removal of hydrophobic trace organic contaminants by forward osmosis and reverse osmosis. Water research 46, 2683-2692

Xie M, Price WE, Nghiem LD (2012b): Rejection of pharmaceutically active compounds by forward osmosis: Role of solution pH and membrane orientation. Separation and Purification Technology 93, 107-114

Xie M, Nghiem LD, Price WE, Elimelech M (2013): Impact of humic acid fouling on membrane performance and transport of pharmaceutically active compounds in forward osmosis. Water Research 47, 4567-4575

Xue W, Wu C, Xiao K, Huang X, Zhou H, Tsuno H, Tanaka H (2010): Elimination and fate of selected micro-organic pollutants in a full-scale anaerobic/anoxic/aerobic process combined with membrane bioreactor for municipal wastewater reclamation. water research 44, 5999-6010

Yang S, Hai FI, Nghiem LD, Price WE, Roddick F, Moreira MT, Magram SF (2013): Understanding the factors controlling the removal of trace organic contaminants by white-rot fungi and their lignin modifying enzymes: a critical review. Bioresource technology 141, 97-108

Yeo BJ, Goh S, Zhang J, Livingston AG, Fane AG (2015): Novel MBRs for the removal of organic priority pollutants from industrial wastewaters: a review. Journal of Chemical Technology and Biotechnology 90, 1949-1967

Yoon Y, Westerhoff P, Snyder SA, Wert EC (2006): Nanofiltration and ultrafiltration of endocrine disrupting compounds, pharmaceuticals and personal care products. Journal of Membrane Science 270, 88-100

Zhang B, Song X, Nghiem LD, Li G, Luo W (2017): Osmotic membrane bioreactors for wastewater reuse: Performance comparison between cellulose triacetate and polyamide thin film composite membranes. Journal of Membrane Science 539, 383-391

Zhang L, Wei C, Zhang K, Zhang C, Fang Q, Li S (2009): Effects of temperature on simultaneous nitrification and denitrification via nitrite in a sequencing batch biofilm reactor. Bioprocess and biosystems engineering 32, 175-182

Figure captions

Figure 1: Schematics of (a) Conventional membrane bioreactor (MBR); (b) membrane distillation bioreactor (MDBR); (c); forward osmosis- membrane bioreactor (FO-MBR); and (d) nanofiltration- membrane bioreactor (NF-MBR)

Figure 2. Qualitative predictive framework for the retention of TrOCs by NF or FO membrane. Modified from (Bellona et al. 2004, Taheran et al. 2016)

Figure 3. Aqueous phase removal of TrOCs by CAS, MBR and HR-MBR. Box-and-whisker plot is showing information about: the interquartile range; median (horizontal line in the box); min and max (whiskers); and average (block square in the box). Complete data set for MBR and CAS is given in Supplementary Data Table S1 and S2, respectively. Data source for HR-MBR: Wijekoon et al. (2014b); Alturki et al. (2012); Holloway et al. (2014); Luo et al. (2015b); and Luo et al. (2017b); Phan et al. (2016b); and Wang (2013).

Figure 4. Effect of SRT on the aqueous phase removal of selected TrOCs by conventional MBR. (**a**) Significant SRT dependent improvement in TrOC removal; and (**b**) insignificant dependence of TrOC removal on SRT. Data source: Alturki et al. (2010); Bouju et al. (2008); Clara et al. (2005); Kimura et al. (2007); Maeng et al. (2013); Radjenovic et al. (2007); Radjenović et al. (2009); Reif et al. (2008); Alturki et al. (2010); Tambosi et al. (2010); and Wijekoon et al. (2013)

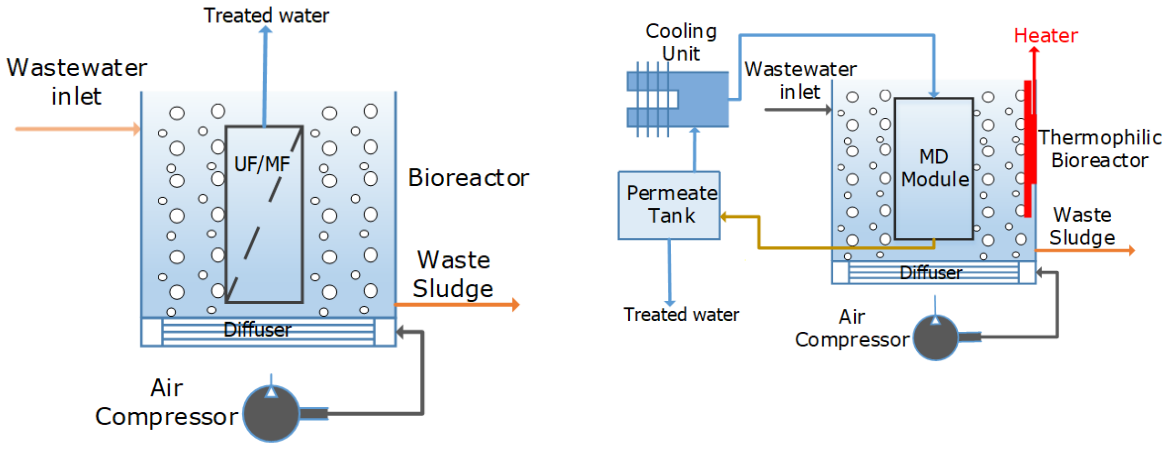
Figure 5. Variations in the biodegradation of TrOCs in CAS (**a**), MBR (**b**) and HR-MBR (**c**). Box-and-whisker plot is showing information about: the interquartile range; median (horizontal line in the box); min and max (whiskers); and average (block square in the box). Numbers in the parenthesis on the x-axis represent the no. of data points (no. of data points: HR-MBR+MBR+CAS). Complete data set for MBR and CAS is given in Supplementary Data Table S1 and S2, respectively. Data source for HR-MBR: Wijekoon et al. (2014b); Alturki et al. (2012); Holloway et al. (2014); Luo et al. (2015b); and Luo et al. (2017b); Phan et al. (2016b); and Wang (2013).

Figure 6. Contribution of different mechanisms for TrOC removal in HR-MBR and conventional MBR. HR-MBR data source: Alturki et al. (2012); Holloway et al. (2014); Luo et al. (2015b); Luo et al. (2017b); and Wijekoon et al. (2014b). Conventional MBR data source: Wijekoon et al. (2013) and Radjenović et al. (2009)

Figure 7. A qualitative framework to predict the contribution of different mechanisms of TrOC removal in HR-MBR categorized based on their physicochemical properties.

List of Figures

(a) Conventional MBR **(b) MDBR**



(c) FO-MBR **(d) NF/RO-MBR**

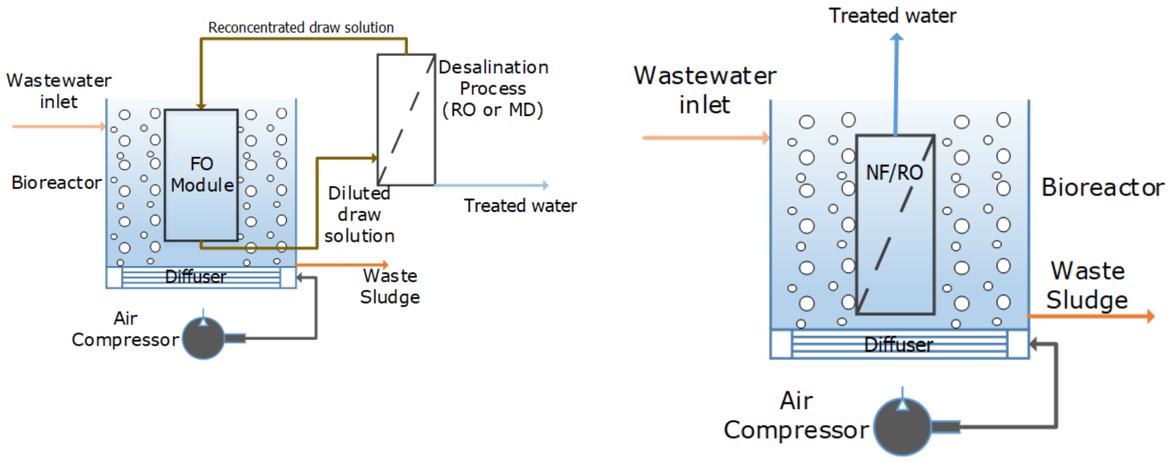


Figure 1: Schematics of (a) Conventional membrane bioreactor (MBR); (b) membrane distillation bioreactor (MDBR); (c); forward osmosis- membrane bioreactor (FO-MBR); and (d) nanofiltration-membrane bioreactor (NF-MBR)

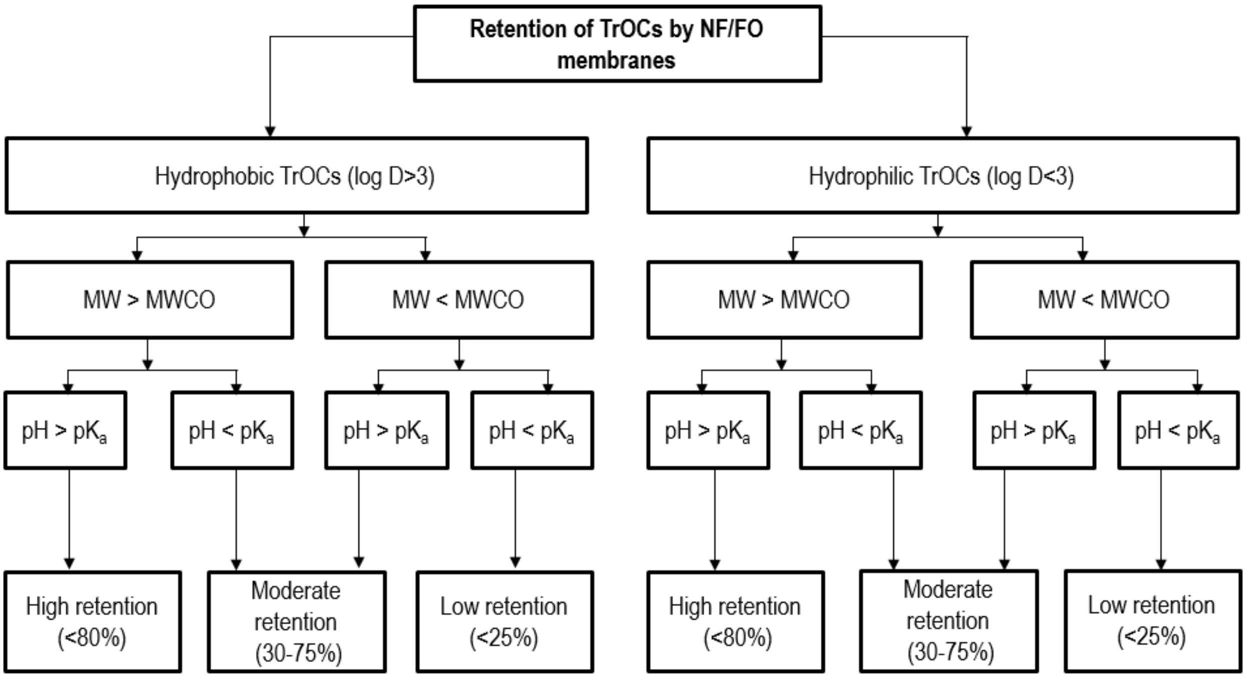


Figure 2. Qualitative predictive framework for the retention of TrOCs by NF or FO membrane. Modified from (Bellona et al. 2004, Taheran et al. 2016)

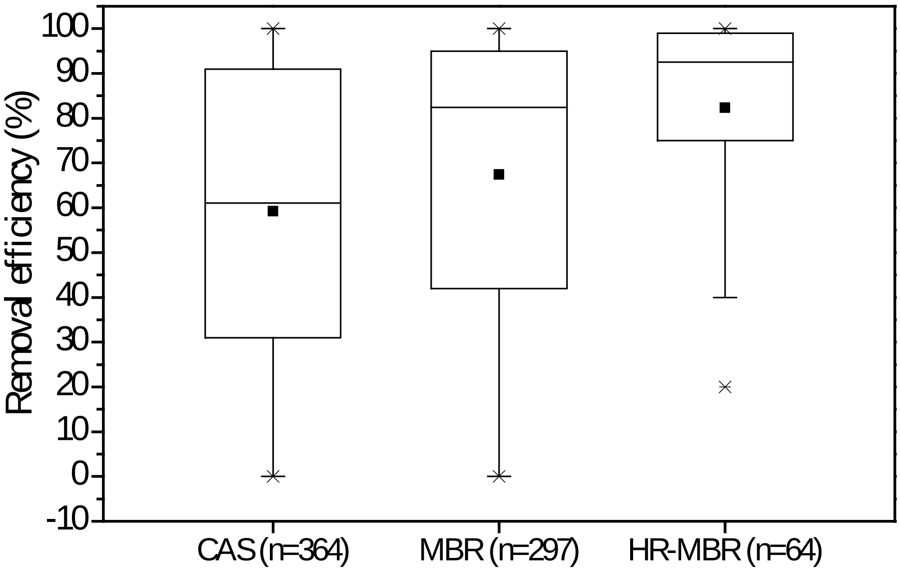


Figure 3. Aqueous phase removal of TrOCs by CAS, MBR and HR-MBR. Box-and-whisker plot is showing information about: the interquartile range; median (horizontal line in the box); min and max (whiskers); and average (block square in the box). Complete data set for MBR and CAS is given in Supplementary Data Table S1 and S2, respectively. Data source for HR-MBR: Wijekoon et al. (2014b); Alturki et al. (2012); Holloway et al. (2014); Luo et al. (2015b); and Luo et al. (2017b); Phan et al. (2016); and Wang (2013).

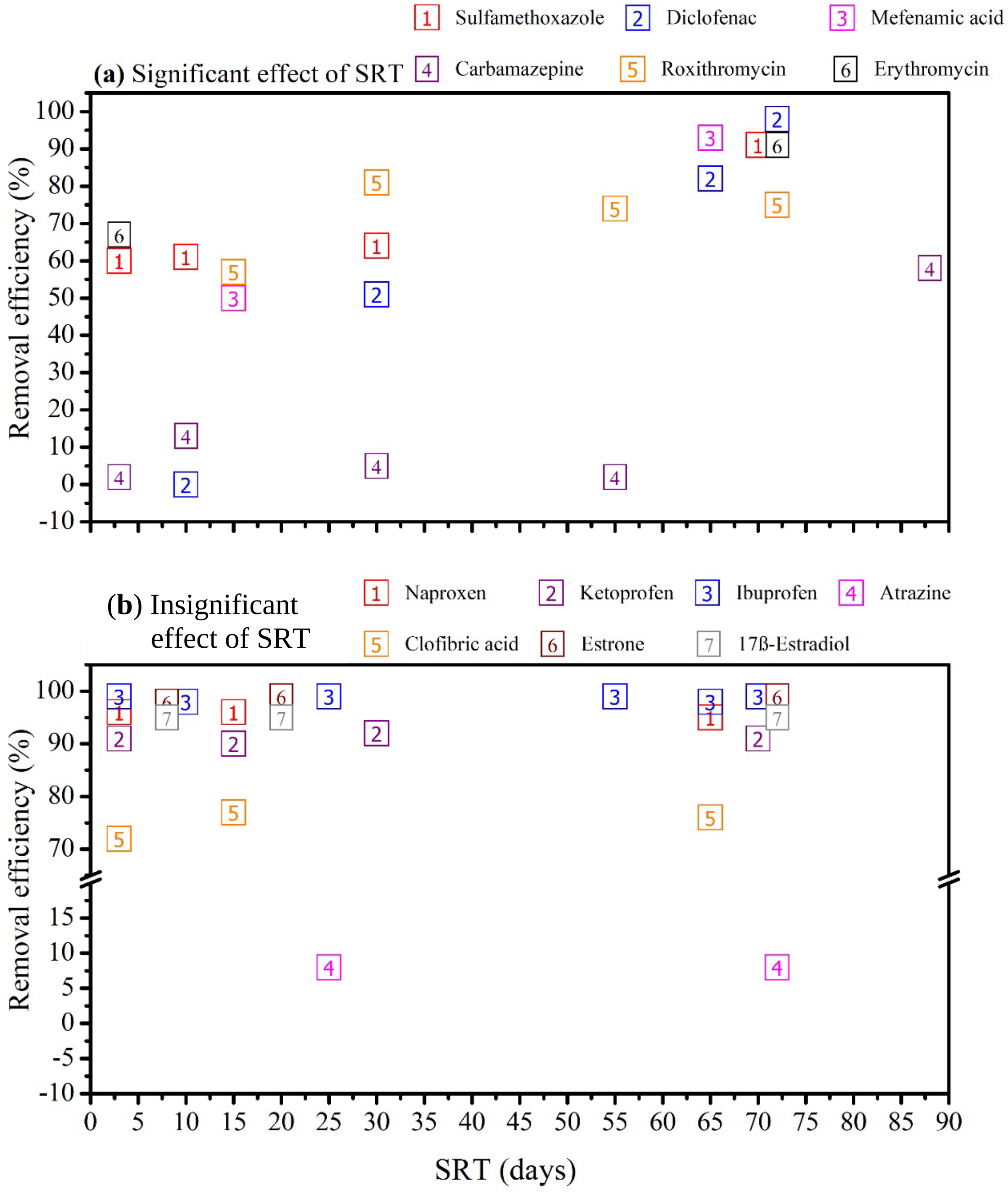


Figure 4. Effect of SRT on the aqueous phase removal of selected TrOCs by conventional MBR. (**a**) Significant SRT dependent improvement in TrOC removal; and (**b**) insignificant dependence of TrOC removal on SRT. Data source: Alturki et al. (2010); Bouju et al. (2008); Clara et al. (2005); Kimura et al. (2007); Maeng et al. (2013); Radjenovic et al. (2007); Radjenović et al. (2009); Reif et al. (2008); Tadkaew et al. (2010); Tambosi et al. (2010); and Wijekoon et al. (2013)

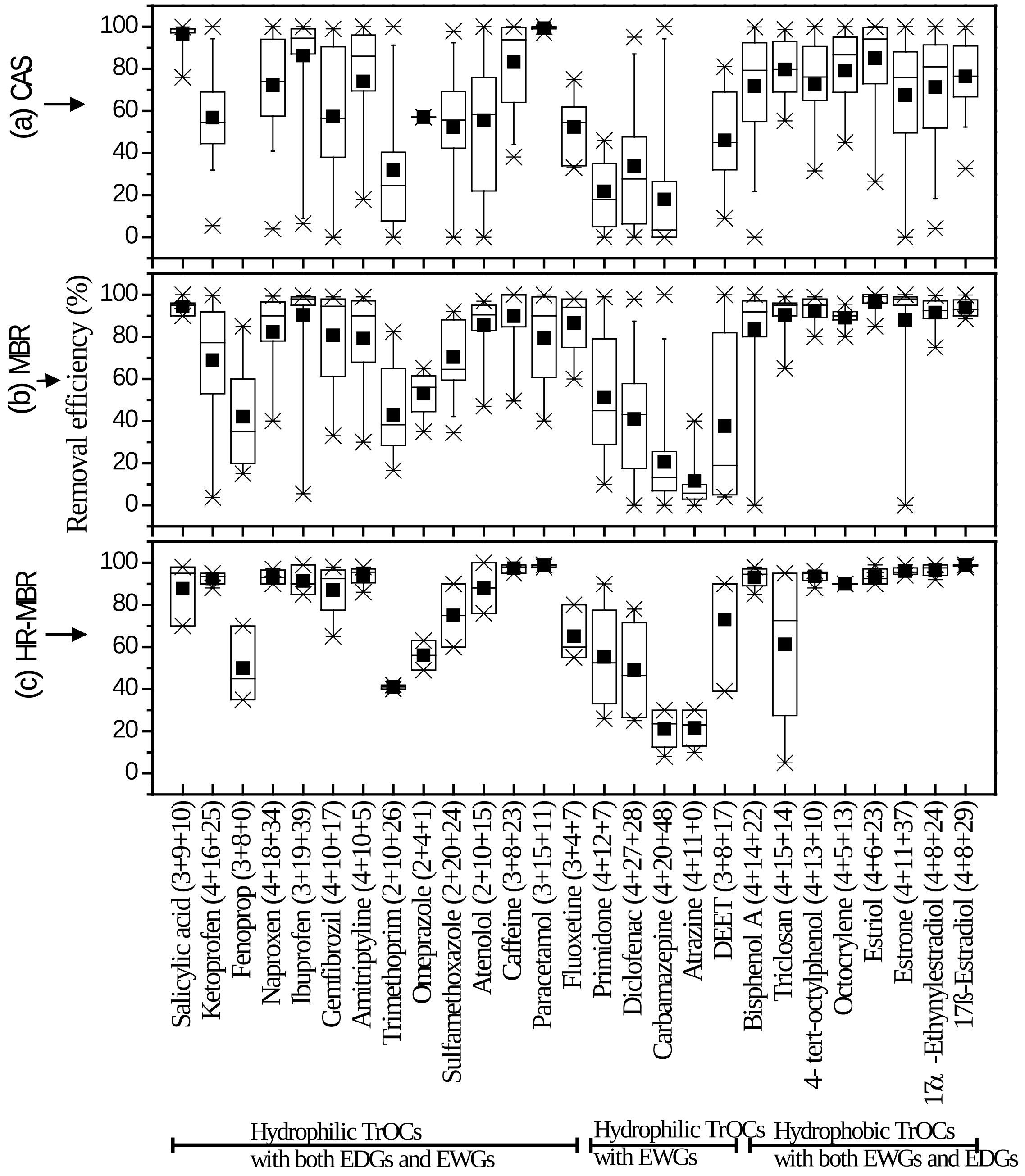


Figure 5. Variations in the biodegradation of TrOCs in CAS (**a**), MBR (**b**) and HR-MBR (**c**). Box-and-whisker plot is showing information about: the interquartile range; median (horizontal line in the box); min and max (whiskers); and average (block square in the box). Numbers in the parenthesis on the x-axis represent the no. of data points (no. of data points: HR-MBR+MBR+CAS). Complete data set for MBR and CAS is given in Supplementary Data Table S1 and S2, respectively. Data source for HR-MBR: Wijekoon et al. (2014b); Alturki et al. (2012); Holloway et al. (2014); Luo et al. (2015b); and Luo et al. (2017b); Phan et al. (2016); and Wang (2013).

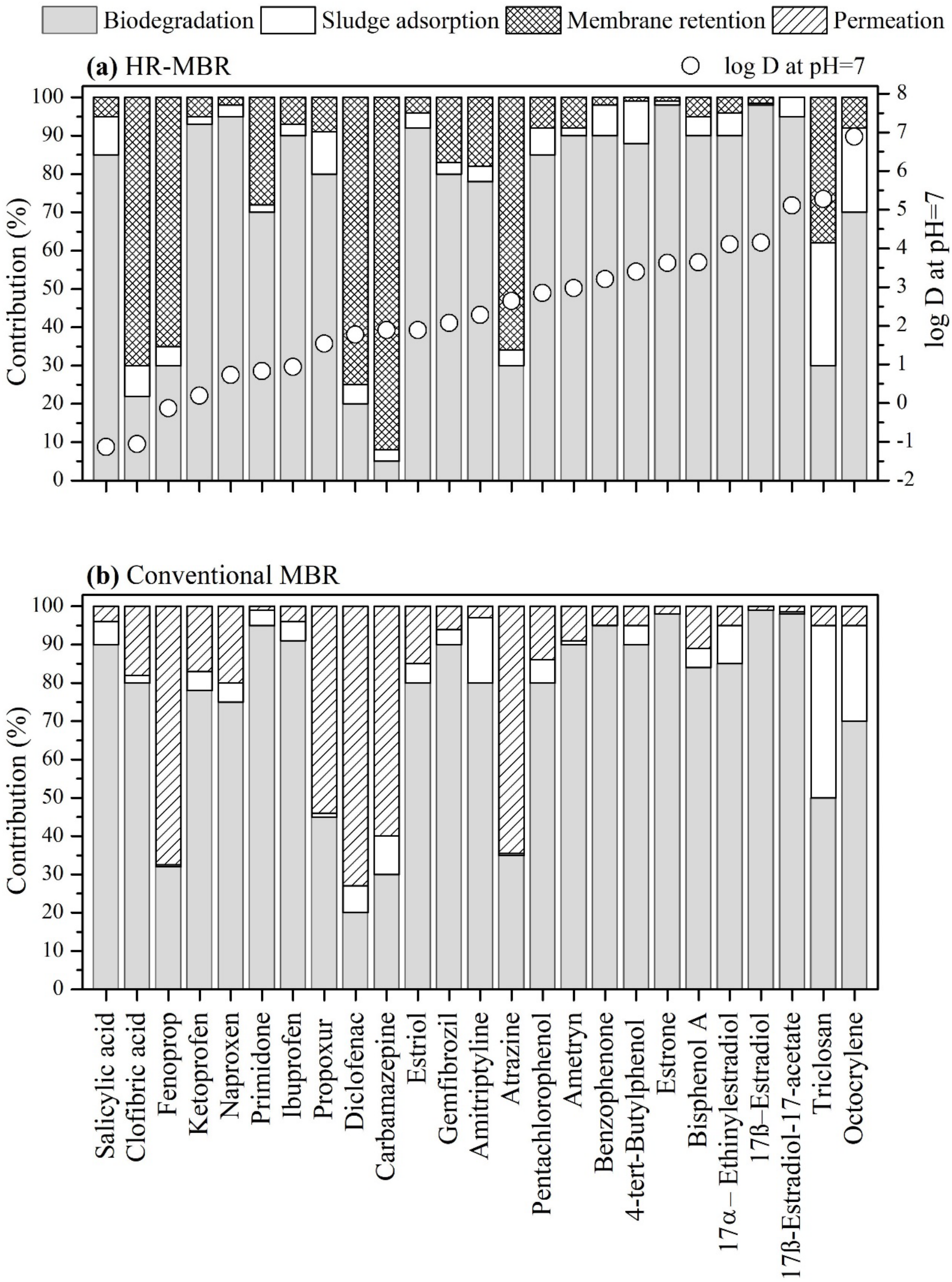


Figure 6. Contribution of different mechanisms for TrOC removal in HR-MBR and conventional MBR. HR-MBR data source: Alturki et al. (2012); Holloway et al. (2014); Luo et al. (2015b); Luo et al. (2017b); and Wijekoon et al. (2014b). Conventional MBR data source: Wijekoon et al. (2013) and Radjenović et al. (2009)

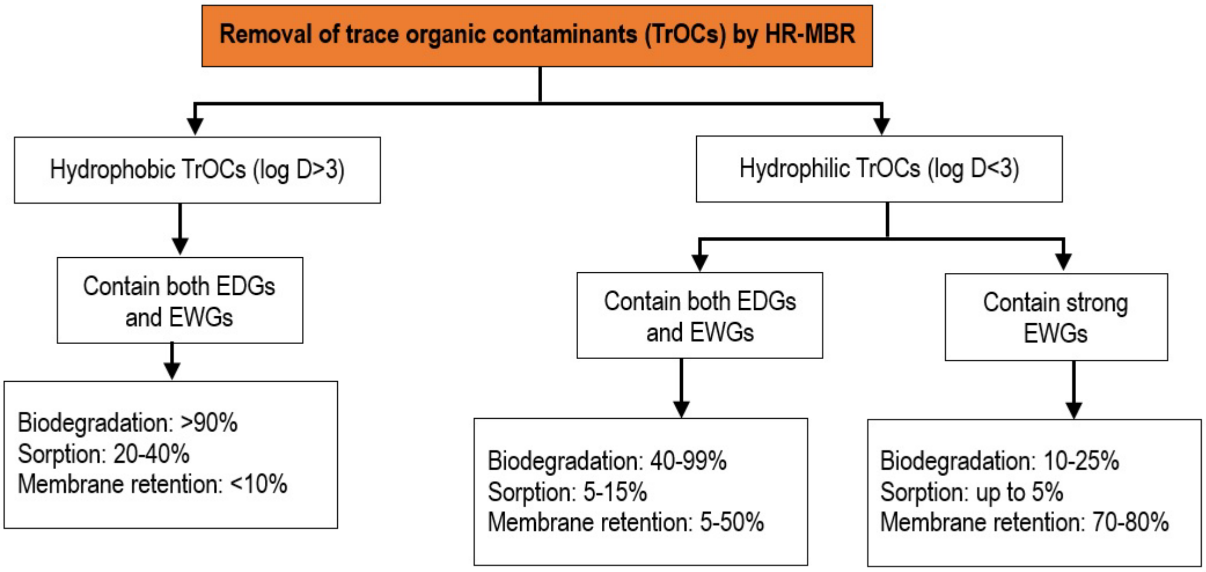


Figure 7. A qualitative framework to predict the contribution of different mechanisms of TrOC removal in HR-MBR categorized based on their physicochemical properties.

List of Tables

Table 1. Factors affecting the retention of TrOCs by high retention membranes

Factors	**MD membrane**	**FO membrane**	**NF membrane**
Fouling	*	*	*
Diffusion of solute	-	*	*
Hydrophobicity	*	*	*
Membrane MWCO	-	*	*
Charge on TrOCs	-	*	*
Membrane surface charge	-	*	*
Polarity	-	*	*
Molecular width	-	*	*
Volatility of TrOCs	*	*	*
Temperature and pH	*	*	*

“ –” : no effect according to available reports

Table 2: Physicochemical properties of TrOCs and their aqueous phase removal by HR-MBR

TrOCs	**Chemical formula** [a]	**Molecular Weight** [a]	**Dissociation coefficient (pK_a)** [a]	**Henry constant (H)** [b]	**pK_H** [b]	**Log D at pH=7** [a]	**Removal efficiency (%)**		
		g/mole					FO-MBR [c]	MDBR [d]	NF-MBR [e]
Primidone	$C_{12}H_{14}N_2O$	218.25	12.26 ± 0.40	1.164E-14	13.93	0.83	>99	>99	-
Ketoprofen	$C_{16}H_{14}O_3$	254.28	4.23 ± 0.10	2.005E-14	13.70	0.19	>99	>99	94
Naproxen	$C_{14}H_{14}O_3$	230.26	4.84 ± 0.30	2.096E-13	12.68	0.73	>99	>99	98
Gemfibrozil	$C_{15}H_{22}O_3$	250.33	4.75	7.677E-13	12.11	2.07	>95	>99	99
Metronidazole	$C_6H_9N_3O_3$	171.15	14.44 ± 0.10	2.073E-12	11.68	-0.14	>95	>99	99
Diclofenac	$C_{14}H_{11}Cl_2NO_2$	296.15	4.18 ± 0.10	3.098E-12	11.51	1.77	>95	90	45-95
Fenoprop	$C_9H_7Cl_3O_3$	269.51	2.93	3.284E-12	11.48	-0.13	83-99	95	-
Ibuprofen	$C_{13}H_{18}O_2$	206.28	4.41 ± 0.10	4.066E-11	10.39	0.94	>99	>99	100
Ametryn	$C_9H_{17}N_5S$	27.33	3.71±0.41	4.418E-10	9.35	2.97	>99	>99	-
Clofibric acid	$C_{10}H_{11}ClO_3$	214.65	3.18 ±0.10	2.909E-10	9.54	-1.06	>99	>99	75
Carbamazepine	$C_{15}H_{12}N_2O$	236.27	13.94 ± 0.20	8.168E-10	9.09	1.89	50-99	95	18-75
Octocrylene	$C_{24}H_{27}N$	361.48	-	3.382E-09	8.47	6.89	80-90	90	95
Amitriptyline	$C_{20}H_{23}N$	277.40	9.18 ± 0.28	6.596E-09	8.18	2.28	>99	>99	83-100
Atrazine	$C_8H_{14}ClN_5$	215.68	2.27 ± 0.10	5.223E-08	7.28	2.64	75-90	>99	16-80
Propoxur	$C_{11}H_{15}NO_3$	209.24	1.49 ± 0.70	5.265E-07	6.28	1.54	>99	>99	-
Benzophenone	$C_{13}H_{10}O$	182.22	-	1.316E-06	5.88	3.21	>99	95	>99
N, N-Diethyl-meta-toluamide (DEET)	$C_{12}H_{17}NO$	191.3	-	1.410E-06	5.85	2.42	40-90	-	60
Estriol	$C_{18}H_{24}O_3$	298.33	10.25 ± 0.70	1.644E-11	10.78	1.89	>99	>99	-
17α – Ethynylestradiol	$C_{20}H_{24}O_2$	269.40	10.24 ± 0.60	3.399E-10	9.47	4.11	>99	>99	-
Oxybenzone	$C_{14}H_{12}O_3$	228.24	7.56±0.35	5.851E-10	9.23	3.89	>99	>99	-
Estrone	$C_{18}H_{22}O_2$	270.37	10.25 ± 0.40	9.286E-10	9.03	3.62	>99	>99	95
17β – Estradiol	$C_{18}H_{24}O_2$	272.38	10.27	1.173E-09	8.93	4.15	>99	>99	-
17β – Estradiol-17-acetate	$C_{20}H_{26}O_3$	314.42	10.26 ± 0.60	2.151E-09	8.67	5.11	>99	>99	-
Bisphenol A	$C_{15}H_{16}O_2$	228.29	10.29 ± 0.10	2.197E-09	8.66	3.64	>99	>99	95-97
Salicylic acid	$C_7H_6O_3$	138.12	3.01 ± 0.10	6.653E-09	8.18	-1.13	>99	95	70
Triclosan	$C_{12}H_7Cl_3O_2$	289.54	7.80 ± 0.35	6.537E-07	6.18	5.28	>99	>99	82
4-tert-Butylphenol	$C_{10}H_{14}O$	150.22	10.13 ± 0.13	7.136E-06	5.15	3.40	>99	>99	88
4-tert-Octylphenol	$C_{14}H_{22}O$	206.32	10.15 ± 0.15	8.670E-06	5.06	5.18	>99	>99	-

[a] Data extracted from SciFinder Scholar;

[b] Henry's law constant (H) = Vapour pressure × molecular weight/water solubility; and $pK_H = -\log_{10} H$.

[c] Wijekoon et al. (2014)

[d] Alturki et al. (2012); Holloway et al. (2014); Lay et al. (2012) Luo et al. (2015); and Luo et al. (2017).

[e] Phan et al. (2016); and Wang (2013)

"–": not available

Understanding the mechanisms of trace organic contaminant removal by high retention membrane bioreactors: A critical review

Muhammad B. Asif [a], Ashley J. Ansari [a], Shiao-Shing Chen [b], Long D. Nghiem [a,c], William E. Price [d], Faisal I. Hai [a]*

Supplementary Data

[a] Strategic Water Infrastructure Lab, School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia.

[b] Institute of Environmental Engineering and Management, National Taipei University of Technology, Taipei 10608, Taiwan.

[c] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia

[d] Strategic Water Infrastructure Lab, School of Chemistry, University of Wollongong, Wollongong, NSW 2522, Australia.

***Corresponding author:** Faisal I. Hai (E-mail: faisal@uow.edu.au; Tel: +61 2 42213054)

Table S1: Removal of TrOCs by conventional MBR

Journal Name	Volume: Pages	TrOC	Removal (%)
Water Research	45: 2439–2451	Caffeine	49.6
Bioresource Technology	192: 192–201	Caffeine	70
Journal of Membrane Science	497: 504–513	Caffeine	100
Science of the Total Environment	550: 176–183	Caffeine	100
Water Science and Technology	66: 1856-1863	Caffeine	100
Water Research	44: 5999-6010	Caffeine	99.81
International Biodeterioration & Biodegradation	102: 40-48	Caffeine	99.46
Environmental Science and Technology	45:3341-3348	Caffeine	100
Water Science and Technology	63: 2486-2497	Sulfamethoxazole	88.13
Water Science and Technology	66: 1856-1863	Sulfamethoxazole	58.8
Water Science and Technology	63: 57-65	Sulfamethoxazole	88.06
Chemosphere	119:1054-1061	Sulfamethoxazole	34.44
Water Research	45: 2439–2451	Sulfamethoxazole	91.9
Bioresource Technology	102: 10386–10390	Sulfamethoxazole	65
PhD Thesis, University of Wollongong		Sulfamethoxazole	90.7
Desalination	261: 148-156	Sulfamethoxazole	55
Desalination	261: 148-156	Sulfamethoxazole	61
Journal of Membrane Sciences	365: 206-215	Sulfamethoxazole	91.4
Water Research	43: 831-841	Sulfamethoxazole	80
Water Research	43: 831-841	Sulfamethoxazole	78
Desalination	221: 511-517	Sulfamethoxazole	52
Analytical and Bioanalytical Chemistry	387: 1365-1377	Sulfamethoxazole	60
Water Research	39: 4797-4807	Sulfamethoxazole	61
Bioresource Technology	101: 1494–1500	Sulfamethoxazole	92
Desalination	236: 127–134	Sulfamethoxazole	50
Bioresource Technology	102 : 5319–5324	Sulfamethoxazole	64
Science of the Total Environment	550: 176–183	Sulfamethoxazole	60
Journal of Membrane Science	497: 504–513	Sulfamethoxazole	85
Water Science and Technology	66: 1856-1863	Trimethoprim	28.5
International Biodeterioration & Biodegradation	102: 40-48	Trimethoprim	65.04
Chemosphere	119:1054-1061	Trimethoprim	29.06
Environmental Science and Technology	45:3341-3348	Trimethoprim	82.41
Journal of Membrane Sciences	365: 206-215	Trimethoprim	17.4
Water Research	43: 831-841	Trimethoprim	66.7
Water Research	43: 831-841	Trimethoprim	47.5
Desalination	221: 511-517	Trimethoprim	36.4
Water Research	45: 2439–2451	Trimethoprim	16.6

Science of the Total Environment	550: 176–183	Trimethoprim	40
Water Science and Technology	63: 2486-2497	Metoprolol	83.81
Water Research	44: 5999-6010	Metoprolol	71.159685
Water Science and Technology	63: 57-65	Metoprolol	83.81
Environmental Science and Technology	45:3341-3348	Metoprolol	37.05
Bioresource Technology	144: 247-254	Carbamazepine	58
International Biodeterioration & Biodegradation	85: 474-482	Carbamazepine	32
Bioresource Technology	148: 234-241	Carbamazepine	23
PhD Thesis, University of Wollongong		Carbamazepine	21
PhD Thesis, University of Wollongong		Carbamazepine	28
Journal of Membrane Sciences	365: 206-215	Carbamazepine	13.2
Desalination	221: 511-517	Carbamazepine	10
Analytical and Bioanalytical Chemistry	387: 1365-1377	Carbamazepine	0
Water Research	39: 4797-4807	Carbamazepine	13
Water Research	39: 4797-4807	Carbamazepine	5
Water Research	39: 4797-4807	Carbamazepine	0
Water Research	44: 5999-6010	Carbamazepine	8.79891606
International Biodeterioration & Biodegradation	102: 40-48	Carbamazepine	0.91
Chemical Engineering Journal	277: 202-208	Carbamazepine	100
Environmental Science and Technology	45:3341-3348	Carbamazepine	0
Water Research	45: 2439–2451	Carbamazepine	13.4
Bioresource Technology	102: 10386–10390	Carbamazepine	10
Water Science and Technology	66: 1856-1863	Carbamazepine	20
Bioresource Technology	101: 1494–1500	Carbamazepine	22
Journal of Membrane Science	383: 144-151	Carbamazepine	35
Water Science and Technology	66: 1856-1863	Estriol	100
Water Research	44: 5999-6010	Estriol	98.5874625
Environment International	59:262-273	Estriol	99.46
Water Research	45: 2439–2451	Estriol	100
Bioresource Technology	144: 247-254	Estriol	96
Journal of Membrane Science	383: 144-151	Estriol	85
Bioresource Technology	144: 247-254	Ketoprofen	94
International Biodeterioration & Biodegradation	85: 474-482	Ketoprofen	66
Bioresource Technology	148: 234-241	Ketoprofen	94
PhD Thesis, University of Wollongong		Ketoprofen	3.9
PhD Thesis, University of Wollongong		Ketoprofen	89.1
Journal of Membrane Sciences	365: 206-215	Ketoprofen	70.5
Analytical and Bioanalytical	387: 1365-1377	Ketoprofen	91.9

Chemistry			
Water Research	43: 831-841	Ketoprofen	44
Water Research	43: 831-841	Ketoprofen	44
Desalination	261: 148-156	Ketoprofen	86
Desalination	261: 148-156	Ketoprofen	89
Environmental Science and Technology	41:3708-3714	Ketoprofen	84
Water Research	39: 2654-2664	Ketoprofen	62
Water Research	45: 2439–2451	Ketoprofen	70
Bioresource Technology	101: 1494–1500	Ketoprofen	3.7
Journal of Membrane Science	383: 144-151	Ketoprofen	53
Water Science and Technology	66: 1856-1863	Ketoprofen	94.54
Water Research	44: 5999-6010	Ketoprofen	99.6688689
Water Science and Technology	66: 1856-1863	Estrone	98.5
Water Research	44: 5999-6010	Estrone	99.6018928
Environmental Science and Technology	38: 3047-3055	Estrone	96
International Biodeterioration & Biodegradation	102: 40-48	Estrone	100
Chemical Engineering Journal	277: 202-208	Estrone	0
Science of the Total Environment	447:248-254	Estrone	86.0465116
Environment International	59:262-273	Estrone	97.31
Water Research	45: 2439–2451	Estrone	95
Bioresource Technology	144: 247-254	Estrone	98
Journal of Environmental Management		Estrone	99
Journal of Membrane Science	383: 144-151	Estrone	99
Water Science and Technology	66: 1856-1863	Naproxen	99.16
International Biodeterioration & Biodegradation	102: 40-48	Naproxen	96.56
Bioresource Technology	144: 247-254	Naproxen	82
International Biodeterioration & Biodegradation	85: 474-482	Naproxen	45
Bioresource Technology	148: 234-241	Naproxen	99
Desalination	261: 148-156	Naproxen	86
Desalination	261: 148-156	Naproxen	89
Journal of Membrane Sciences	365: 206-215	Naproxen	40
Water Research	43: 831-841	Naproxen	91
Water Research	43: 831-841	Naproxen	92
Desalination	221: 511-517	Naproxen	84
Analytical and Bioanalytical Chemistry	387: 1365-1377	Naproxen	99.3
Environmental Science and Technology	41:3708-3714	Naproxen	96
Environmental Science and Technology	41:3708-3714	Naproxen	96.3
Water Research	39: 2654-2664	Naproxen	71

Water Research	45: 2439–2451	Naproxen	40
Journal of Membrane Science	383: 144-151	Naproxen	78
Science of the Total Environment	550: 176–183	Naproxen	98
Water Research	45: 2473-2484	Bisphenol A	70.69
Water Science and Technology	66: 1856-1863	Bisphenol A	100
Water Research	44: 5999-6010	Bisphenol A	98.1802991
Science of the Total Environment	447:248-254	Bisphenol A	0
Journal of Membrane Science	383: 144-151	Bisphenol A	100
Water Research	45: 2439–2451	Bisphenol A	90
International Biodeterioration & Biodegradation	85: 474-482	Bisphenol A	80
Bioresource Technology	148: 234-241	Bisphenol A	75
Bioresource Technology	101: 1494–1500	Bisphenol A	97.00
International Biodeterioration & Biodegradation	85: 483-490	Bisphenol A	85.00
Process Biochemistry	43: 451–456	Bisphenol A	93.7
Water Research	39: 4797-4807	Bisphenol A	95
Desalination	236: 127–134	Bisphenol A	90
Bioresource Technology	113: 174–180	Bisphenol A	96
Water Science and Technology	63: 2486-2497	Propranolol	45.7
Water Science and Technology	63: 57-65	Propranolol	45.75
Water Research	44: 5999-6010	EE2	98.1802991
Environmental Science and Technology	38: 3047-3055	EE2	75
Science of the Total Environment	447:248-254	EE2	87.6267748
Environment International	59:262-273	EE2	99.64
Water Research	45: 2439–2451	EE2	90
Journal of Membrane Science	383: 144-151	EE2	90
Bioresource Technology	144: 247-254	EE2	95
Water Science and Technology	66: 1856-1863	EE2	96
Bioresource Technology	144: 247-254	Ibuprofen	99
International Biodeterioration & Biodegradation	85: 474-482	Ibuprofen	96
Bioresource Technology	148: 234-241	Ibuprofen	98
Bioresource Technology	101: 1494–1500	Ibuprofen	5.5
Bioresource Technology	101: 1494–1500	Ibuprofen	99
Journal of Membrane Sciences	365: 206-215	Ibuprofen	97
Water Research	43: 831-841	Ibuprofen	99
Water Research	43: 831-841	Ibuprofen	99
Environmental Science and Technology	41:3708-3714	Ibuprofen	94.6
Environmental Science and Technology	41:3708-3714	Ibuprofen	98.2
Water Research	39: 4797-4807	Ibuprofen	98

Water Research	39: 4797-4807	Ibuprofen	99
Water Research	39: 4797-4807	Ibuprofen	97
Water Research	39: 2654-2664	Ibuprofen	71
Journal of Membrane Science	383: 144-151	Ibuprofen	95
Science of the Total Environment	550: 176–183	Ibuprofen	99
Water Science and Technology	66: 1856-1863	Ibuprofen	99.5
International Biodeterioration & Biodegradation	102: 40-48	Ibuprofen	98.55
Bioresource Technology	101: 1494–1500	Ibuprofen	73
Water Science and Technology	66: 1856-1863	17β-Estradiol	97.07
Water Research	44: 5999-6010	17β-estradiol	99.8877982
Environmental Science and Technology	38: 3047-3055	17β-estradiol	98
Science of the Total Environment	447:248-254	17B-estradiol	91.0301954
Environment International	59:262-273	17B-estradiol	88.51
Water Research	45: 2439–2451	17B-estradiol	90
Journal of Membrane Science	383: 144-151	17B-estradiol	90
Bioresource Technology	144: 247-254	17B-estradiol	95
Water Science and Technology	63: 2486-2497	Diclofenac	57.2
Water Science and Technology	66: 1856-1863	Diclofenac	43.1
Water Research	44: 5999-6010	Diclofenac	16.8236229
Water Science and Technology	63: 57-65	Diclofenac	57.9
International Biodeterioration & Biodegradation	102: 40-48	Diclofenac	57.79
Chemosphere	119:1054-1061	Diclofenac	24.08
Environmental Science and Technology	45:3341-3348	Diclofenac	55.55
Bioresource Technology	144: 247-254	Diclofenac	26
International Biodeterioration & Biodegradation	85: 474-482	Diclofenac	15
Bioresource Technology	148: 234-241	Diclofenac	50
International Biodeterioration & Biodegradation	85: 483-490	Diclofenac	55
Bioresource Technology	101: 1494–1500	Diclofenac	0.8
Bioresource Technology	101: 1494–1500	Diclofenac	42
Journal of Membrane Sciences	365: 206-215	Diclofenac	17.4
Water Research	43: 831-841	Diclofenac	63
Water Research	43: 831-841	Diclofenac	66
Desalination	221: 511-517	Diclofenac	98
Analytical and Bioanalytical Chemistry	387: 1365-1377	Diclofenac	87.4
Environmental Science and Technology	41:3708-3714	Diclofenac	50
Environmental Science and Technology	41:3708-3714	Diclofenac	81.6
Water Research	39: 2654-2664	Diclofenac	23
Water Research	39: 4797-4807	Diclofenac	0

Water Research	39: 4797-4807	Diclofenac	51
Water Research	39: 4797-4807	Diclofenac	33
Journal of Membrane Science	383: 144-151	Diclofenac	23
Bioresource Technology	101: 1494–1500	Diclofenac	0.22
Bioresource Technology	102: 6299–6303	Diclofenac	10
Water Science and Technology	66: 1856-1863	Triclosan	96.65
International Biodeterioration & Biodegradation	102: 40-48	Triclosan	67.03
Bioresource Technology	102: 6299–6303	Triclosan	90
Water Research	45: 2439–2451	Triclosan	91.80
Bioresource Technology	144: 247-254	Triclosan	96
International Biodeterioration & Biodegradation	85: 474-482	Triclosan	99
Bioresource Technology	148: 234-241	Triclosan	98
Journal of Membrane Science	383: 144-151	Triclosan	99
Journal of Membrane Sciences	365: 206-215	Triclosan	94
Water Science and Technology	66: 1856-1863	Gemfibrozil	61.09
International Biodeterioration & Biodegradation	102: 40-48	Gemfibrozil	92.03
Environmental Science and Technology	45:3341-3348	Gemfibrozil	87.98
Bioresource Technology	144: 247-254	Gemfibrozil	97
International Biodeterioration & Biodegradation	85: 474-482	Gemfibrozil	97
Bioresource Technology	148: 234-241	Gemfibrozil	98
Water Research	43: 831-841	Gemfibrozil	33
Water Research	43: 831-841	Gemfibrozil	42
Water Research	45: 2439–2451	Gemfibrozil	98.95
Journal of Membrane Science	383: 144-151	Gemfibrozil	99
Water Research	44: 5999-6010	Galaxolide	60.1892829
Science of the Total Environment	447:248-254	Galaxolide	71.2418301
Water Research	45: 2473-2484	Nonylphenol	82.33
Water Research	44: 5999-6010	Nonylphenol	70.4879077
Bioresource Technology	159: 311–319	Nonylphenol	95
Journal of Membrane Science	383: 144-151	Nonylphenol	90
Bioresource Technology	113: 169–173	Nonylphenol	95
Water Research	44: 5999-6010	Tonalide	49.8812766
Biresource Technology	165: 96–104	Salicylic acid	95
Journal of Membrane Science	383: 144–151	Salicylic acid	93
Biresource Technology	148: 234–241	Salicylic acid	90
Bioresource Technology	144: 247-254	Salicylic acid	90
International Biodeterioration & Biodegradation	109: 61–72	Salicylic acid	99.1
International Biodeterioration & Biodegradation	85: 474-482	Salicylic acid	95

Bioresource Technology	113: 169–173	Salicylic acid	100
Bioresource Technology	159: 311–319	Salicylic acid	90
Desalination	273: 142–147	Salicylic acid	96
Biresource Technology	148: 234–241	Fenoprop	60
Journal of Membrane Science	383: 144–151	Fenoprop	35
Biresource Technology	113: 169–173	Fenoprop	30
Bioresource Technology	144: 247-254	Fenoprop	85
International Biodeterioration & Biodegradation	109: 61–72	Fenoprop	49.6
Journal of Membrane Science	383: 144–151	Fenoprop	20
Bioresource Technology	159: 311–319	Fenoprop	15
Biresource Technology	148: 234–241	Amitriptyline	85
Biresource Technology	165: 96–104	Amitriptyline	95
Water Science and Technology	66: 1856-1863	Amitriptyline	56
Water Research	45: 2439–2451	Amitriptyline	95
Bioresource Technology	144: 247-254	Amitriptyline	97
Water Science and Technology	66: 1856-1863	Amitriptyline	68
International Biodeterioration & Biodegradation	102: 40-48	Amitriptyline	30
Water Science and Technology	69: 2221-2229	Amitriptyline	68
International Biodeterioration & Biodegradation	109: 61–72	Amitriptyline	98.4
Bioresource Technology	192: 192–201	Amitriptyline	99
Water Science and Technology	66: 1856-1863	Omeprazole	65
Water Research	45: 2439–2451	Omeprazole	35
Journal of Membrane Science	365: 206–215	Omeprazole	58
Journal of Membrane Science	497: 504–513	Omeprazole	54
Journal of Membrane Science	365: 206–215	Atenolol	96.9
Water Research	45: 2439–2451	Atenolol	96
Water Research	43: 831-841	Atenolol	76.6
Bioresource Technology	192: 192–201	Atenolol	47
Water Science and Technology	66: 1856-1863	Atenolol	93
Science of the Total Environment	550: 176–183	Atenolol	85
Science of the Total Environment	550: 176–183	Atenolol	95
International Biodeterioration & Biodegradation	102: 40–48	Atenolol	83
International Biodeterioration & Biodegradation	102: 40–48	Atenolol	94
Analytical and Bioanalytical Chemistry	387: 1365-1377	Atenolol	88
Analytical and Bioanalytical Chemistry	387: 1365-1377	Paracetamol /Acetaminophen	99
Water Research	43: 831-841	Paracetamol /Acetaminophen	97
Desalination	261: 148-156	Paracetamol /Acetaminophen	99.9
Water Research	43: 831-841	Paracetamol /Acetaminophen	64.5

Water Research	43: 831-841	Paracetamol /Acetaminophen	60.7
Desalination	221: 511-517	Paracetamol /Acetaminophen	91.5
Science of the Total Environment	550: 176–183	Paracetamol /Acetaminophen	99
Science of the Total Environment	550: 176–183	Paracetamol /Acetaminophen	99
Water Science and Technology	66: 1856-1863	Paracetamol /Acetaminophen	99
Journal of Membrane Science	383: 144-151	Paracetamol /Acetaminophen	45
Journal of Membrane Science	383: 144-151	Paracetamol /Acetaminophen	40
Journal of Membrane Science	383: 144-151	Paracetamol /Acetaminophen	58
Journal of Membrane Science	383: 144-151	Paracetamol /Acetaminophen	69
Bioresource Technology	159: 311–319	Paracetamol /Acetaminophen	80
Journal of Membrane Science	365: 206–215	Paracetamol /Acetaminophen	90
Water Research	43: 831-841	Fluoxetine	98
Water Science and Technology	66: 1856-1863	Fluoxetine	60
Water Research	45: 5323–5333	Fluoxetine	90
Desalination	250: 653–659	Fluoxetine	98
Water Research	45: 2439–2451	Primidone	12.4
Biresource Technology	165: 96–104	Primidone	55
Journal of Membrane Science	383: 144–151	Primidone	50
Biresource Technology	113: 169–173	Primidone	90
Biresource Technology	148: 234–241	Primidone	96
Journal of Membrane Science	383: 144–151	Primidone	30
Journal of Membrane Science	383: 144–151	Primidone	35
Journal of Membrane Science	383: 144–151	Primidone	40
Bioresource Technology	144: 247-254	Primidone	99
International Biodeterioration & Biodegradation	102: 40–48	Primidone	28
Bioresource Technology	159: 311–319	Primidone	68
Journal of Membrane Science	365: 206–215	Primidone	10
Journal of Membrane Science	365: 206–215	Atrazine	10
Water Research	40: 3419-3428	Atrazine	9
Desalination	224: 1-6	Atrazine	40
Bioresource Technology	144: 247-254	Atrazine	35
Bioresource Technology	102: 6299–6303	Atrazine	2
International Biodeterioration & Biodegradation	109: 61–72	Atrazine	5.8
International Biodeterioration & Biodegradation	109: 61–72	Atrazine	5.7
Biresource Technology	165: 96–104	Atrazine	5
Biresource Technology	165: 96–104	Atrazine	0
Journal of Membrane Science	365: 206–215	Atrazine	3

Water Research	40: 3419-3428	DEET	19
Water Research	41: 1013-1021	DEET	19
Water Research	45: 2439–2451	DEET	4.6
Science of the Total Environment	550: 176–183	DEET	5
Science of the Total Environment	550: 176–183	DEET	4
Water Science and Technology	66: 1856-1863	DEET	100
International Biodeterioration & Biodegradation	102: 40–48	DEET	82
International Biodeterioration & Biodegradation	102: 40–48	DEET	96
Water Research	40: 3419-3428	DEET	9
Water Research	40: 3419-3428	Simazine	10
Bioresource Technology	189: 391–398	Simazine	54
Water Research	45: 2439–2451	Triclosan	95
Biresource Technology	165: 96–104	Triclosan	95
Biresource Technology	113: 169–173	Triclosan	98
Journal of Membrane Science	383: 144–151	Triclosan	95
Bioresource Technology	102: 6299–6303	Triclosan	90
Bioresource Technology	144: 247-254	Triclosan	96
Journal of Membrane Science	383: 144–151	Triclosan	93
Journal of Membrane Science	383: 144–151	Triclosan	90
Journal of Membrane Science	383: 144–151	Triclosan	88
Biresource Technology	148: 234–241	Triclosan	97
Water Science and Technology	66: 1856-1863	Triclosan	99
Journal of Membrane Science	365: 206–215	Triclosan	95
Bioresource Technology	159: 311–319	Triclosan	93
International Biodeterioration & Biodegradation	102: 40–48	Triclosan	65
International Biodeterioration & Biodegradation	102: 40–48	Triclosan	66
Biresource Technology	165: 96–104	Octocylene	90
Bioresource Technology	144: 247-254	Octocylene	88
International Biodeterioration & Biodegradation	109: 61–72	Octocylene	92
International Biodeterioration & Biodegradation	109: 61–73	Octocylene	95.5
Biresource Technology	165: 96–104	Octocylene	80
Biresource Technology	165: 96–104	4- tert octylphenol	85
Biresource Technology	113: 169–173	4- tert octylphenol	95
Journal of Membrane Science	383: 144–151	4- tert octylphenol	98
Biresource Technology	148: 234–241	4- tert octylphenol	99
Bioresource Technology	144: 247-254	4- tert octylphenol	99
Journal of Membrane Science	383: 144–151	4- tert octylphenol	95
Journal of Membrane Science	383: 144–151	4- tert octylphenol	90
Journal of Membrane Science	383: 144–151	4- tert octylphenol	90
Bioresource Technology	113: 169–173	4- tert octylphenol	99
Journal of Membrane Science	365: 206–215	4- tert octylphenol	95

Bioresource Technology	159: 311–319	4- tert octylphenol	85
Biresource Technology	165: 96–104	4- tert octylphenol	80
International Biodeterioration & Biodegradation	109: 61–72	4- tert octylphenol	95
International Biodeterioration & Biodegradation	109: 61–72	4- tert octylphenol	89.1

Table S2: Removal of TrOCs by conventional activated sludge process

Journal Name	Volume: Pages	TrOC	Removal (%)
Science of the Total Environment	466-467: 976-984	Caffeine	100
Science of the Total Environment	466-467: 976-984	Caffeine	98
Water Air and Soil Pollution	223: 2611-2621	Caffeine	100
Ecological Engineering	37: 1595-1600	Caffeine	97.53
Chemosphere	66: 993-1002	Caffeine	89.8305085
Water, Air and Soil Pollution	216: 463-471	Caffeine	100
Water Environmental Research	87: 414-424	Caffeine	99.8068877
Water Environmental Research	87: 414-424	Caffeine	99.9096541
Chemosphere	134: 395-401	Caffeine	99.3
Chemosphere	134: 133-140	Caffeine	86.3839286
Environmental Science and Pollution Research	21:4276-4285	Caffeine	93.78
Journal of Environmental Sciences	26:1949-1959	Caffeine	98.79
Environmental Science and Technology	45:3341-3348	Caffeine	99.73
Journal of Hazardous Materials	239-240:40-47	Caffeine	56.78
Journal of Hazardous Materials	164:1509-1516	Caffeine	75
Journal of Hazardous Materials	164:1509-1516	Caffeine	44
Journal of Hazardous Materials	164:1509-1516	Caffeine	64
Journal of Hazardous Materials	164:1509-1516	Caffeine	55
Environment International	33:596-601	Caffeine	86.7
Environment International	33:596-601	Caffeine	38.15
Science of the Total Environment	409: 4351-4360	Caffeine	99.2
Environment International	33:596-601	Caffeine	76.3
Environment International	33:596-601	Caffeine	56.88
Water Research	43: 831-841	Sulfamethoxazole	73.8
Science of the Total Environment	409: 4351-4360	Sulfamethoxazole	51.9
Science of the Total Environment	437: 403-412	Sulfamethoxazole	64.8
Chemosphere	87: 453-462	Sulfamethoxazole	92.33
Journal of Hazardous Materials	260: 389-398	Sulfamethoxazole	0
Science of the Total	466-467: 976-984	Sulfamethoxazole	57

Journal Name	Volume: Pages	TrOC	Removal (%)
Environment			
Science of the Total Environment	466-467: 976-984	Sulfamethoxazole	81
Ecological Engineering	37: 1595-1600	Sulfamethoxazole	42.36
Water Research	38: 2918-2926	Sulfamethoxazole	56.8965517
Water Research	45: 5399-5411	Sulfamethoxazole	0
Environmental Toxicology and Chemistry	29: 1658-1668	Sulfamethoxazole	0
Water Science and Technology	63: 2486-2497	Sulfamethoxazole	52.52
Science of the Total Environment	454-455: 411-425	Sulfamethoxazole	52
Science of the Total Environment	532:762-770	Sulfamethoxazole	42.4
Chemosphere	119:1054-1061	Sulfamethoxazole	64.74
Chemosphere	119:1054-1061	Sulfamethoxazole	37.76
Chemosphere	119:1054-1061	Sulfamethoxazole	54.36
Chemosphere	99:160-170	Sulfamethoxazole	60.83
Archives of Environmental Contamination and Toxicology	66:538-548	Sulfamethoxazole	97.85
Archives of Environmental Contamination and Toxicology	66:538-548	Sulfamethoxazole	90.94
Chemosphere	111:418-426	Sulfamethoxazole	58
Journal of Environmental Sciences	26:1949-1959	Sulfamethoxazole	74.11
Water Science and Technology	52:29-35	Sulfamethoxazole	48.62
Science of the Total Environment	470-471:618-630	Sulfamethoxazole	0
Water Research	43: 831-841	Trimethoprim	40.4
Science of the Total Environment	466-467: 976-984	Trimethoprim	88
Science of the Total Environment	466-467: 976-984	Trimethoprim	71
Water Air and Soil Pollution	223: 2611-2621	Trimethoprim	100
Water Research	45: 5399-5411	Trimethoprim	91.221374
Environmental Toxicology and Chemistry	29: 1658-1668	Trimethoprim	0
Science of the Total Environment	454-455: 411-425	Trimethoprim	31
Chemosphere	87: 453-462	Trimethoprim	27.48
Science of the Total Environment	473-474: 235-243	Trimethoprim	7.79220779
Science of the Total	473-474: 235-243	Trimethoprim	15.4545455

Journal Name	Volume: Pages	TrOC	Removal (%)
Environment			
Water Environmental Research	87: 414-424	Trimethoprim	10.6382979
Water Environmental Research	87: 414-424	Trimethoprim	0
Chemosphere	134: 395-401	Trimethoprim	0
Science of the Total Environment	532:762-770	Trimethoprim	0
Chemosphere	119:1054-1061	Trimethoprim	17.45
Chemosphere	119:1054-1061	Trimethoprim	34.86
Chemosphere	119:1054-1061	Trimethoprim	0
Science of the Total Environment	470-471:844-854	Trimethoprim	32.2033898
Chemosphere	99:160-170	Trimethoprim	29.77
Environmental Science and Pollution Research	21:4276-4285	Trimethoprim	0
Chemosphere	111:418-426	Trimethoprim	20
Journal of Environmental Sciences	26:1949-1959	Trimethoprim	68.09
Science of the Total Environment	409: 4351-4360	Trimetoprim	69
Environmental Science and Technology	45:3341-3348	Trimethoprim	11.15
Bulletin of Environmental Contamination and Toxicology	87:31-35	Trimethoprim	38.7875
Science of the Total Environment	470-471:618-630	Trimethoprim	21.79
Water Research	43: 831-841	Metoprolol	24.7
Science of the Total Environment	409: 4351-4360	Metoprolol	23
Environmental Toxicology and Chemistry	29: 1658-1668	Metoprolol	0
Water Science and Technology	63: 2486-2497	Metoprolol	46.76
Science of the Total Environment	454-455: 411-425	Metoprolol	29
Science of the Total Environment	532:762-770	Metoprolol	0
Chemosphere	99:160-170	Metoprolol	0
Environmental Science and Pollution Research	21:4276-4285	Metoprolol	0
Journal of Environmental Sciences	26:1949-1959	Metoprolol	24.25
Environmental Science and Technology	45:3341-3348	Metoprolol	0
Environmental Science and Pollution Research	21:7578-7585	Metoprolol	31.7361543
Water Research	41:1001-1012	Metoprolol	34
Science of the Total	470-471:618-630	Metoprolol	15.92

Journal Name	Volume: Pages	TrOC	Removal (%)
Environment			
Science of the Total Environment	466-467: 976-984	Carbamazepine	6.3
Science of the Total Environment	466-467: 976-984	Carbamazepine	2.9
Journal of Xenobiotics	2: e3	Carbamazepine	9.44
Ecological Engineering	37: 1595-1600	Carbamazepine	0
Water Research	45: 5399-5411	Carbamazepine	0
Chemosphere	66: 993-1002	Carbamazepine	13.3333333
Environmental Toxicology and Chemistry	29: 1658-1668	Carbamazepine	15
Science of the Total Environment	454-455: 411-425	Carbamazepine	36
Chemosphere	66: 993-1002	Carbamazepine	54.2857143
Science of the Total Environment	514: 273-280	Carbamazepine	0
Science of the Total Environment	514: 273-280	Carbamazepine	0
Water Environmental Research	87: 414-424	Carbamazepine	0
Water Environmental Research	87: 414-424	Carbamazepine	0
Chemosphere	134: 395-401	Carbamazepine	0
Chemosphere	134: 133-140	Carbamazepine	58.8235294
Chemical Engineering Journal	277: 202-208	Carbamazepine	87.1
Chemical Engineering Journal	277: 202-208	Carbamazepine	94.2
Chemical Engineering Journal	277: 202-208	Carbamazepine	100
Chemical Engineering Journal	277: 202-208	Carbamazepine	37.1
Chemical Engineering Journal	277: 202-208	Carbamazepine	100
Science of the Total Environment	532:762-770	Carbamazepine	0
Environmental Science and Pollution Research	22:5864-5876	Carbamazepine	41.125
Chemosphere	119:1054-1061	Carbamazepine	0
Chemosphere	119:1054-1061	Carbamazepine	0
Chemosphere	119:1054-1061	Carbamazepine	0
Science of the Total Environment	470-471:844-854	Carbamazepine	35.0877193
Chemosphere	99:160-170	Carbamazepine	0
Environmental Science and Pollution Research	21:4276-4285	Carbamazepine	27.85
Archives of Environmental Contamination and Toxicology	66:538-548	Carbamazepine	0

Journal Name	Volume: Pages	TrOC	Removal (%)
Archives of Environmental Contamination and Toxicology	66:538-548	Carbamazepine	0
Chemosphere	111:418-426	Carbamazepine	0
Journal of Environmental Sciences	26:1949-1959	Carbamazepine	0
Water Research	40:3297-3303	Carbamazepine	3.331875
Environmental Science and Technology	45:3341-3348	Carbamazepine	0
Bulletin of Environmental Contamination and Toxicology	87:31-35	Carbamazepine	0
Journal of Hazardous Materials	239-240:40-47	Carbamazepine	47.06
Journal of Hazardous Materials	164:1509-1516	Carbamazepine	11
Journal of Hazardous Materials	164:1509-1516	Carbamazepine	7
Journal of Hazardous Materials	164:1509-1516	Carbamazepine	7
Journal of Hazardous Materials	164:1509-1516	Carbamazepine	8
Environment International	33:596-601	Carbamazepine	24.97
Environment International	33:596-601	Carbamazepine	0
Environment International	33:596-601	Carbamazepine	6.28
Science of the Total Environment	409: 4351-4360	Carbamazepine	23.1
Environment International	33:596-601	Carbamazepine	0
Water Research	41:1001-1012	Carbamazepine	0
Science of the Total Environment	470-471:618-630	Carbamazepine	0
Water Research	46:5600-5612	Carbamazepine	3.6
Chemosphere	92: 986-992	Estriol	65.6
Chemosphere	92: 986-992	Estriol	93.3
Science of the Total Environment	409: 4351-4360	Estriol	100
		Estriol	72.9
Science of the Total Environment	468-469: 584-597	Estriol	100
Environment International	33: 654-669	Estriol	89.8181818
Environmental Monitoring and Assessment	186: 525-539	Estriol	70
Environmental Monitoring and Assessment	186: 525-539	Estriol	81

Journal Name	Volume: Pages	TrOC	Removal (%)
Chemosphere	134: 395-401	Estriol	66.8
Science of the Total Environment	447:248-254	Estriol	26.4150943
Analytica Chimica Acta	501:79-88	Estriol	96.7741935
Chemosphere	82:1124-1128	Estriol	99.9
Environmental Monitoring and Assessement	184:6799-6813	Estriol	98.3275
Environment International	59:262-273	Estriol	87.79
Environment International	59:262-273	Estriol	92.64
Environment International	59:262-273	Estriol	94.07
Environment International	59:262-273	Estriol	99.82
Environment International	59:262-273	Estriol	99.64
Water Research	40:3297-3303	Estriol	99.7666667
Water Research	41:2117-2126	Estriol	99.5
Journal of Environmental Monitoring	13:1366-1373	Estriol	94.3950178
Journal of Hazardous Materials	239-240:40-47	Estriol	26.34
Journal of Environmental Monitoring	14:2204-2211	Estriol	100
Water Research	43: 831-841	Ketoprofen	54.6
Chemosphere	87: 453-462	Ketoprofen	47.8
Journal of Hazardous Materials	260: 389-398	Ketoprofen	100
Journal of Hazardous Materials	244-245: 259-267	Ketoprofen	89
Journal of Hazardous Materials	244-245: 259-267	Ketoprofen	83
Agricultural Water Management	86: 72-80	Ketoprofen	77
Water Air and Soil Pollution	223: 2611-2621	Ketoprofen	31.9
Environmental Toxicology and Chemistry	29: 1658-1668	Ketoprofen	5.55555556
Science of the Total Environment	454-455: 411-425	Ketoprofen	49
Environmental Science and Pollution Research	22:5864-5876	Ketoprofen	44.5
Water Research	40:3297-3303	Ketoprofen	45.15
Environmental Science and Technology	41:3708-3714	Ketoprofen	54.5454545
Environmental Science and Pollution Research	20:108-116	Ketoprofen	69

Journal Name	Volume: Pages	TrOC	Removal (%)
Bulletin of Environmental Contamination and Toxicology	87:31-35	Ketoprofen	43.7575
Journal of Hazardous Materials	239-240:40-47	Ketoprofen	37.34
Journal of Hazardous Materials	164:1509-1516	Ketoprofen	52
Journal of Hazardous Materials	164:1509-1516	Ketoprofen	56
Journal of Hazardous Materials	164:1509-1516	Ketoprofen	72
Journal of Hazardous Materials	164:1509-1516	Ketoprofen	58
Environment International	33:596-601	Ketoprofen	36.76
Science of the Total Environment	409: 4351-4360	Ketoprofen	94.2
Environment International	33:596-601	Ketoprofen	38.16
Environment International	33:596-601	Ketoprofen	65.23
Environment International	33:596-601	Ketoprofen	65.91
Science of the Total Environment	485-486:300-308	Ketoprofen	48
International Journal of Environmental Science and Technology	8: 245-254	Estrone	85.6
International Journal of Environmental Science and Technology	8: 245-254	Estrone	84.2
Chemosphere	92: 986-992	Estrone	85.47
Chemosphere	92: 986-992	Estrone	45.93
Science of the Total Environment	409: 4351-4360	Estrone	87.1
		Estrone	57.9
Water Research	38: 2918-2926	Estrone	0
Environmental Science and Technology	38: 3047-3055	Estrone	49
Environmental Science and Technology	38: 3047-3055	Estrone	96
Environmental Science and Technology	38: 3047-3055	Estrone	99
Science of the Total Environment	468-469: 584-597	Estrone	72
Environment International	33: 654-669	Estrone	0
Water, Air and Soil Pollution	216: 463-471	Estrone	100
Environmental Monitoring and Assessment	186: 525-539	Estrone	75

Journal Name	Volume: Pages	TrOC	Removal (%)
Science of the Total Environment	407: 2760-2770	Estrone	78
Environmental Monitoring and Assessment	186: 525-539	Estrone	88
Chemosphere	134: 395-401	Estrone	93.7
Chemical Engineering Journal	277: 202-208	Estrone	70.65
Chemical Engineering Journal	277: 202-208	Estrone	45.82
Chemical Engineering Journal	277: 202-208	Estrone	100
Chemical Engineering Journal	277: 202-208	Estrone	38.06
Chemical Engineering Journal	277: 202-208	Estrone	22.26
Journal of Environmental Health Science & Engineering	12:97	Estrone	71.82
Science of the Total Environment	447:248-254	Estrone	75.862069
Analytica Chimica Acta	501:79-88	Estrone	54.2857143
Chemosphere	82:1124-1128	Estrone	97
Environmental Monitoring and Assessement	184:6799-6813	Estrone	82.0675
Environment International	59:262-273	Estrone	70.02
Environment International	59:262-273	Estrone	82.94
Environment International	59:262-273	Estrone	72.89
Environment International	59:262-273	Estrone	93.36
Environment International	59:262-273	Estrone	95.69
Water Research	40:3297-3303	Estrone	86.1666667
Water Research	41:2117-2126	Estrone	0
Journal of Environmental Monitoring	13:1366-1373	estrone	49.5049505
Water Science and Technology	52:29-35	Estrone	0
Journal of Environmental Monitoring	14:2204-2211	Estrone	88.8888889
Water Research	43: 831-841	Naproxen	71.8
Chemosphere	87: 453-462	Naproxen	91.2
Journal of Hazardous Materials	260: 389-398	Naproxen	100
Journal of Hazardous Materials	244-245: 259-267	Naproxen	95

Journal Name	Volume: Pages	TrOC	Removal (%)
Journal of Hazardous Materials	244-245: 259-267	Naproxen	91
Agricultural Water Management	86: 72-80	Naproxen	88
Journal of Xenobiotics	2: e3	Naproxen	63.91
Water Air and Soil Pollution	223: 2611-2621	Naproxen	83.34
Ecological Engineering	37: 1595-1600	Naproxen	77.83
Water Research	38: 2918-2926	Naproxen	48.387445
Environmental Toxicology and Chemistry	29: 1658-1668	Naproxen	4
Science of the Total Environment	454-455: 411-425	Naproxen	79
Science of the Total Environment	473-474: 235-243	Naproxen	63.75
Science of the Total Environment	473-474: 235-243	Naproxen	99.4827586
Science of the Total Environment	407: 2760-2770	Naproxen	94
Water Environmental Research	87: 414-424	Naproxen	97.5352113
Water Environmental Research	87: 414-424	Naproxen	98.5981308
Chemosphere	134: 395-401	Naproxen	96.2
Environmental Science and Pollution Research	22:5864-5876	Naproxen	47
Water Research	40:3297-3303	Naproxen	46.019375
Environmental Science and Technology	41:3708-3714	Naproxen	64.1304348
Environmental Science and Pollution Research	20:108-116	Naproxen	76
Water Science and Technology	52:29-35	Naproxen	48.62
Journal of Hazardous Materials	239-240:40-47	Naproxen	57.54
Journal of Hazardous Materials	164:1509-1516	Naproxen	43
Journal of Hazardous Materials	164:1509-1516	Naproxen	71
Journal of Hazardous Materials	164:1509-1516	Naproxen	48
Journal of Hazardous Materials	164:1509-1516	Naproxen	60
Environment International	33:596-601	Naproxen	40.92
Environment International	33:596-601	Naproxen	88.81
Science of the Total Environment	409: 4351-4360	Naproxen	95.7
Environment International	33:596-601	Naproxen	59.65
Environment	33:596-601	Naproxen	66.59

Journal Name	Volume: Pages	TrOC	Removal (%)
International			
Science of the Total Environment	485-486:300-308	Naproxen	96.5
Journal of Hazardous Materials	244-245: 259-267	Bisphenol A	96
Journal of Hazardous Materials	244-245: 259-267	Bisphenol A	55
		Bisphenol A	87.7
Chemosphere	66: 993-1002	Bisphenol A	72.8571429
Environmental Toxicology and Chemistry	29: 1658-1668	Bisphenol A	53
Environment International	33: 654-669	Bisphenol A	38.0714286
Water, Air and Soil Pollution	216: 463-471	Bisphenol A	99.9
Environmental Monitoring and Assessment	186: 525-539	Bisphenol A	76
Water Research	45: 2473-2484	Bisphenol A	79.19
Water Research	45: 2473-2484	Bisphenol A	70.47
Chemosphere	92: 986-992	Bisphenol A	29.68
Chemosphere	92: 986-992	Bisphenol A	21.76
Desalination	272: 240-245	Bisphenol A	96
Environmental Monitoring and Assessment	186: 525-539	Bisphenol A	85
Environmental Toxicology and Pharmacology	25:20-26	Bisphenol A	99.4912304
Water Research	42:1796-1804	Bisphenol A	79.4520548
Science of the Total Environment	447:248-254	Bisphenol A	0
Analytica Chimica Acta	501:79-88	Bisphenol A	90.4191617
Water Research	40:3297-3303	Bisphenol A	92.4
Journal of Environmental Monitoring	13:1366-1373	Bisphenol A	72.5814063
Chemosphere	119:43-51	Bisphenol A	90.4
Journal of Environmental Monitoring	14:2204-2211	Bisphenol A	92.7488464
Water Research	43: 831-841	Propranolol	58.8
Water Air and Soil Pollution	223: 2611-2621	Propranolol	17.75
Environmental Toxicology and Chemistry	29: 1658-1668	Propranolol	0
Water Science and Technology	63: 2486-2497	Propranolol	18.35
Science of the Total	454-455: 411-425	Propranolol	29

Journal Name	**Volume: Pages**	**TrOC**	**Removal (%)**
Environment			
Science of the Total Environment	514: 273-280	Propranolol	0
Science of the Total Environment	514: 273-280	Propranolol	0
Science of the Total Environment	532:762-770	Propranolol	0
Journal of Environmental Sciences	26:1949-1959	Propranolol	49.09
Journal of Hazardous Materials	239-240:40-47	Propranolol	16.47
International Journal of Environmental Science and Technology	8: 245-254	EE2	57.34
International Journal of Environmental Science and Technology	8: 245-254	EE2	72.73
		EE2	4.2
Chemosphere	92: 986-992	EE2	53.75
Chemosphere	92: 986-992	EE2	18.46
Environmental Science and Technology	38: 3047-3055	EE2	71
Environmental Science and Technology	38: 3047-3055	EE2	94
Environmental Science and Technology	38: 3047-3055	EE2	93
Science of the Total Environment	468-469: 584-597	EE2	90
Water, Air and Soil Pollution	216: 463-471	EE2	44.1
Environmental Monitoring and Assessment	186: 525-539	EE2	86
Environmental Monitoring and Assessment	186: 525-539	EE2	87
Journal of Environmental Health Science & Engineering	12:97	EE2	80.43
Science of the Total Environment	447:248-254	EE2	87.2321021
Chemosphere	82:1124-1128	EE2	75.52
Environmental Monitoring and Assesement	184:6799-6813	EE2	92.5975
Environment International	59:262-273	EE2	49.91
Environment International	59:262-273	EE2	88.51
Environment International	59:262-273	EE2	36.27
Environment International	59:262-273	EE2	81.51

Journal Name	Volume: Pages	TrOC	Removal (%)
Environment International	59:262-273	EE2	99.64
Journal of Environmental Monitoring	13:1366-1373	EE2	100
Journal of Hazardous Materials	239-240:40-47	EE2	47.06
Journal of Environmental Monitoring	14:2204-2211	EE2	100
Journal of Environmental Monitoring	5: 823-830	Ibuprofen	97.436495
Water Research	43: 831-841	Ibuprofen	99.1
Chemosphere	87: 453-462	Ibuprofen	100
Journal of Hazardous Materials	260: 389-398	Ibuprofen	100
Journal of Hazardous Materials	244-245: 259-267	Ibuprofen	100
Journal of Hazardous Materials	244-245: 259-267	Ibuprofen	100
Agricultural Water Management	86: 72-80	Ibuprofen	87
Journal of Xenobiotics	2: e3	Ibuprofen	96.19
Water Air and Soil Pollution	223: 2611-2621	Ibuprofen	92.3
Ecological Engineering	37: 1595-1600	Ibuprofen	98.18
Water Research	38: 2918-2926	Ibuprofen	64.4415205
Chemosphere	66: 993-1002	Ibuprofen	91.547619
Environmental Toxicology and Chemistry	29: 1658-1668	Ibuprofen	9
Science of the Total Environment	454-455: 411-425	Ibuprofen	92
Science of the Total Environment	473-474: 235-243	Ibuprofen	74.7826087
Science of the Total Environment	473-474: 235-243	Ibuprofen	99.6734694
Science of the Total Environment	407: 2760-2770	Ibuprofen	99
Water Environmental Research	87: 414-424	Ibuprofen	99.3041058
Water Environmental Research	87: 414-424	Ibuprofen	99.9264165
Chemosphere	134: 395-401	Ibuprofen	99.7
Chemosphere	134: 133-140	Ibuprofen	6.54250239
Environmental Science and Pollution Research	22:5864-5876	Ibuprofen	62.875
Chemosphere	99:160-170	Ibuprofen	94.53
Water Research	40:3297-3303	Ibuprofen	95.83125
Environmental Science and Technology	41:3708-3714	Ibuprofen	97.965412

Journal Name	Volume: Pages	TrOC	Removal (%)
Environmental Science and Pollution Research	20:108-116	Ibuprofen	87
Water Science and Technology	52:29-35	Ibuprofen	64.05
Journal of Hazardous Materials	239-240:40-47	Ibuprofen	87.47
Journal of Hazardous Materials	164:1509-1516	Ibuprofen	87
Journal of Hazardous Materials	164:1509-1516	Ibuprofen	84
Journal of Hazardous Materials	164:1509-1516	Ibuprofen	80
Journal of Hazardous Materials	164:1509-1516	Ibuprofen	87
Environment International	33:596-601	Ibuprofen	92.25
Environment International	33:596-601	Ibuprofen	98.51
Science of the Total Environment	409: 4351-4360	Ibuprofen	98.2
Environment International	33:596-601	Ibuprofen	94.34
Environment International	33:596-601	Ibuprofen	95.74
Science of the Total Environment	485-486:300-308	Ibuprofen	99
Science of the Total Environment	470-471:618-630	Ibuprofen	51.4
		17β-estradiol	52.4
Environmental Science and Technology	38: 3047-3055	17β-estradiol	80
Environmental Science and Technology	38: 3047-3055	17β-estradiol	97
Environmental Science and Technology	38: 3047-3055	17β-estradiol	98
Science of the Total Environment	468-469: 584-597	17β-estradiol	78
Environment International	33: 654-669	17β-estradiol	90.3614458
Water, Air and Soil Pollution	216: 463-471	17β-estradiol	63.1
International Journal of Environmental Science and Technology	8: 245-254	17β-estradiol	96.51
International Journal of Environmental Science and Technology	8: 245-254	17β-estradiol	98.7
Chemosphere	92: 986-992	17β-estradiol	32.64
Chemosphere	92: 986-992	17β-estradiol	78.79
Environmental Monitoring and Assessment	186: 525-539	17β-estradiol	57
Environmental Monitoring and	186: 525-539	17β-estradiol	81

Journal Name	Volume: Pages	TrOC	Removal (%)
Assessment			
Journal of Environmental Health Science & Engineering	12:97	17β-estradiol	68.18
Science of the Total Environment	447:248-254	17B-estradiol	96.4957265
Analytica Chimica Acta	501:79-88	17B-estradiol	76
Chemosphere	82:1124-1128	17B-estradiol	69.98
Environmental Monitoring and Assessement	184:6799-6813	17B-estradiol	96.3
Environment International	59:262-273	17B-estradiol	76.48
Environment International	59:262-273	17B-estradiol	73.79
Environment International	59:262-273	17B-estradiol	53.5
Environment International	59:262-273	17B-estradiol	68.04
Environment International	59:262-273	17B-estradiol	65.71
Water Research	40:3297-3303	17B-estradiol	90.8333333
Water Research	41:2117-2126	17B-estradiol	85.7
Journal of Environmental Monitoring	13:1366-1373	17B-estradiol	69.28
Water Science and Technology	52:29-35	17B-estradiol	66.67
Journal of Hazardous Materials	239-240:40-47	17B-estradiol	54.48
Journal of Environmental Monitoring	14:2204-2211	17B-estradiol	100
Water Research	43: 831-841	Diclofenac	21.8
Chemosphere	87: 453-462	Diclofenac	0
Journal of Hazardous Materials	244-245: 259-267	Diclofenac	75
Journal of Hazardous Materials	244-245: 259-267	Diclofenac	39
Agricultural Water Management	86: 72-80	Diclofenac	18
Science of the Total Environment	466-467: 976-984	Diclofenac	82
Science of the Total Environment	466-467: 976-984	Diclofenac	87
Journal of Xenobiotics	2: e3	Diclofenac	4.62
Ecological Engineering	37: 1595-1600	Diclofenac	16.09
Chemosphere	66: 993-1002	Diclofenac	40
Environmental Toxicology and Chemistry	29: 1658-1668	Diclofenac	0
Water Science and	63: 2486-2497	Diclofenac	8.27

Journal Name	Volume: Pages	TrOC	Removal (%)
Technology			
Science of the Total Environment	454-455: 411-425	Diclofenac	35
Science of the Total Environment	407: 2760-2770	Diclofenac	0
Water Environmental Research	87: 414-424	Diclofenac	36.7816092
Water Environmental Research	87: 414-424	Diclofenac	2.2556391
Environmental Science and Pollution Research	22:5864-5876	Diclofenac	37.5
Chemosphere	119:1054-1061	Diclofenac	24.93
Chemosphere	119:1054-1061	Diclofenac	0
Chemosphere	119:1054-1061	Diclofenac	0
Environmental Science and Technology	45:3341-3348	Diclofenac	30.55
Environmental Science and Technology	41:3708-3714	Diclofenac	42.2310757
Environmental Science and Pollution Research	21:7578-7585	Diclofenac	75
Science of the Total Environment	409: 4351-4360	Diclofenac	81.4
Environmental Science and Pollution Research	20:108-116	Diclofenac	53
Bulletin of Environmental Contamination and Toxicology	87:31-35	Diclofenac	22.1225
Journal of Hazardous Materials	239-240:40-47	Diclofenac	14.07
Science of the Total Environment	485-486:300-308	Diclofenac	95
Journal of Hazardous Materials	244-245: 259-267	Triclosan	93
Journal of Hazardous Materials	244-245: 259-267	Triclosan	91
Agricultural Water Management	86: 72-80	Triclosan	69
Journal of Xenobiotics	2: e3	Triclosan	62.17
Chemosphere	66: 993-1002	Triclosan	88.8888889
Journal of Environmental Monitoring	11: 2207-2215	Triclosan	96
Science of the Total Environment	473-474: 235-243	Triclosan	79.6666667
Science of the Total Environment	473-474: 235-243	Triclosan	98.6363636
Environmental Chemistry	21: 1323-1329	Triclosan	95.4
Science of the Total Environment	409: 4351-4360	Triclosan	79.6
Environmental Chemistry	21: 1323-1329	Triclosan	58

Journal Name	Volume: Pages	TrOC	Removal (%)
Chemosphere	134: 395-401	Triclosan	55.3
Water Research	42:1796-1804	Triclosan	77.5510204
Water Research	40:3297-3303	Triclosan	71.01875
Chemosphere	87: 453-462	Gemfibrozil	0
Agricultural Water Management	86: 72-80	Gemfibrozil	68
Science of the Total Environment	466-467: 976-984	Gemfibrozil	91
Science of the Total Environment	466-467: 976-984	Gemfibrozil	83
Water Air and Soil Pollution	223: 2611-2621	Gemfibrozil	26.09
Environmental Toxicology and Chemistry	29: 1658-1668	Gemfibrozil	0
Science of the Total Environment	454-455: 411-425	Gemfibrozil	46
Water Environmental Research	87: 414-424	Gemfibrozil	56.5217391
Water Environmental Research	87: 414-424	Gemfibrozil	90.4761905
Chemosphere	134: 395-401	Gemfibrozil	50.8
Environmental Science and Pollution Research	22:5864-5876	Gemfibrozil	41.75
Science of the Total Environment	409: 4351-4360	Gemfibrozil	92.3
Chemosphere	99:160-170	Gemfibrozil	80.02
Archives of Environmental Contamination and Toxicology	66:538-548	Gemfibrozil	98.98
Archives of Environmental Contamination and Toxicology	66:538-548	Gemfibrozil	97.59
Environmental Science and Technology	45:3341-3348	Gemfibrozil	37.96
Journal of Hazardous Materials	239-240:40-47	Gemfibrozil	14.32
Journal of Environmental Monitoring	5: 823-830	Galaxolide	87.7575
Environmental Science and Technology	34: 959-965	Galaxolide	91.5
Environmental Science and Technology	36: 2839-2847	Galaxolide	87.8
Water Research	38: 2918-2926	Galaxolide	80.4379613
Archives of Environmental Contamination and Toxicology	66:538-548	Galaxolide	62.46
Archives of Environmental	66:538-548	Galaxolide	48.47

Journal Name	**Volume: Pages**	**TrOC**	**Removal (%)**
Contamination and Toxicology			
Science of the Total Environment	447:248-254	Galaxolide	67.4050633
Frontiers in Environmental Science Engineering	7:166-172	Galaxolide	64.6
Archives of Environmental Contamination and Toxicology	52:451-457	Galaxolide	62.9014396
Archives of Environmental Contamination and Toxicology	52:451-457	Galaxolide	54.5454545
Water Science and Technology	52:29-35	Galaxolide	81.08
Chemosphere	57:863-870	Galaxolide	64.1937146
Water Science and Technology	65: 2242-2250	Nonylphenol	58.3333333
Chemosphere	67: 335-343	Nonylphenol	96.7539267
Water Science and Technology	65: 2242-2250	Nonylphenol	68.4210526
Journal of Hazardous Materials	244-245: 259-267	Nonylphenol	78
Journal of Hazardous Materials	244-245: 259-267	Nonylphenol	91
		Nonylphenol	65.3
Water Research	40: 3559-3570	Nonylphenol	90
Water Research	45: 2473-2484	Nonylphenol	73.60
Water Research	45: 2473-2484	Nonylphenol	82.78
Chemosphere	92: 986-992	Nonylphenol	90
Chemosphere	92: 986-992	Nonylphenol	62.64
Desalination	272: 240-245	Nonylphenol	70
Environmental Toxicology and Chemistry	29: 1658-1668	Nonylphenol	60
Environment International	33: 654-669	Nonylphenol	89.0879479
International Journal of Environmental Science and Technology	8: 245-254	Nonylphenol	96.5
International Journal of Environmental Science and Technology	8: 245-254	Nonylphenol	99.6
Environmental Monitoring and Assessment	186: 525-539	Nonylphenol	61
Environmental Monitoring and Assessment	186: 525-539	Nonylphenol	76
Environmental	25:20-26	Nonylphenol	96.1048689

Journal Name	Volume: Pages	TrOC	Removal (%)
Toxicology and Pharmacology			
Analytica Chimica Acta	501:79-88	Nonylphenol	74.9125209
Water Research	40:3297-3303	Nonylphenol	68.7
Journal of Environmental Monitoring	13:1366-1373	Nonylphenol	78.6475837
Journal of Environmental Monitoring	5: 823-830	Tonalide	91.85
Water Research	38: 2918-2926	Tonalide	86.1481739
Environmental Science and Technology	34: 959-965	Tonalide	89
Environmental Science and Technology	36: 2839-2847	Tonalide	88.8
Frontiers in Environmental Science Engineering	7:166-172	Tonalide	73.4
Archives of Environmental Contamination and Toxicology	52:451-457	Tonalide	63
Archives of Environmental Contamination and Toxicology	52:451-457	Tonalide	44.1649899
Water Science and Technology	52:29-35	Tonalide	85.44
Chemosphere	57:863-870	Tonalide	63.6363636
Journal of Hazardous Materials	239-240: 40-47	Salicylic acid (10)	99
Journal of Hazardous Materials	239-240: 40-47	Salicylic acid	99
Journal of Hazardous Materials	239-240: 40-47	Salicylic acid	98
Journal of Hazardous Materials	239-240: 40-47	Salicylic acid	99.9
Water Research	40: 3297–3303	Salicylic acid	99
Water Research	43: 363–380	Salicylic acid	99
Water Research	43: 363–380	Salicylic acid	97
Water Air and Soil Pollution	223: 2611-2621	Salicylic acid	99
Science of the Total Environment	454-455: 411-425	Salicylic acid	76
Water	35–39	Salicylic acid	97
Water Research	43: 363–380	Amitriptyline (5)	86
Water Research	43: 363–380	Amitriptyline	100
Science of the Total Environment	532:762-770	Amitriptyline	18
Science of the Total Environment	454: 442–456	Amitriptyline	69.46
Water Research	43: 363–380	Amitriptyline	96

Journal Name	Volume: Pages	TrOC	Removal (%)
Science of the Total Environment	409: 4351-4360	Omeprazole (2)	7.5
Water Research	44: 578–588	Omeprazole	8.5
Water Research	43: 363–380	Atenolol (15)	100
Water Research	43: 363–380	Atenolol	100
Environment Science and Technology	40: 357-363	Atenolol	0
Environment Science and Technology	40: 357-363	Atenolol	21
Environment Science and Technology	40: 357-363	Atenolol	36
Water Research	41: 1001–1012	Atenolol	58.49
Analytical and Bioanalytical Chemistry	387: 1365-1377	Atenolol	57
Water Research	43: 831-841	Atenolol	8.2
Water Science and Technology	50: 253–260	Atenolol	66
Environment Science and Technology	40: 357-363	Atenolol	76
Science of the Total Environment	466-467: 976-984	Atenolol	58.3
Science of the Total Environment		Atenolol	64.5
Science of the Total Environment	454-455: 411-425	Atenolol	65
Environmental Toxicology and Chemistry	29: 1658-1668	Atenolol	99.9
Science of the Total Environment	532:762-770	Atenolol	22
Science of the Total Environment		Paracetamol /Acetaminophen	999
Agricultural Water Management	86: 72–80	Paracetamol /Acetaminophen	99
Analytical and Bioanalytical Chemistry	387: 1365-1377	Paracetamol /Acetaminophen	99.1
Water Research	43: 831-841	Paracetamol /Acetaminophen	99.5
Chemoshpere	66: 993–1002	Paracetamol /Acetaminophen	99.4
Water Environmental Research	78: 2276	Paracetamol /Acetaminophen	98.4
Science of the Total Environment	466-467: 976-984	Paracetamol /Acetaminophen	100
Chemosphere	66: 993-1002	Paracetamol /Acetaminophen	100
Chemosphere	134: 133-140	Paracetamol /Acetaminophen	100
Chemosphere	134: 395-401	Paracetamol /Acetaminophen	97.1
Journal of Hazardous Materials	277: 69–75	Paracetamol /Acetaminophen	100
Water Research	43: 831-841	Fluoxetine (7)	33.1

Journal Name	Volume: Pages	TrOC	Removal (%)
Science of the Total Environment	454-455: 411-425	Fluoxetine	59
Thesis of Master of Science, Texas State University		Fluoxetine	75
Water Research	44: 578–588	Fluoxetine	61.9
Science of the Total Environment	407: 2760–2770	Fluoxetine	54.5
Water Research	43: 363–380	Fluoxetine	48.71
Environment International	36: 15–26	Fluoxetine	34
Environmental Toxicology and Chemistry	29: 1658-1668	Primidone (7)	0
Water Research	43: 1060-1074	Primidone	15
Water Research	43: 1060-1074	Primidone	5
Water Research	43: 1060-1074	Primidone	35
Water Research	43: 1060-1074	Primidone	46
Water Science and Technology	57 : 65-71	Primidone	33
Science of the Total Environment	532:762-770	Primidone	18
Water Research	40: 3297–3303	DEET (17)	9
Water Research	40: 3297–3303	DEET	11
Water Research	40: 3297–3303	DEET	19
Water Research	40: 3297–3303	DEET	21
Water Research	40: 3297–3303	DEET	32
Water Research	40: 3297–3303	DEET	35
Water Research	40: 3297–3303	DEET	38
Water Research	40: 3297–3303	DEET	45
Water Research	40: 3297–3303	DEET	48
Water Research	40: 3297–3303	DEET	49
Water Research	40: 3297–3303	DEET	69
Water Research	40: 3297–3303	DEET	70
Water Research	40: 3297–3303	DEET	75
Water Research	40: 3297–3303	DEET	81
Chemosphere	66: 993-1002	DEET	77.2
Environmental Science and Pollution Research	21:4276-4285	DEET	35
Environmental Science and Technology	45:3341-3348	DEET	68
Water Research	40: 3297–3303	Triclosan (17)	45
Water Research	40: 3297–3303	Triclosan	58
Water Research	40: 3297–3303	Triclosan	59
Water Research	40: 3297–3303	Triclosan	64
Water Research	40: 3297–3303	Triclosan	65
Water Research	40: 3297–3303	Triclosan	70

Journal Name	**Volume: Pages**	**TrOC**	**Removal (%)**
Water Research	40: 3297–3303	Triclosan	72
Water Research	40: 3297–3303	Triclosan	75
Water Research	40: 3297–3303	Triclosan	78
Water Research	40: 3297–3303	Triclosan	80
Water Research	40: 3297–3303	Triclosan	85
Water Research	40: 3297–3303	Triclosan	91
Chemosphere	66: 993-1002	Triclosan	88.88
Chemosphere	66: 993-1002	Triclosan	55.3
Journal of Hazardous Materials	277: 69–75	Triclosan	35
Environmental Toxicology and Chemistry		Triclosan	38
Science of the Total Environment		Triclosan	79.6
Water Research	40: 3297–3303	4- tert octylphenol (10)	32
Water Research	40: 3297–3303	4- tert octylphenol	65
Water Research	40: 3297–3303	4- tert octylphenol	65
Water Research	39: 4797-4807	4- tert octylphenol	90.61
Water Research	39: 4797-4807	4- tert octylphenol	100
Water Research	39: 4797-4807	4- tert octylphenol	65.6
Water Research	39: 4797-4807	4- tert octylphenol	86.7
Water Research	39: 4797-4807	4- tert octylphenol	31.5
Desalination	272: 240–245	4- tert octylphenol	99.1
Chemosphere	69: 644–654	4- tert octylphenol	89.7
Emvironmental Pollution	65: 225–232	Octocylene (13)	100
Emvironmental Pollution	65: 225–232	Octocylene	45
Water Research	40: 2603–2612	Octocylene	53
Water Pollution	164: 267–273	Octocylene	95
Water Research	53: 58–67	Octocylene	100
Analytical Methods	5: 428–433	Octocylene	50
Analytical Methods	5: 428–433	Octocylene	88.16
Analytical Methods	5: 428–433	Octocylene	68.89
Analytical Methods	5: 428–433	Octocylene	91.3
Analytical Methods	5: 428–433	Octocylene	86.69
Analytical Methods	5: 428–433	Octocylene	78.15
Analytical Methods	5: 428–433	Octocylene	74.07
Water Research	44: 578–588	Omperazol	57