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Validating the rejection of trace organic chemicals by reverse osmosis membranes using a pilot-scale system

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Keywords

trace organic chemicals (TrOCs), low pressure reverse osmosis, rejection validation, operating conditions, potable water reuse

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Abstract

A protocol to validate the rejection of organic chemicals of potential health risk by low pressure reverse osmosis (LPRO) membranes was developed for decision making support regarding the monitoring level required for potable water reuse. Ten organic chemicals were selected for evaluation, based on their recorded usage, the scarcity of rejection data, and difficulty in analytical determination at concentrations relevant to their potential impact on human-health. An analytical method was developed for these organic chemicals. The target validations of 90 and 99% for neutral and charged chemicals respectively were successfully achieved under the standard operating condition with the exception of bisoprolol and carazolol rejection by the TFC-HR membrane. These lower rejections by the TFC-HR can be attributed to its highest water permeability amongst the three membranes while both bisoprolol and carazolol are positively charged. Changes in operating conditions including permeate flux, feed temperature and chemical cleaning can exert a considerable impact on conductivity rejection by the three LPRO membranes investigated here. Feed temperature showed an apparent impact on the rejection of the selected organic chemicals. However, their rejections were still higher than the target validation values. The protocol developed here can be expanded for the validation of other organic chemicals.

Keywords: trace organic chemicals (TrOCs); low pressure reverse osmosis; rejection validation; operating conditions; potable water reuse.

1. Introduction

The widespread occurrence of thousands of trace organic chemicals (TrOCs) of both natural and industrial origins in wastewater impacted water bodies is an important environmental issue of our time [1]. Some of these chemicals pose toxicological threats to wildlife as well as potential adverse human health effects. These TrOCs are present in reclaimed water at concentrations in the range from less than one part-per-trillion (ng/L) to a few part-per-billion (µg/L). Thus, they can only be detectable by some of the most advanced analytical techniques. The difficulties associated with their analysis and accurately evaluating their impact on human health present a major scientific challenge in addressing water quality problems caused by these TrOCs. One notable example is the uncertainty related to the removal of these chemicals by advanced water treatment processes, which could severely hinder the development of potable water reuse projects.

Concerns over possible adverse health impacts due to chronic and acute exposure to TrOCs via potable water recycling trigger the need to monitor their concentrations in the product water or to ascertain their removal efficiency. Routine monitoring is essential when there is a sufficient probability that certain TrOCs may occur in the product water at the threshold concentration which may result in adverse health impact. On the other hand, TrOCs (e.g. obsolete herbicides, industrial chemicals, and therapeutic drugs used in large quantity in the hospital) often do not occur in municipal wastewater or only occur at below the detection limits of most advanced analytical techniques. Thus their fates during water reclamation are largely unknown. To minimise the risk of accidental release of these TrOCs into the recycled water, a multiple barrier approach including the source water control and advanced water treatment processes has been employed in many indirect potable water reuse schemes [2].

The low pressure reverse osmosis (LPRO) filtration process is an important treatment component of many recent potable water recycling schemes. LPRO membranes are expected to effectively remove a range of TrOCs. However, to date, only a small fraction of TrOCs has been evaluated for their rejection by LPRO membranes [3-7]. Recent research in this area has resulted in a qualitative framework for assessing the removal of TrOCs by LPRO membranes. As a notable example, Bellona et al., (2004) [8] developed a rejection diagram to predict the rejection of TrOCs of known physiochemical properties. Bellona's rejection diagram is based

on the premise that the rejection of TrOCs by polyamide (PA) -based reverse osmosis (RO) membranes is mainly governed by size exclusion [8] and to a lesser extent by electrostatic interaction if the compound carries a charge. The measured rejections of most TrOCs that occur frequently in municipal wastewater at sufficiently high concentration are consistent with values estimated from this qualitative assessment framework. However, there remain many TrOCs that can potentially be introduced to municipal wastewater via uncontrolled or accidentally release but otherwise their concentrations are below the detection limits of most advanced analytical techniques. As a result, theoretical estimations of expected TrOC rejection have been suggested based on experimental results and the qualitative prediction framework by Bellona et al. [8]. Rigorous mathematic [9, 10] and artificial neural network [11] models have also been developed to predict and simulate the rejection of TrOCs by LPRO membranes under a range of operating conditions. However, the availability of these predictive tools does not replace the need to experimentally validate the rejection of TrOCs if they are not routinely monitored in potable water recycling applications.

Given the need to prioritise the monitoring efforts to manage the risk associated with TrOCs in recycled water, this study aims to identify whether the theoretical TrOC rejection based on the qualitative prediction framework by Bellona et al. [8] is valid using a spiral wound membrane system under a realistic range of filtration conditions. TrOCs were selected for this validation exercise based on an extensive literature review (to ensure that their rejections by LPRO membrane have not been previously reported in the literature) and a human health risk assessment. An analytical method was developed and optimised for the selected TrOCs. RO filtration experiments were conducted using three different LPRO membranes under a range of operating conditions (e.g. permeate flux, feed temperature and chemical cleaning). Overall, this study provides the insight of TrOC rejections by LPRO membrane for the validation of RO system performance. The validation protocol described is intended to be easily adaptable for a larger range of TrOCs selected on the basis of future membrane performance validation requirements.

2. Materials and methods

2.1. Chemicals

The selection of TrOCs for this validation exercise was based on an investigation undertaken for a large Australian water utility. In total 135 TrOCs were screened based on acceptable health-based concentrations published by the Queensland Government [12], registered usage in Australia, reported occurrences in wastewater, secondary treated effluent, and RO permeate. Bellona et al. [8] conducted a comprehensive literature review to show that TrOC rejection can be qualitatively predicted based on their physicochemical properties. Based on their physicochemical properties, TrOCs can be classified into 10 categories and the rejection of each category by RO membrane can be estimated (Supplementary Material Figure S1). For each category, an assumed rejection has been determined based on conservative estimates of 0-3 Log removals of TrOCs under normal RO filtration operating conditions (Supplementary Material Table S2). The rejection categories and their assumed rejections are rough estimates based on their properties; thus, the assumed rejection values are yet to be comprehensively validated. Accordingly, a conservative validation target has been set for each category (Supplementary Material Table S2). The 10 TrOCs considered in this study have molecular weight larger than the MWCO of RO membranes and are hydrophilic at environmental pH (i.e. pH 7). Based on the qualitative prediction framework proposed here (Supplementary Material Table S2), their conservative validation targets were set at 90% for neutral (rejection category 7 and 9) and 99% for charged compounds (rejection category 10). Health ratio – a relationship between maximum reported TrOC concentration and their guideline limit – of selected chemical was high (0.1-1.3). All charged TrOCs selected here (Table 1) have over 99% dissociation in pH 7.4 solution. The Log *D* value represents the distribution-coefficient at given pH indicating the hydrophobicity/hydrophilicity of a compound.

Di-*n*-butyl phthalate, bisoprolol, carazolol, carazolol-D7, dichloroprop, metsulfuron-methyl, molinate, penicillin V, pirimiphos-ethyl, trichlorfon, 17α-estradiol, methanol, methyl-*tert*-butylether, ammonium acetate, and formic acid were purchased from Sigma-Aldrich (Castle Hill, NSW, Australia). Di-*n*-butyl phthalate-D4, carbamazepine-D10, gemfibrozil-D6 and 17β-estradiol-D4 were purchased from CDN isotopes (Pointe-Claire, Quebec, Canada). Bisoprolol-D5 and penicillin V-D5 were purchased from Toronto Research Chemicals

(Toronto, Ontario, Canada). Dichloroprop-D6 and pirimiphos-ethyl-D10 were purchased from Dr Ehrenstorfer GmbH (Augsburg, Germany). All chemicals were of 98.5% purity or higher. All isotope labelled standards were of at least 98% atom abundance. A stock solution containing all selected TrOCs for rejection validation (Table 1) was prepared at 50-200 mg/L in methanol. A stock containing the isotope labelled versions of the target compounds was also prepared at 1 mg/L in methanol and used as the surrogate standard. A stock containing carbamazepine-D10 was prepared at 1 mg/L in methanol and used as the internal standard from compounds that did not have isotope labelled homologues. Unless otherwise stated, water used for method validation samples was taken from a Milli-Q water purification system (Millipore Kilsyth, Victoria, Australia).

[Table 1]

2.2. RO feed

RO feed was collected from a full-scale water recycling plant in Australia. The treatment plant train prior to sampling point comprises primary treatment, bioreactor, sand filtration, and microfiltration. Conductivity and pH of the RO feed were 820 µS/cm and 7.7, respectively.

2.3. Pilot-scale RO filtration system and RO elements

A pilot-scale cross-flow RO filtration system was used. The system comprised three 4-inch fibreglass pressure vessels, a high pressure pump (CRN 3-25, Grundfos, Bjerringbro, Denmark) and 300 L polyethylene feed reservoir (Figure 1). The feed stream of the three pressure vessels was connected in series. One 4 inch × 40 inch LPRO membrane element was held in each pressure vessel. Stainless steel pipes and PVC pipes were used in the feed and permeate stream, respectively. The concentrate flow was monitored at the exit of the third vessel and the permeate flow was monitored at the exit of each pressure vessel. These flows were controlled by adjusting the opening of a glove valve and the power output of the pump using a variable frequency drive. The permeate and concentrate were recirculated into the feed reservoir. A chiller/heater unit (Aqua Cooler S360PD-CT, Chester Hill, NSW, Australia) connected to stainless steel heat exchanging pipes was used to control the feed solution temperature in the feed reservoir.

148 Three different LPRO membranes namely ESPA2-4040 (Hydranautics, Oceanside, CA,
149 USA), TFC-HR 4040 (Koch Membrane Systems, San Diego, CA, USA) and TMG10 (Toray,
150 Tokyo, Japan) were used (Table 2). These PA-based LPRO membranes are commonly used
151 for brackish water treatment. The ESPA2 and TFC-HR membranes have been deployed in
152 several full-scale RO installations in the USA and Australia for potable water reuse
153 applications [13].

154 **[Figure 1]**

155 **[Table 2]**

156 ## *2.4. Filtration protocols*

157 Prior to the first filtration experiment, the analyte stock solution of the selected TrOCs was
158 dosed into 100 L RO feed water at a ratio of 10 mL-stock/100L-water to obtain
159 approximately 5-20 µg/L of each TrOC. The membrane system was then operated at
160 approximately 300 kPa for at least 12 hours before the first samples were taken for analysis.
161 The standard system operating condition used in this investigation was system permeate flux
162 20 L/m^{2}h and feed temperature 20 °C. The impact of feed temperature was first investigated
163 by incrementally increasing feed temperature from 10 to 35 °C. During the experiment, the
164 system permeate flux was maintained at 20 L/m^{2}h. The impact of permeate flux was
165 investigated by first adjusting permeate flux to 30 L/m^{2}h. Then, the permeate flux was
166 stepwise decreased down to 10 L/m^{2}h. The feed temperature during the experiment was
167 maintained at 20±0.1 °C. The system recovery was maintained at 25% for all experiments. It
168 is noteworthy that full-scale RO plants are operated at up to 85% water recovery [14] and the
169 increase in system recovery can decrease solute rejection [9].

170 Following experiments described above, chemical cleaning was conducted using NaOH
171 solution (pH 11-11.5). The chemical cleaning protocols include: (a) flushing the RO system
172 with 150 L of tap water; (b) recirculating NaOH solution for 1 hour at 35 °C; (c) soaking with
173 the NaOH solution for 3 hours; (d) recirculating the NaOH solution for 1 hour at 35 °C; (e)
174 flushing the RO system with 150 L of tap water. During the chemical recirculation, glove
175 valve installed in the exit of the feed stream (Figure 1) was fully opened in order to minimise
176 permeation through LPRO membranes, and feed flow was maintained at 24 L/min. Following
177 the chemical cleaning, the membrane system was operated using the RO feed water at

approximately 300 kPa for at least 12 hours. Then, feed and permeate samples were collected under the standard system operating condition (i.e. system permeate flux 20 L/m^{2}h and feed temperature 20 °C). The rejection of chemicals was calculated using the following equation.

$$\text{Rejection } R\,[\%] = \left(1 - \frac{C_p}{C_f}\right) \times 100 \qquad (1)$$

where C_p and C_f are permeate and feed concentrations, respectively.

2.5. Analytical techniques

2.5.1. Sample collection

Samples were collected in 0.5 L amber glass bottles. Sample volume taken for validation was 0.5 L. Immediately after sampling 100 µL of the 1 mg/L surrogate standard stock was added to each sample and well mixed before commencement of extraction. Samples were extracted immediately after sampling otherwise stored in the dark at 4 °C and extracted within 48 hours.

2.5.2. Solid phase extraction

Solid phase extraction (SPE) of TrOCs in each sample was performed using a method previously reported elsewhere [3]. TrOCs were extracted onto 500 mg hydrophilic/lipophilic balance (HLB) solid-phase extraction SPE cartridges (Waters, Millford, MA, USA). Cartridges were pre-conditioned with *tert*-butyl methyl ether (MTBE), methanol, and Milli-Q water. Samples were drawn through the cartridge at approximately 10 mL/min. The cartridges were then rinsed with Milli-Q water (5mL), dried and stored at 4 °C in sealed bags under nitrogen until elution. Target TrOCs were eluted from the cartridges with methanol followed by methanol/MTBE under gravity. The solvent was removed under nitrogen to approximately 1 mL using a solvent evaporator (Turbovap, Caliper Life Sciences, Hopkinton, MA, USA). The residue was transferred to a 2 mL amber auto-sampler vial. 50 µL of the internal standard was added to each sample before capping with crimped seal.

2.5.3. Liquid Chromatography (LC) – tandem Mass Spectrometry (MS)

TrOCs were chromatographed using an Agilent (Palo Alto, CA, USA) 1200 series HPLC system equipped with a 150 x 4.6 mm, 5 µm particle size, Luna C18 (*2*) column (Phenomenex, Torrence CA, USA). An API 4000 triple quadrupole mass spectrometer

(Applied Biosystems, Foster City, CA, USA) equipped with a turbo-V ion source employed in both positive and negative Electrospray ionisation (ESI) modes for all target compounds except 17α-estradiol which was analysed using atmospheric-pressure chemical ionisation (APCI) in positive mode. Using multiple reaction monitoring (MRM) two precursor ion – product ion transitions for all target compounds and isotope labelled surrogates were monitored for unequivocal confirmation. Only the first transition was used for quantitation. Relative retention times of the analyte and isotopically labelled surrogate standard were also monitored to ensure correct identification.

The use of isotope labelled versions of target compounds enabled quantification by isotope dilution which enables losses due to incomplete extraction to be accounted for. An isotopic version of each of the organic chemicals investigated here was used as their internal standard to account for any losses during SPE as well as changes in the final volume. Isotopically labelled versions were not available for metsulfuron-methyl, molinate, and trichlorfon. Thus, carbamazepine D10 was used as the internal standard for these chemicals to account for any changes in the final volume.

Both ESI and APCI in positive and negative modes were investigated for all standards to establish the best ionization configuration. To determine suitable precursor ions a solution of each standard was directly infused into the ion source and scanned using quadrupole 1 (Q1) from *m/z* 50 – 450. The most intense ion observed was used to determine optimal source parameters such as declustering potential, collision energy and collision cell exit potential for each of up to 8 product ions detected in quadrupole 2 (Q2). Precursor-product ion transitions were incorporated into ESI positive, ESI negative or APCI positive methods and run using the chromatographic conditions stated above. For each analyte and surrogate standard the two most intense transitions were used in the final methods.

The instrument was calibrated at the beginning of each analytical run. Using working stocks, method calibration standards were prepared at 0.5, 1, 5, 10, 50, 100, 500 and 1000 ng/mL in methanol. For each calibration standard, 100 ng and 50 ng of surrogate and internal standard respectively were added so that a relative response versus relative concentration curve can be generated. At least six calibration points were used for each target compound. Recoveries of target compounds from both Milli-Q grade and RO feed water were determined by spiking

and extracting samples at 10, 100 and 1000 ng/L. Due to presence of some compounds in RO feed water, recoveries were determined only at 100 ng/L for this matrix.

2.5.4. General water quality analysis

During RO filtration experiments, pH, electrical conductivity and temperature of solutions was measured using Orion 4-Star Plus pH/conductivity meter (Thermo Fisher Scientific, Waltham, MA, USA).

3. Results and discussion

3.1. Analytical technique development and validation

Recoveries of the other TrOCs from Milli-Q water and RO feed are summarised in Supplementary Material Table S3. All target TrOCs were recovered within satisfactory tolerances with the exception of molinate and trichlofon which were poorly recovered. To mitigate this low recovery, higher feed concentrations for these two compounds were used for the RO filtration work. On the other hand, di-n-butyl phthalate recoveries were significantly affected by background contamination, thus its reporting levels were adjusted in this investigation accordingly. It is noteworthy that for quantification purpose any variations in recovery of the target analysts were corrected using the isotopic standards to remove any interference from the variation in recovery.

The calibrations and reporting detection limits of the tested TrOCs are summarised in Supplementary Material Table S4. The instrument detection limit (IDL) was determined as the lowest concentration of a standard that affords a signal to noise ratio (s/n) of 3 or greater. The method detection limit (MDL) was the concentration of a target compound in sample that has been processed through the entire method giving a s/n greater or equal to 3. Reporting limits were determined as being the greatest value of either the 2nd lowest calibration point or 3 times the MDL. Reporting limits were also dependant on any background contamination present in analysed samples. Reporting limits in the RO feed were up to five times higher than those in Milli-Q water (Supplementary Material Table S4). Details of the optimization are summarized in Supplementary Material Table S5 and S6. The molecular structures of all precursor ions and proposed structures of the monitored product ions are summarized in Supplementary Material Table S7.

Of the 10 TrOCs, dichloroprop, bisoprolol, varazolol, and molinate were detected in the RO feed solution collected at a full-scale plant at slightly above their reporting detection limits of 5, 20, 7, and 11 ng/L, respectively. The concentrations of other TrOCs were below the detection limits reported in Supplementary Material Table S4. For validation purpose, if the target TrOC was not detectable in the RO permeate, the reporting detection limit was used to calculate a minimum rejection value.

3.2. Validation during RO filtration

3.2.1. Effects of physicochemical properties of TrOCs and membranes

The target validation rejection of 90% of neutral TrOCs could be readily achieved by all three LPRO membranes (Table 3). The neutral TrOCs selected here have the molecular weight of over 180 g/mol whereas the molecular weight cut-off of LPRO membranes is reported to be about 100 g/mol [15]. In fact, Fujioka et al. [16] evaluated the rejection of neutral compounds (i.e. N-nitrosamines) using a laboratory-scale setup and reported that neutral compounds with the molecular weight of over 114 g/mol exhibited greater than 90% rejection by five different LPRO membranes that are often used for water recycling applications.

The target validation rejection of 99% of charged chemicals were also achieved using all three LPRO membranes with only two exceptions. Rejections of bisoprolol and carazolol by the TFC-HR membrane were 97.7% and 97.2%, respectively (Table 3). These two TrOCs are positively charged and TFC-HR has the highest water permeability compared to the other LPRO membranes investigated here. The low rejection of these positively charged TrOCs can be explained by electrostatic attraction with the negatively charged active skin layer surface of the LPRO membranes, causing a localised increase in concentration at the membrane surface, and leading to a low rejection. Verliefde et al. [17] called this phenomenon as “charge concentration polarisation”. The target validation rejection of 99% was achieved with all negatively charged TrOCs (i.e. dichloroprop, metsulfuron-methyl and penicillin V) examined here. The active skin layer of typical LPRO membranes is negatively changed [18, 19]. In fact, two of the LPRO membranes used in this study (ESPA2 and TFC-HR) have a negative charge (-11 and -23 mV, respectively) at the test solution pH (i.e. pH 7.7) [20]. Thus, high rejection of negatively charged TrOCs can be obtained due to electrostatic repulsion between these solutes and the membrane surface.

Penicillin V was successfully incorporated in the analytical method described earlier. However, it was detectable in the RO permeate of the TMG membrane only (Table 3). Thus, the validation of Penicillin V rejection was omitted from subsequent experiments. Significant decrease in pirimiphos-ethyl concentration in the RO feed was observed. Concentration of this TrOC in the feed decreased from 10,000 ng/L to 80-140 ng/L after 12 hours of filtration. Pirimiphos-ethyl has the highest hydrophobicity among TrOCs selected here (Log D = 5.1). Thus, its adsorption onto membrane surface due to hydrophobic interaction can possibly be attributed to the decreasing pirimiphos-ethyl concentration in the feed [21, 22]. It is noteworthy that pirimiphos-ethyl rejection calculation was conservative and was based on its measured concentrations in the feed and permeate. Nevertheless, the calculated rejection (94-96%) was still above the target validation value of 90%.

The validation was further examined using the rejections of eight other TrOCs (i.e. N-nitrosamines) that were evaluated by RO membranes (i.e. ESPA2 and TFC-HR) using the same pilot-scale system [9, 23]. N-nitrosamines are uncharged and generally hydrophilic at the environment pH (e.g. pH 6-8). The target validation rejection of each N-nitrosamine was achieved under the standard operating conditions (Table 4). The results reported here support that the rejection targets determined based on the qualitative prediction framework can be applicable to estimate the rejection of a variety of TrOCs.

[Table 3]

[Table 4]

There was an apparent variation in the rejection of TrOCs among the three tested RO membranes (i.e. ESPA2, TFC-HR and TMG). Although the relationship between membrane permeability and conductivity rejection could be clearly observed, this relationship is not readily transferable to the rejection of TrOCs (Figure 2). Nevertheless, it is apparent that the ESPA2 which has the lowest water permeability amongst the three membranes examined here exhibits high and less scattered TrOC rejection. On the other hand, rejections of the nine TrOCs to be validated in this study by the TMG and TFC-HR membranes scattered quite widely. In the pore-flow model, membrane permeability increases and solute rejection decreases with increasing the free-volume hole-size of RO membrane active skin layer [24]. In addition to free-volume hole-size, the porosity of the active skin layer has been suggested

as an important factor determining the membrane's separation performance [25]. Nevertheless, the porosity of the active skin layer cannot be accurately quantified by any analytical techniques available to date.

[Figure 2]

3.2.2. Effects of operating conditions

Variation in operating conditions is often seen at full-scale RO plants. For example, seasonal variation in RO feed temperature at a full-scale plant can be over 10 °C [26, 27]. Although full-scale RO systems deployed for water recycling applications commonly employ a similar average flux of 17-21 L/m^{2}h [14], a large variation in local permeate flux (e.g. 10-25 L/m^{2}h) in an RO stage can also be expected [9]. Changes in these operating conditions including permeate flux, feed temperature may exert a considerable influence on the rejection of TrOCs by LPRO membrane [28]. Chemical cleaning may modify the PA structure of the RO active skin layer, causing a deterioration in TrOC rejection [29]. Thus, the impact of operating conditions and chemical cleaning on the validation results was investigated in this study.

Conductivity rejection by the ESPA2 membrane decreased from 99.3 to 98.3% as the permeate flux decreased from 30 to 10 L/m^{2}h (Figure 3a). On the other hand, the rejection of these TrOCs by the ESPA2 membrane remained almost constant for the increased permeate flux. A similar trend was observed for the TMG membrane (Figure 3c). When the TFC-HR membrane was used, the impact of the increased permeate flux was particularly apparent for the rejection of two positively charged TrOCs (i.e. carazolol and bisoprolol) (Figure 3b). These two TrOCs exhibited the lowest rejections (97-98%) among the TrOCs that concentrations in the permeate were above their reporting detection limits.

[Figure 3]

In general, an increase in feed temperature resulted in a decrease in conductivity rejection, while the impact on TrOC rejection was negligible (Figure 4). Regardless of the variation in feed temperature, rejections of both neutral and charged TrOCs by the ESPA2 membrane were above the target validation values (Figure 4). Similar results were observed with the TMG membrane except the two positively charged TrOCs (i.e. carazolol and bisoprolol) at feed temperature of 30 and 35 °C (Figure 4). The rejections of these positively charged

TrOCs by the TFC-HR membrane were also observed at lower than their rejection validations (Figure 4). The decreased TrOC rejection against increased feed temperature is likely to occur due to an increase in diffusivity of solutes through membrane [28]. The results reported here indicate that the rejections of positively charged TrOCs selected here by the TFC-HR membrane are more likely to fall below their target rejection validations during a hot weather period.

[Figure 4]

Effects of chemical cleaning were also investigated. Chemical cleaning resulted in a small but discernible decrease in conductivity rejection by all LPRO membranes (Figure 5). This implies that chemical cleaning can cause a negative impact on solute rejection. In fact, feed pressure to maintain the permeate flux of 20 L/m^{2}h commonly decreased by 3-5% for all LPRO membranes as a result of chemical cleaning, indicating that permeability of the membranes increased. A previous study has reported the rejection of several TrOCs is inversely proportional to membrane permeability [16]. However, the impact of chemical cleaning on TrOC rejection was not apparent. After chemical cleaning, the rejection of triclorfon by the ESPA2 membrane decreased to below the validation target of 90% (Figure 5a). It is noteworthy that when the filtration experiment was performed after the chemical cleaning, triclorfon concentrations in the feed and permeate were very low (48 and <5 ng/L, respectively), resulting in a rather low rejection value. Despite the inconclusive nature of the data reported here regarding the impact of chemical cleaning on TrOC rejection, it is noteworthy that extended chemical cleaning simulating multiple chemical cleanings over the years may cause deterioration in compound rejection as previously reported in the literature [29].

[Figure 5]

4. Conclusions

A protocol to validate the rejection of TrOCs was developed for decision making support regarding the monitoring level required for potable water reuse. Analytical method was successfully developed for quantifying the concentration of 10 TrOCs initially selected in this study. The results show that LPRO membranes can achieve more than 90% of all neutral TrOCs selected which ensures that the rejection diagram previously developed based on their

physicochemical properties is valid. However, the validation target of 99% of two charged TrOCs (i.e. bisoprolol and carazolol) could not be achieved with the TFC-HR membrane. This may be because bisoprolol and carazolol are both positively charged and the TFC-HR has the highest water permeability amongst all three LPRO membranes investigated here. The results also demonstrate that LPRO membrane with low water permeability is more likely to satisfy the validation target. Operating conditions including permeate flux, feed temperature and chemical cleaning can exert a considerable impact on conductivity rejection by the three LPRO membranes investigated here. However, only feed temperature showed an apparent impact on the rejection of TrOCs. The decreased rejection of TrOCs with increasing temperature may be due to the increased diffusivity through the membranes. Indeed, the rejection of positively charged TrOCs is more likely to fall below their target rejection validation value during the summer when the feed temperature is high.

5. Acknowledgements

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Table 1: Physicochemical characteristics, regulated concentrations and rejection categories of the selected TrOCs.

	TrOC[a]	Molecular formula [-]	Molecular weight [g/mol]	pK_a (pK_b)[b] [-]	Log *D* at pH 7.4[c] [-]	PHR guideline value[d]	Maximum reported concentration in source water[e] [µg/L]	Health ratio[e]	Rejection category[e,f]	Validation target [%]
Neutral	molinate (n)	$C_8H_{15}NOS$	187.3	n.a.	2.7	5	<0.5	<0.100	7	90
	trichlorfon (n)	$C_4H_8Cl_3O_4P$	257.4	10.1	0.5	5	<1	<0.200	9	90
	17α-estradiol (n)	$C_{18}H_{24}O_2$	272.4	10.3	4.1	0.175	0.074	0.423	7	90
	di-n-butyl phthalate (n)	$C_{16}H_{22}O_4$	278.3	n.a.	4.8	35	10.4	0.297	7	90
	pirimiphos-ethyl (n)	$C_{13}H_{24}N_3O_3PS$	333.4	(5.1)	5.1	0.5	<0.5	1.000	7	90
Charged	dichloroprop (-)	$C_9H_8Cl_2O_3$	235.1	3.0	-0.7	n.a.	n.a.	n.a.	10	99
	carazolol (+)	$C_{18}H_{22}N_2O_2$	298.4	(9.7)	1.4	0.35	0.12	0.343	10	99
	bisoprolol (+)	$C_{18}H_{31}NO_4$	325.4	(9.7)	0.1	0.63	0.37	0.587	10	99
	penicillin V (-)	$C_{16}H_{18}N_2O_5S$	350.4	3.4	-1.9	1.5	2	1.333	10	99
	metsulfuron-methyl (-)	$C_{14}H_{15}N_5O_6S$	381.4	3.5	-0.3	30	<20	0.667	10	99

[a] (n) neutral; (+) positively charged; (-) negatively charged.
[b] Chemaxon (http://www.chemicalize.org/).
[c] Chemspider (http://www.chemspider.com/), data calculated using Advanced Chemistry Development (ACD/Labs).
[d] Public Health Regulation 2005 [12].
[e] Viridis Consultants Pty Ltd, Chemical Classification, Review and classification of regulated chemicals for recycled water augmentation of drinking water supplies in South East Queensland, (2011).
[f] Supplementary Material Table S2.
n.a.: not available.

496 **Table 2:** Performance data of membrane element provided by manufacturer.

Membrane type	Manufacturer	Membrane area [m^2]	Product flow rate [m^3/day]	Salt rejection [%]	Water permeability[d] [L/m^2hbar]
ESPA2	Hydranautics	7.9	7.2[a]	99.6[a]	4.4
TFC-HR	KMS	7.9	8.6[b]	99.55[b]	5.7
TMG10	Toray	8.0	9.1[c]	99.5[c]	5.5

497 [a] Filtration condition: 1500 ppm NaCl, 1.05 MPa, 25 °C, pH 6.5-7.0 and 15% recovery.
498 [b] Filtration condition: 2000 ppm NaCl, 1.55 MPa, 25 °C, pH 7.5 and 15% recovery.
499 [c] Filtration condition: 500 ppm NaCl, 0.96 MPa, 25 °C, pH 7.0 and 15% recovery.
500 [d] Measured with deionised water at 20 °C feed temperature using a single spiral wound
501 element.

Table 3: Rejection of TrOCs in the RO feed by the (a) ESPA2, (b) TFC-HR and (c) TMG membranes (system permeate flux 20 L/m^{2}h, feed pH 7.65, system recovery 25%, feed temperature 20.0 ± 0.1°C). Values reported here are the average and ranges of duplicate samples.

Parameter	Target Rejection [%]	Rejection [%]/Validation					
		ESPA2		TFC-HR		TMG	
molinate	90	99.8±0.0	Yes	98.3±0.3	Yes	99.8±0.0	Yes
trichlorfon	90	99.9±0.0*	Yes	99.9±0.0*	Yes	99.4±0.0*	Yes
17α-estradiol	90	99.8±0.0	Yes	98.1±0.1	Yes	98.7±0.0	Yes
di-n-butyl phthalate	90	97.3±0.0*	Yes	96.5±0.4	Yes	91.5±0.0	Yes
pirimiphos-ethyl	90	96.0±0.0*	Yes	93.8±0.0*	Yes	96.3±0.0*	Yes
dichloroprop	99	99.9±0.0*	Yes	99.4±0.0	Yes	99.9±0.0*	Yes
carazolol	99	99.8±0.0	Yes	97.7±0.2	No	99.5±0.1	Yes
bisoprolol	99	99.8±0.0	Yes	97.2±0.2	No	99.5±0.0	Yes
penicillin V	99	N.D.	-	N.D.	-	99.5±0.0*	Yes
metsulfuron-methyl	99	99.9±0.0*	Yes	99.3±0.0	Yes	99.9±0.0*	Yes

* Permeate concentration was below their detection limits.

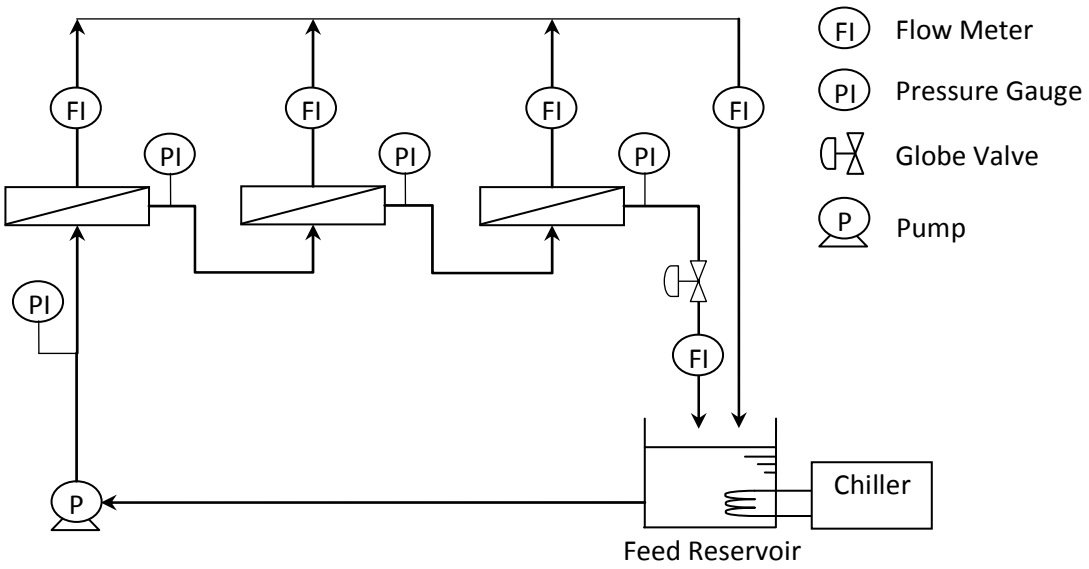
N.D.: feed concentration was below their detection limits.

Table 4: Rejection of N-nitrosamines in the RO feed by the ESPA2 and TFC-HR membranes (system permeate flux 20 L/m^{2}h, feed pH 8, system recovery 25%, feed temperature 20.0 ± 0.1°C).

Parameter	Molecular weight [g/mol]	Log D at pH 8	Molecular width (MWd) [nm]	Rejection category [a]	Target Rejection[a] [%]	Rejection [%]/Validation			
						ESPA2 [9]		TFC-HR [23]	
N-nitrosodimethylamine	74.1	0.04	0.270	3	0	56	Yes	31	Yes
N-nitrosomethylethylamine	88.1	0.4	0.306	3	0	83	Yes	64	Yes
N-nitrosopyrrolidine	100.1	0.44	0.318	8	20	93	Yes	71	Yes
N-nitrosodiethylamine	102.1	0.75	0.322	8	20	94	Yes	85	Yes
N-nitrosopiperidine	114.1	0.89	0.325	8	20	98	Yes	94	Yes
N-nitrosomorpholine	116.1	-0.18	0.317	8	20	97	Yes	79	Yes
N-nitrosodipropylamine	130.1	1.80	0.365	8	20	98	Yes	94	Yes
N-nitrosodi-n-butylamine	158.1	2.69	0.405	7	90	97	Yes	N.A.	

[a] Supplementary Material Table S2.
N.A.: not available.

LIST OF FIGURES



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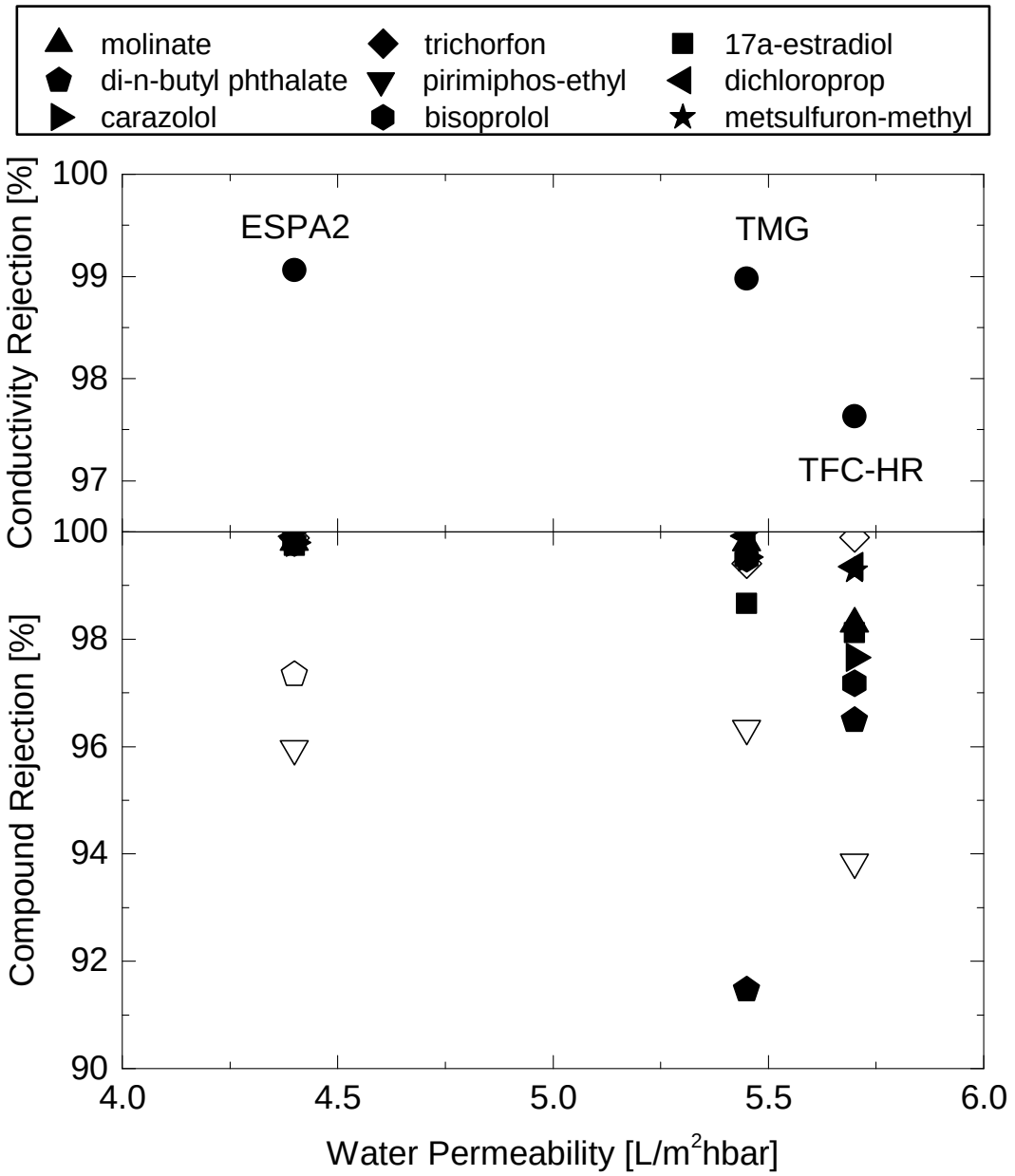

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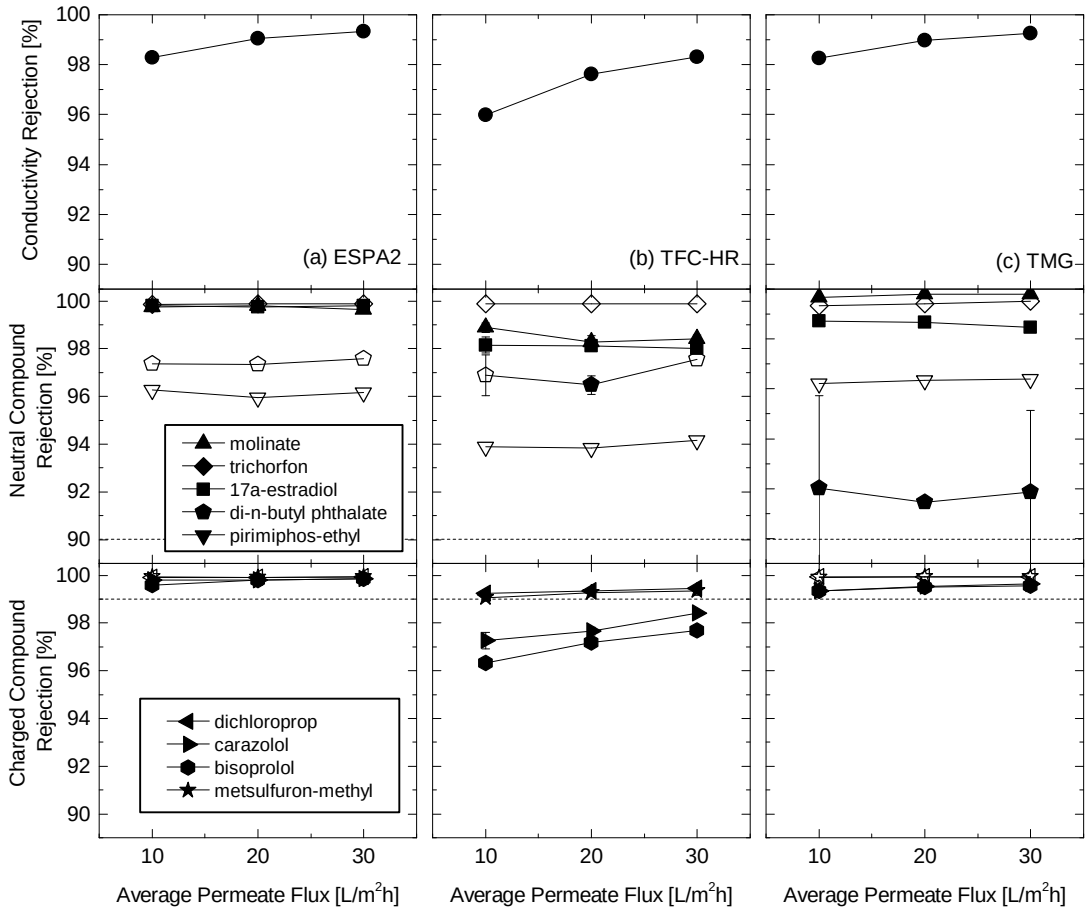

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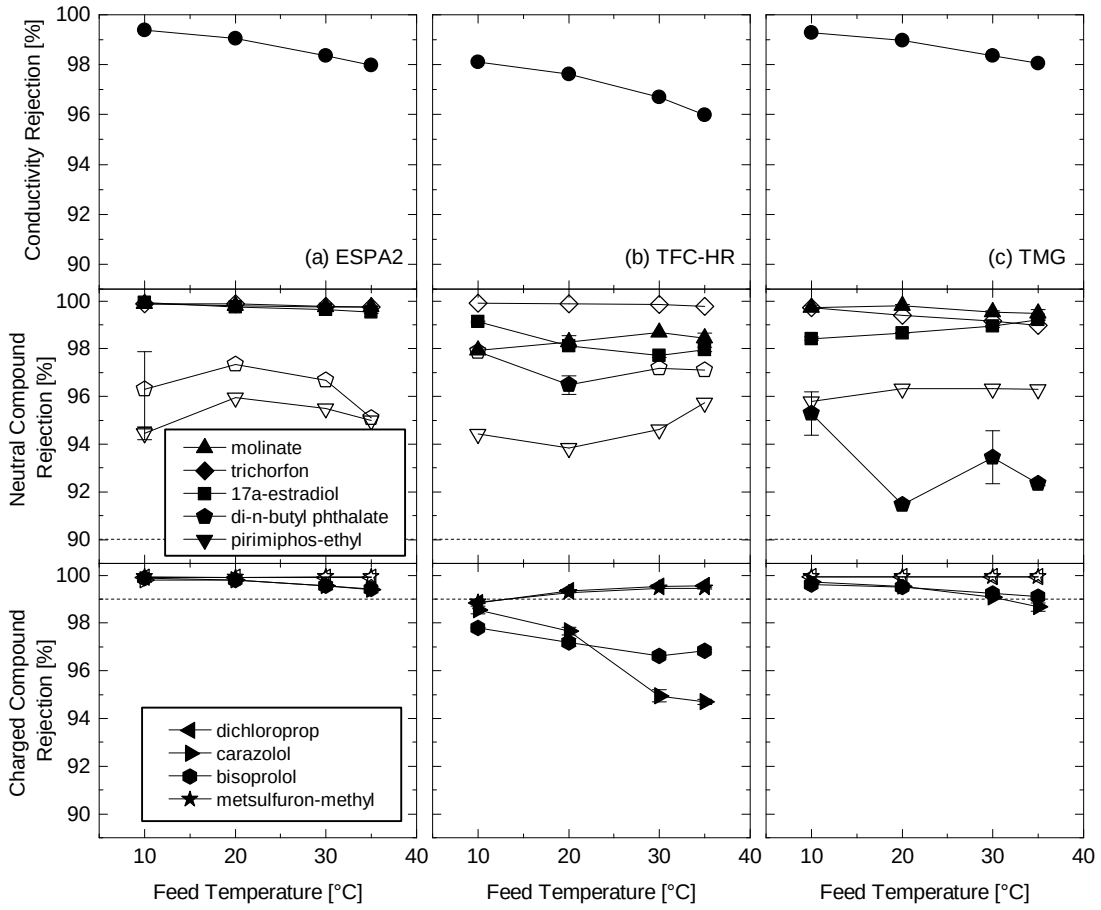
537 **Figure 3**



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539 **Figure 4**

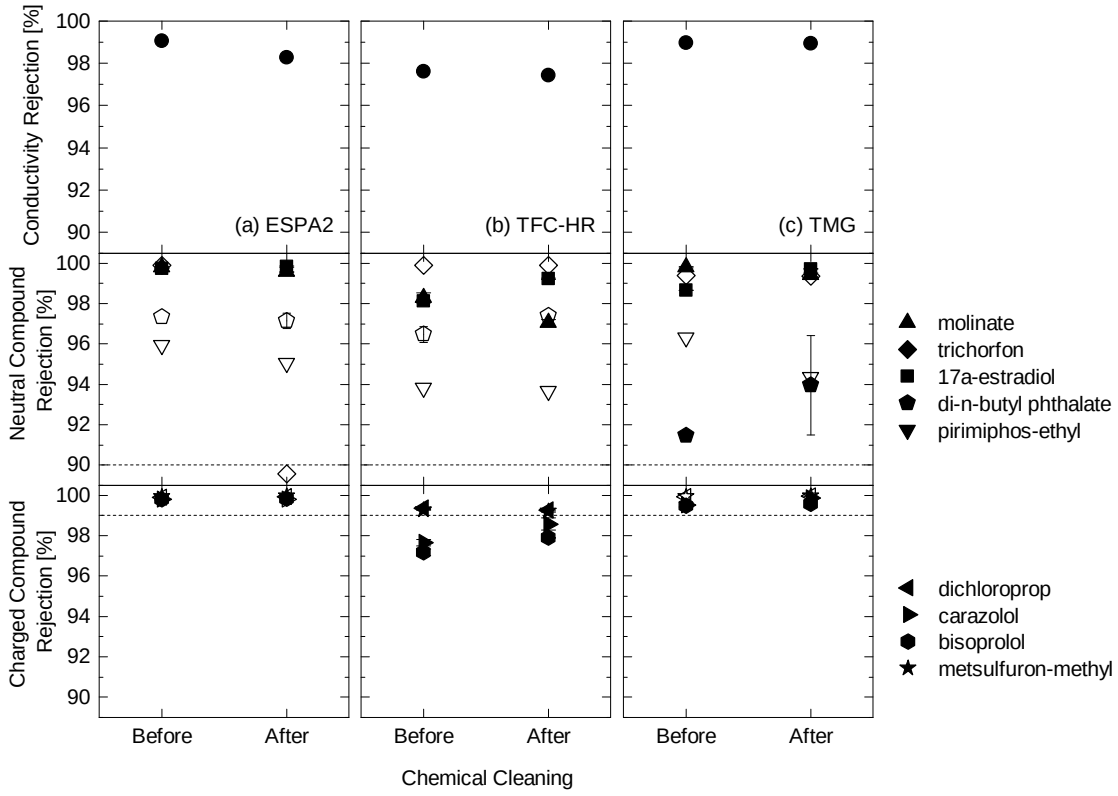
Conductivity Rejection [%]
Neutral Compound Rejection [%]
Charged Compound Rejection [%]
(a) ESPA2
(b) TFC-HR
(c) TMG
Before
After
Chemical Cleaning
molinate
trichorfon
17a-estradiol
di-n-butyl phthalate
pirimiphos-ethyl
dichloroprop
carazolol
bisoprolol
metsulfuron-methyl

Figure 5

Validating the rejection of trace organic chemicals by reverse osmosis membranes using a pilot-scale system

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SUPPLEMENTARY MATERIAL

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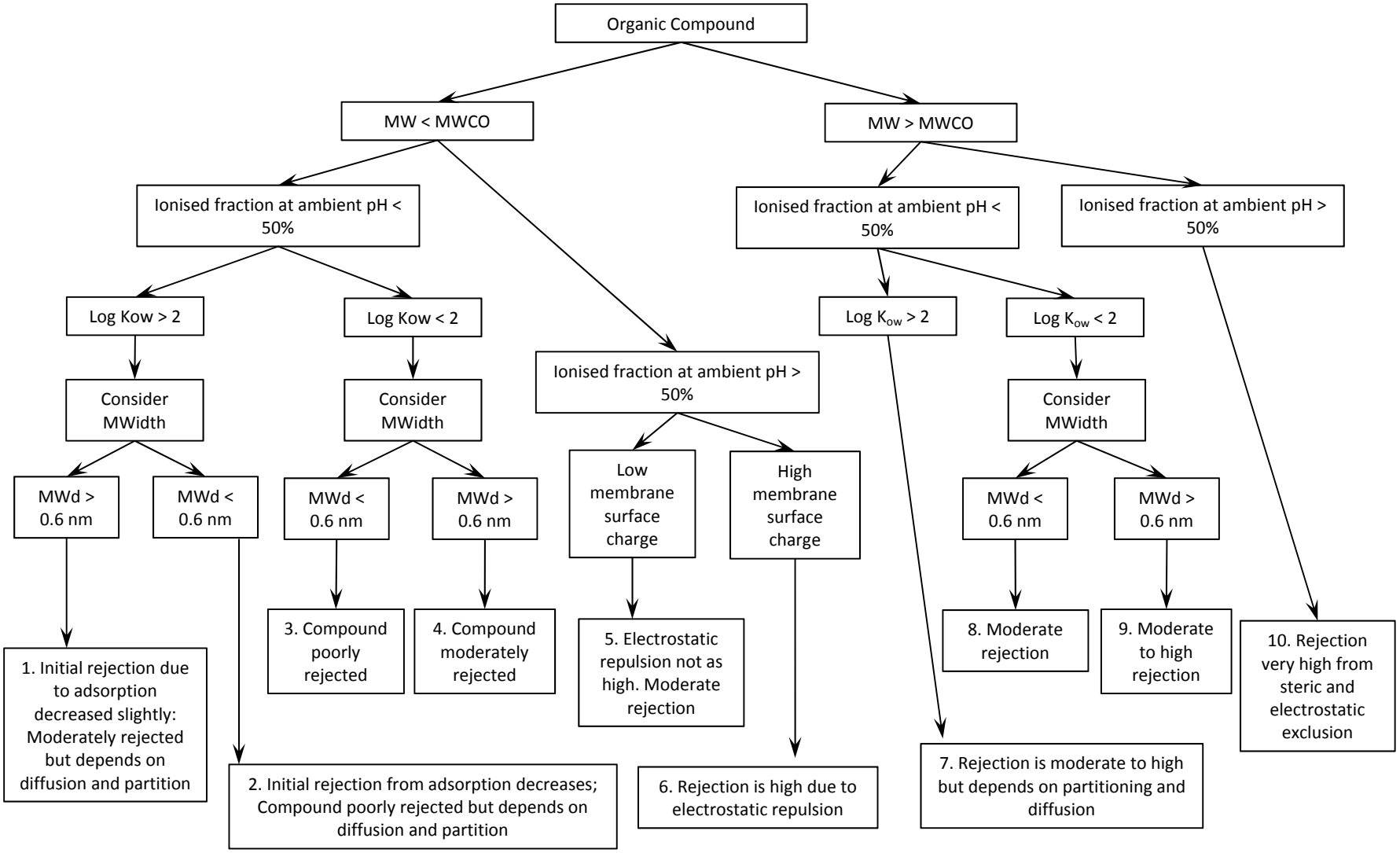


Figure S1: Modified membrane rejection diagram. (Viridis Consultants Pty Ltd, Chemical Classification, Review and classification of regulated chemicals for recycled water augmentation of drinking water supplies in South East Queensland, (2011)).

Table S2: Rejection categories, assumed rejection and validation target. (Viridis Consultants Pty Ltd, Chemical Classification, Review and classification of regulated chemicals for recycled water augmentation of drinking water supplies in South East Queensland, (2011)).

Rejection category	Description	Assumed rejection [%]	Validation target [%]
1	Initial rejection due to adsorption decreases slightly; Moderately rejected but depend on diffusion and partition	20-90	20
2	Initial rejection from adsorption decreases; Compound poorly rejected but depends on diffusion and partition	0-10	0
3	Compound poorly rejected	0-10	0
4	Compound moderately rejected	20-90	20
5	Electrostatic repulsion not as high: Moderate rejection	20-90	20
6	Rejection is high due to electrostatic repulsion	99-99.9	99
7	Rejection moderate to high but depends on partitioning and diffusion	90-99	90
8	Moderate rejection	20-90	20
9	Moderate to high rejection	90-99	90
10	Rejection very high from steric and electrostatic exclusion	99-99.9	99

Table S3: Recoveries of TrOCs with spiking concentrations of 10, 100, and 1,000 ng/L from Milli-Q water and RO feed (mean ± standard deviation of three replicates).

TrOC	Milli-Q			RO feed
	10 ng/L	100 ng/L	1,000 ng/L	100 ng/L
17α-estradiol	81 ± 2	81 ± 2	79 ± 3	120 ± 2
dichloroprop	96 ± 4	88 ± 1	84 ± 3	95 ± 2
di-*n*-butyl phthalate	566 ± 4	154 ± 1	101 ± 2	455 ± 8
bisoprolol	79 ± 11	83 ± 4	78 ± 6	117 ± 2
carazolol	81 ± 16	86 ± 12	78 ± 7	106 ± 4
metsulfuron-methyl	80 ± 31	88 ± 10	93 ± 6	85 ± 20
molinate	30 ± 20	36 ± 15	35 ± 8	45 ± 15
pirimiphos-ethyl	86 ± 3	83 ± 1	78 ± 4	98 ± 2
trichorfon	37 ± 15	41 ± 23	37 ± 13	30 ± 14
penicillin V	86 ± 12	84 ± 7	75 ± 3	99 ± 9

Table S4: Method quality parameters

TrOC	Method	Calibration range [ng/L]	R^2	IDL [pg on column]	MDL [ng/L]	Reporting limit [ng/L]	
						Milli-Q	RO feed
17α-estradiol	APCI positive	0.5 - 1000	0.999	5	0.1	5	5
dichloroprop	ESI negative	0.5 - 1000	0.995	11	0.5	5	5
di-n-butyl phthalate	ESI positive	0.5 - 1000	0.985	6	0.02	50	250
bisoprolol		0.5 - 1000	0.991	2	0.01	5	20
carazolol		1 - 1000	0.994	6	0.02	5	10
metsulfuron-methyl		0.5 - 1000	0.993	2	0.01	5	5
molinate		0.5 - 1000	0.990	213	1	5	10
penicillin V		0.5 - 1000	0.994	3	0.1	5	5
pirimiphos-ethyl		0.5 - 1000	0.990	69	0.5	5	5
trichlorfon		1 - 1000	0.996	32	0.4	5	5

Table S5: Optimized chemical dependent acquisition parameters

TrOC	Retention time [min]	Precursor ion molecular weight [g/mol]	Product ion molecular weight [g/mol]	Declustering potential [V]	Collision energy [eV]	Collision cell exit potential [V]
ESI positive						
molinate-1	9.1	188.1	125.5	51	19	22
molinate-2	9.1	188.1	82.9	51	25	14
trichorfon-1	5.4	256.9	109.0	76	27	18
trichorfon-2	5.4	256.9	126.7	76	25	22
di-*n*-butylphthalate-1	10.1	279.2	148.9	61	19	26
di-*n*-butylphthalate-2	10.2	279.2	204.7	61	11	12
di-*n*-butylphthalate-D4-1	10.1	283.2	209.0	41	11	12
di-*n*-butylphthalate-D4-2	10.1	283.2	152.7	41	19	26
pirimiphos-ethyl-1	10.5	334.1	198.1	61	31	16
pirimiphos-ethyl-2	10.5	334.1	181.9	61	31	16
pirimiphos-ethyl-D10-1	10.5	344.1	198.7	91	33	18
pirimiphos-ethyl-D10-2	10.5	344.1	183.0	91	33	12
carazolol-1	5.2	299.1	115.6	76	29	20
carazolol-2	5.2	299.1	221.6	76	29	18
carazolol-D7-1	5.2	306.2	122.8	81	29	22
carazolol-D7-2	5.2	306.2	221.6	81	29	20
bisoprolol-1	5.8	326.2	115.8	76	25	20
bisoprolol-2	5.8	326.2	73.5	76	43	12
bisoprolol-D5-1	5.8	331.2	120.8	96	25	10
bisoprolol-D5-2	5.8	331.2	78.9	96	43	12
penicillin V-1	5.7	383.1	159.8	71	23	14
penicillin V-2	5.7	383.1	113.9	71	51	20
penicillin-V-D5-1	5.7	388.1	160.0	71	23	28
penicillin-V-D5-2	5.7	388.1	113.6	71	55	20
metsulfuron-methyl-1	4.5	382.0	167.0	71	23	10
metsulfuron-methyl-2	4.5	382.0	198.6	71	31	34
carbamazepine-D10	7.1	247.1	204.3	51	29	10
ESI negative						
dichloroprop-1	6.1	232.8	160.7	-50	-18	-9
dichloroprop-2	6.1	232.8	124.5	-50	-40	-9
dichloroprop-D6-1	6.1	238.8	163.2	-50	-18	-7
dichloroprop-D6-2	6.1	238.8	126.7	-50	-40	-5
APCI positive						
17α-estradiol-1	10.2	255.2	159.3	61	27	10
17α-estradiol-2	10.2	255.2	133.2	61	27	10
17α-estradiol-1-D4-1	10	259.1	161.1	61	27	8
17α-estradiol-1-D4-2	10	259.1	135.1	61	25	11

Optimisation of ion source parameters

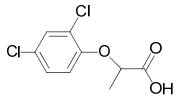
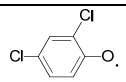
When employing the ESI mode, the mobile phases consisted of 5 mM ammonium acetate in water (A) and 100% methanol (B) was pumped at a flow rate of 800 µL/min. For positive ESI analysis the eluents were held at 10% B for 0.50 min and then linearly ramped to 50% at 0.51 min. Thereafter, the eluents were increased linearly to 100% at 8 min, then held at 100% B for 2 min with a total run time of 14.4 min. For negative ESI analysis, 10% B were held for 0.50 min, stepped to 60% B at 0.51 min and increased linearly to 100% B at 8 min, then held at 100% B for 3 min with a total run time of 14.4 min. A 5 min equilibration step at 10% B was used at the beginning of each run.

When employing the APCI mode, the eluents consisted of 0.1% v/v formic acid in water (A) and methanol (B) with the following ramp at a flow rate of 700 µL/min. 60% B were held for 5 min, increased linearly to 100% B at 20 min, and then held at 100% B for 3 min with a total run time of 13 min. A 3 min equilibrium step preceded injection. An injection volume of 10 µL was used for all methods.

Table S6: Optimised ion source parameters

	ESI positive	ESI negative	APCI positive
curtain gas [psig]	19	19	15
collision gas [psig]	high	high	high
nebulizer current [mA]	3	-3	3
temperature [°C]	550	550	450
ion source gas 1 [psig]	60	60	40
ion source gas 2 [psig]	50	50	N/A
run time [min]	14.4	14.4	13

29 **Table S7:** Molecular structures of target chemicals and proposed structures for product ions.

	Q1	structure	Q2	proposed structure
Dichloroprop	233		161	
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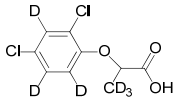
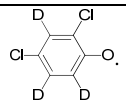
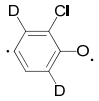
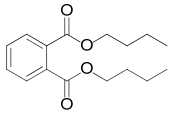
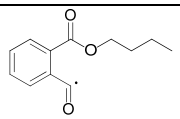
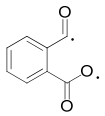
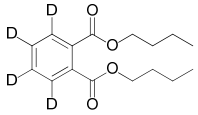
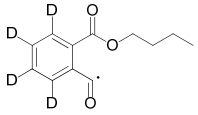
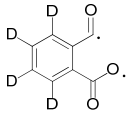
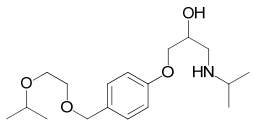
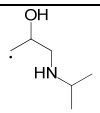
Dichloroprop D6	239		163	
			127	
Di-*n*-butyl phthalate	279		205	
			149	
Di-*n*-butyl phthalate D4	283		209	
			153	
Bisoprolol	326		116	
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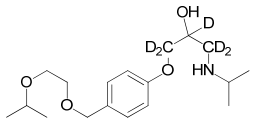
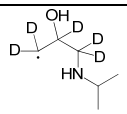
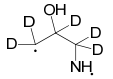
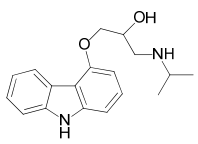
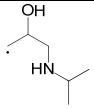
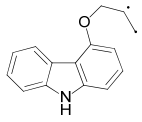
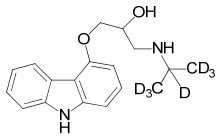
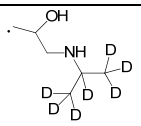
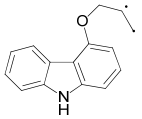
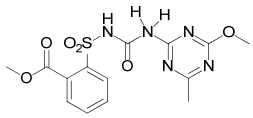
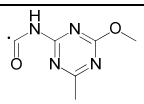
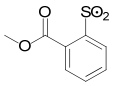
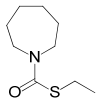
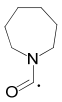
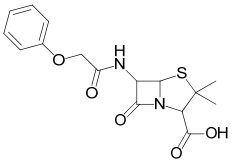
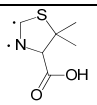
Bisoprolol D5	331		121	
			79	
Carazolol	299		116	
			222	

	Q1	structure	Q2	proposed structure
Carazolol D7	306		123	
			222	
Metsulfuron-methyl	382		167	
			199	
Molinate	188		126	
			83	
Penicillin V	383		160	
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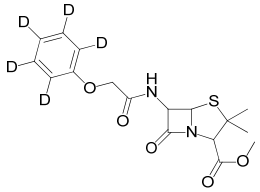
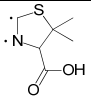
Penicillin V-D5	388		160	
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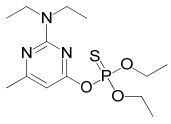
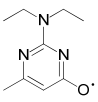
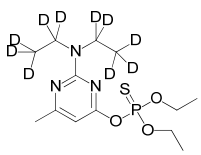
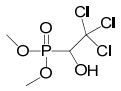
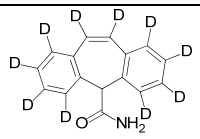
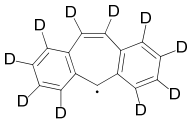
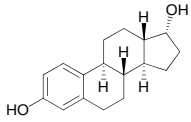
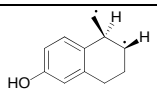
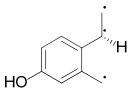
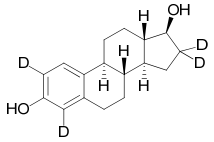
Pirimiphos-ethyl	334		198	
			182	
Pirimiphos-ethyl-D10	344		199	
			183	

	Q1	structure	Q2	proposed structure
Trichlorfon	257		109 127	
Carbamazepine D10	247		204	
17α-estradiol	255		159 133	 
17α-estradiol-D4	259		161 135