

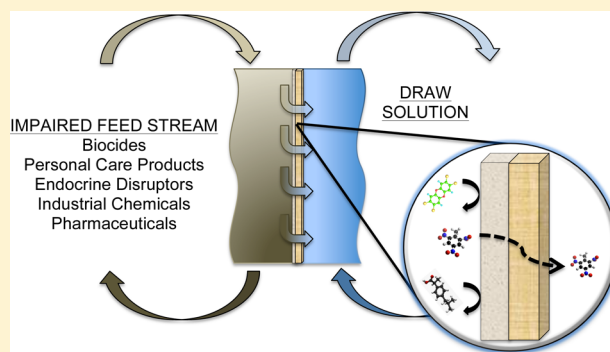
Rejection of Trace Organic Compounds by Forward Osmosis Membranes: A Literature Review

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ABSTRACT: To meet surging water demands, water reuse is being sought as an alternative to traditional water resources. However, contamination of water resources by trace organic compounds (TOrcs), including pharmaceuticals, personal care products, disinfection byproducts, and industrial chemicals is of increasing concern. These compounds are not readily removed by conventional water treatment processes and require new treatment technologies to enable potable water reuse. Forward osmosis (FO) has been recognized in recent years as a robust process suitable for the treatment of highly impaired streams and a good barrier to TOrcs. To date, at least 14 studies have been published that investigated the rejection of various TOrcs by FO membranes under a variety of experimental conditions. In this paper, TOrc rejection by FO has been critically reviewed, evaluating the effects of membrane characteristics and orientation, experimental scale and duration, membrane fouling, feed solution chemistry, draw solution composition and concentration, and transmembrane temperature on process performance. Although it is important to continue to investigate the removal of diverse TOrcs by FO, and especially with new FO membranes, it is critically important to adhere to standard testing conditions to enable comparison of results between studies. Likewise, feed concentration of TOrcs during FO testing must be environmentally relevant (most commonly 10–100 ng/L range for most wastewaters) and not excessively high, and in addition to testing TOrc rejection in clean feedwater, the effects of real water matrix and membrane fouling on TOrc rejection must be evaluated.



1. INTRODUCTION

1.1. Trace Organic Compounds (TOrcs). As urbanization, population growth, and drought continue to strain overburdened fresh water resources, water reuse has become an acceptable option to supplement potable water supplies.^{1–3} However, ubiquitous contamination by endocrine-disrupting chemicals (EDC), pharmaceutically active compounds, personal care products (PCP), disinfection byproducts, and industrial chemicals in surface water, groundwater, and reclaimed water poses significant human and environmental health threats because they are physiologically active at trace concentrations.^{4–12} Exposure routes may include dermal contact and consumption of potable water and aquatic and agricultural products.

1.2. Water and Wastewater Treatment Limitations. The prevalence of TOrcs in wastewater effluent and drinking water sources has gained increasing interest in recent decades; however, identifying suitable barriers to TOrcs has been historically difficult. TOrc concentrations ranging from ~100 ng/L to 100 µg/L are possible in raw domestic wastewaters,¹³ and their removal by conventional treatment processes varies substantially, resulting in the potential contamination of drinking water, receiving water bodies, and aquatic environments.^{8,14–19} Irrigation with reclaimed water can also lead to sorption of TOrcs in agricultural crops and to contamination

of groundwater.^{20–23} Inadequate TOrc rejection by conventional drinking water treatment has also been reported, in addition to a lack of understanding of the transformation products that may result from implementing advanced treatment technologies.^{5,16,24–29} Removal performance of TOrcs by traditional coagulation and lime-softening processes is typically low (<20%).^{26,30} This is especially true for recalcitrant TOrcs such as organohalogenes, organic pesticides, and surfactants. Common examples in water and wastewater treatment include TCEP, carbamazepine, diclofenac, atrazine, and meprobamate.^{31,32} Traditionally, advanced treatment processes that are being heavily investigated for TOrc removal or destruction include activated carbon,^{33–37} advanced oxidation processes (AOP),^{38–41} reverse osmosis (RO),^{42–48} nanofiltration (NF),^{43,45,46,48–51} and, more recently, forward osmosis (FO).^{52–65} Removal efficiency >90% is possible when using many of these technologies, but is largely dependent on TOrc hydrophobicity, charge, and biological or chemical degradability.^{26,30}

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Table 1. Major Water Quality Parameters and Experimental Conditions Used for Evaluating FO Membrane TOrC Rejection at the Bench and Pilot Scales

draw solution (DS)	DS concn	feed solution (FS)	FS pH	water flux (LMH)	membrane active area (cm ²)	no. of TOrCs	time (h)	ref
Cellulose Triacetate Membrane								
NaCl	0.5–2 M	Milli-Q	6.0	7–19	162	40	25	53 ^a
NaCl	0.5–2 M	Milli-Q	6.0	5.5–11	162	40	25	53
NaCl	1.2 M	Milli-Q	6.5	15	80	2	9–10	54
NaCl	1 M	Milli-Q	7.0	8–20	41	6	20	58 ^b
NaCl	1–4 M	10 mM NaCl	3–8	9–16	42	4	2	59
NaCl	0.5 M	20 mM NaCl + 1 mM NaHCO ₃	7.0	5.4	123.5	3	10	62
NaCl	1 M	20 mM NaCl + 1 mM NaHCO ₃	3.5–7.5	6–7.5	123.5	2	10	64
NaCl	1 M	20 mM NaCl + 1 mM NaHCO ₃	3.5–7.5	9.2–10	123.5	2	10	64 ^a
NaCl	0.5 M	20 mM NaCl + 1 mM NaHCO ₃	6.5	5.4	NA ^c	3	NA	62
NaCl	0.5 M	20 mM NaCl + 1 mM NaHCO ₃	6.5	5.5	123.5	12	NA	65 ^f
NaCl	0.5 M	2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.2	123.5	2	10	63
NaCl	0.5 M	50 mg/L humic + 2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.4	NA	3	NA	62
NaCl	0.5 M	50 mg/L humic + 2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.2	123.5	2	10	63 ^e
NaCl	1.2 M	hygiene WW	6.5	15	80	2	9–10	54
NaCl	1.0 M	synthetic WW	7.4	4	162	50	168	52 ^a
NaCl	3.0 M	Milli-Q	7.4	9.3	124	20	10	56
NaCl	3.0 M	200 mg/L sodium alginate	7.4	8.8	124	20	10	56
NaCl	3.0 M	200 mg/L bovine serum albumin	7.4	8.5	124	20	10	56
NaCl	0.5 M	synthetic SBMBR permeate	7.0	5	455	32	4–5	57
synthetic seawater	35 g/L	Milli-Q	7.0	5.7	620	4	4–5	55
synthetic seawater	35 g/L	secondary wastewater effluent	7.5	5.7	620	6	192	55 ^d
synthetic seawater	30 g/L	synthetic SBMBR permeate (inorganics)	7.0	5	455	32	4–5	57
synthetic seawater	30 g/L	synthetic SBMBR permeate	7.0	5	455	32	4–5	57
synthetic seawater	30–60 g/L	SBMBR permeate	7.1	8	15,800	32	960	57 ^d
seawater	40.5 g/L	synthetic WW (inorganics)	7.6	6	202	13	120	60
seawater	40.5 g/L	secondary wastewater effluent	7.6	6	202	13	120	60
MgSO ₄	2.5 M	20 mM NaCl + 1 mM NaHCO ₃	7.0	5.4	123.5	3	10	62
MgSO ₄	2.5 M	20 mM NaCl + 1 mM NaHCO ₃	6.5	5.4	NA	3	NA	62
MgSO ₄	2.5 M	2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.2	123.5	2	10	63
MgSO ₄	2.5 M	50 mg/L humic + 2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.4	NA	3	NA	62
MgSO ₄	2.5 M	50 mg/L humic + 2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.2	123.5	2	10	63 ^e
glucose	3 M	20 mM NaCl + 1 mM NaHCO ₃	7.0	5.4	123.5	3	10	62
glucose	3 M	20 mM NaCl + 1 mM NaHCO ₃	6.5	5.4	NA	3	NA	62
glucose	3.0 M	2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.2	123.5	2	10	63
glucose	3 M	50 mg/L humic + 2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.4	NA	3	NA	62
glucose	3.0 M	50 mg/L humic + 2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.2	123.5	2	10	63 ^e
urea	3.5 M	2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.2	123.5	2	10	63
urea	3.5 M	50 mg/L humic + 2 mM Ca + 20 mM NaCl + 1 mM NaHCO ₃	6.5	5.2	123.5	2	10	63 ^e
Polyamide Thin-Film Composite Membrane								
NaCl	0.5 M	20 mM NaCl + 1 mM NaHCO ₃	6.5	17.5	123.5	12	NA	65 ^e
NaCl	1–4 M	10 mM NaCl	3–8	12–30	42	4	2	59

^aForward osmosis membrane operated with active layer facing the draw solution (PRO). ^bCross flow velocities were varied to elucidate the impacts of concentration polarization on TOrCs rejection. ^cNA, information not available. ^dPilot-scale FO TOrCs rejection studies. ^eCalcium ion concentrations were varied in the feed solution to elucidate the impacts of tailored membrane fouling on TOrCs rejection. ^fFeed and draw solution temperatures were varied to elucidate the impacts of transmembrane temperature difference on TOrCs rejection.

1.3. Membrane Processes for TOrC Rejection. RO and NF can provide high rejection of TOrCs;^{42,43,45–51} however, rejection of some TOrCs, and especially those having low

molecular weight, might be limited, particularly with NF. Some TOrCs, which are expected to be well rejected by RO, can adsorb and diffuse through the membrane into the perme-

ate.^{43,66} TOrC rejection by RO and NF also depends on specific compound characteristics and their interactions with the membrane, which are affected by electrostatic repulsion, steric hindrance, and partitioning and diffusion of TOrCs through the membrane.^{66,67} Consequently, a multibarrier approach to TOrC rejection is necessary, and in many membrane applications, AOPs are used as post-treatment.

Forward osmosis has been extensively investigated in recent years for water and wastewater treatment, both as a standalone process and as a dual-barrier system when coupled with RO,^{68–72} and it has been utilized as an advanced pretreatment for downstream processes such as RO and thermal distillation. Similarly to NF and RO, FO utilizes semipermeable membranes, which provide a suitable barrier to most feed stream contaminants; however, FO is an osmotically driven membrane process, whereas NF and RO are driven by hydraulic pressure. Currently, a systematic understanding of the rejection mechanisms and impacts of operating conditions on the removal of TOrCs by FO is lacking. In FO, water from an impaired feed stream diffuses through a dense, semipermeable polymeric membrane into a concentrated draw solution having high osmotic pressure. The permeate stream is largely free of feed stream contaminants, with rejection comparable to RO. In past studies, FO has been investigated for water recovery from seawater, municipal wastewater, urban runoff, anaerobic digester centrate, and oil and gas exploration and production wastewaters.^{68,70,72–76} More recently, surging interest in water reuse and public concerns regarding TOrCs in drinking water and wastewater have led to several investigations that specifically focus on the performance of FO for TOrC rejection.^{55,57,72,77–79}

2. RECENT INVESTIGATIONS

2.1. FO Rejection of TOrCs: A Survey of Past Studies.

In the past decade, at least 14 studies have been conducted on TOrC rejection by FO membranes. The first study was conducted by Cartinella et al.,⁵⁴ who investigated the rejection of natural steroid hormones in advanced life support systems for use in space exploration. The main objective of the study was to evaluate the retention of two EDCs, which are excreted in urine and might be present in hygiene wastewater. Their results were the first to suggest that FO is a suitable barrier for EDCs and to demonstrate that TOrC rejection by FO depends on feed solution chemistry.

Five years later, surging interest in water reclamation and purification of impaired streams inspired five new studies on TOrC rejection by FO. Cath et al.⁵⁵ investigated a multibarrier FO–RO hybrid treatment system for dilution of seawater prior to desalination while simultaneously concentrating secondary wastewater effluent. Bench-scale FO tests were conducted with deionized water spiked with four TOrCs, and pilot-scale FO–RO tests were conducted with secondary wastewater effluent and TOrCs of similar concentration. Although this was the largest scale study of its time, it investigated only a limited number of compounds and tests were conducted for only 8 days. Therefore, Hancock et al.⁵⁷ expanded upon this research, conducting pilot-scale tests for 40 days using a commercial spiral wound FO membrane module (Hydration Technology Innovations, Inc. (HTI), Albany, OR, USA) while evaluating the rejection of 32 compounds present in a membrane bioreactor (MBR) permeate. Additional bench-scale tests used flat sheet membrane coupons and synthetic feed solution spiked with the same TOrCs and total dissolved solids (TDS)

concentration. Their study was the first attempt to systematically elucidate the mechanisms dictating TOrC rejection by FO membranes. Interestingly, this is the last pilot-scale test and longest FO TOrC rejection study to be performed to date. In the same year, Linares et al.⁶⁰ published results from bench-scale experiments that tested and compared the rejection of 13 TOrCs by clean membranes and membranes fouled by secondary wastewater effluent. Following suit, Alturki et al.^{52,53} published the first study of TOrC rejection in a bench-scale osmotic membrane bioreactor (OMBR) and the most inclusive surveys of TOrCs to date, investigating up to 50 compounds. These studies were conducted for up to 7 days, a duration that has not been exceeded by other bench-scale investigations. All four studies^{52,55,57,60} concluded that membrane fouling generally increased the effective sorption and rejection of TOrCs in the short term; however, their results accounted for only a narrow range of feed and draw solution chemistries, and their system operating conditions were different.

Four additional bench-scale studies were published in 2012 and were the first attempts to investigate the impacts of feed and draw solution chemistry and membrane surface properties on TOrC adsorption and rejection.^{59,62,64} Jin et al.⁵⁹ were the first to compare the short-term TOrCs rejection of an asymmetric cellulose triacetate (CTA) membrane and hand-cast polyamide thin-film composite (TFC) membranes synthesized especially for FO. TOrC rejection was discussed, focusing specifically on the physiochemical characteristics of four pharmaceutical compounds and on FO membrane surface properties while operating the system under different water fluxes and feed solution pH values.⁵⁹ Xie et al.^{62–65} published the three remaining studies in 2012 and another two in 2013. Although these studies were short (<10 h) and tested a very limited number of compounds (<5 TOrCs), they are the only studies that investigated the effects of draw solution solute selection, differences in transmembrane temperature, and levels of membrane fouling on the rejection mechanisms of TOrCs. They are also the only studies that have standardized bench-scale testing conditions, such as similar draw solution concentrations and osmotic driving forces, feed solution composition, membrane cell size and orientation, and solution flow rates. Although following slightly different testing conditions, D'Haese et al.⁵⁶ and Heo et al.⁵⁸ recently investigated the impacts of fouling in closed loop FO operations and different cross-flow velocities on TOrC rejection, respectively.

2.2. Experimental Testing Conditions. Despite the relatively few studies that investigated FO as a suitable process for TOrC removal, a broad range of testing conditions have been investigated for their impacts on TOrC rejection by FO (Table 1). Two inorganic (NaCl and MgSO₄)^{62,63} and two organic (glucose and urea)^{62,63} solutes were used as synthetic draw solutions with concentrations typically ranging from 0.5 to 4 M. Select studies used synthetic and natural seawater as draw solution, typically at environmental concentrations.^{55,57,60}

Feed solution chemistries were controlled to elucidate the mechanisms and conditions that influence TOrC rejection and sorption. Feed solution compositions ranged from Milli-Q deionized water to preconditioned wastewater streams, both natural and synthetic. Several studies amended Milli-Q water with select inorganic salts to mimic the ionic composition and strength of potential feed solutions, without the presence of organic foulants.^{53–55,57,59,60–65} In studies that focused on the

Table 2. Classification and Feed Stream Concentration of TOrCs Used for Evaluating FO Membrane TOrC Rejection at the Bench and Pilot Scales

TOrCs (Da)	concentration of TOrCs in the feed (ng/L)														
	ref S2	ref S3	ref S7	ref S7	ref S6	ref 60	ref 65	ref S5	ref S9	ref S4	ref S8	ref 62	ref 64	ref 62	ref 63
positively charged															
amitriptyline (227)	750	750	3				2000								
atenolol (266)	750	750	26.7	30	2000										
clozapine (327)	750	750													
diphenhydramine (255)			132	150											
hydroxyzine (375)	750	750													
methformin (129.16)					2000										
metoprolol (267.36)					2000										
propranolol (259.34)					2000										
trimethoprim (290)	750	750	21.6	40	2000		2000								
negatively charged															
bezafibrate (362)					2000		2000								
clofibrac acid (214.65)					2000										
diclofenac (296)	750	750	38.4	50	2000		2000	155	2.50E5			500			
fenoprofen (242)						10.9									
gemfibrozil (250)	750	750			2000	11.3		960							
ibuprofen (206)	750	750	34.1	40	2000	0.7		385	2.50E5						
ketoprofen (254)	750	750			2000	7.9									
naproxen (230)	750	750	74.1	100	2000	9.9		435	2.50E5						
pentachlorophenol (266)	750						2000								
phenylphenol (170)	750														
salicylic acid (138)	750	750			2000			260							
simvastatin hydroxyl acid (419)	750	750													
sulfamethoxazole (253)	750		185	250	2000		2000				1.30E5		250	500	500
triarterene (253)	750	750													
hydrophobic nonionic															
androstenedione (286)	750	750													
androsterone (290)	750	750													
atrazine (216)	750	750									1.08E6				
benzophenone (182)			90.1	100											
bisphenol A (228)			89.6	100		7.6						500			
carbamazepine (236)	750		388	500	2000	9.9	2000		2.50E5		1.18E6		250	500	500
4-chlorophenol (128.6)											6.43E5				
chlorthalidone (351)	750														
diazepam (285)			0.63												
diazinon (304)	750														
dilantin (252)	750	750	133	150			2000								
diuron (233)	750														
17 β -estradiol (272)	750	750								1000					
17 α -estradiol (272)	750	750													
17 α -ethynylestradiol (296)	750	750				6.4					1.48E6				
enalapril (376)	750														
estriol (288)	750	750													
estrone (270)	750	750								1000					
etiocholanolone (290)	750	750													
fluoxetine (309)	750	750	18.3	20											
linuron (249)	750	750					2000								
methotrexate (454)	750														
nonylphenol (220)	750	750													
tert-octylphenol (206)	750	750													
omeprazole (345)	750	750													
oxybenzone (228)			25.9	30											
phenol (94.1)											4.75E4				
polyparaben (180)	750	750													
risperidone (410)	750	750													
simazine (202)	750														
simvastatin (419)	750	750													

Table 2. continued

TOrCs (Da)	concentration of TOrCs in the feed (ng/L)														
	ref 52	ref 53	ref 57	ref 57	ref 56	ref 60	ref 65	ref 55	ref 59	ref 54	ref 58	ref 62	ref 64	ref 62	ref 63
TCEP (287)			366	400				800							
testosterone (288)	750	750													
triclocarban (316)	750	750	267	300											
triclosan (290)	750	750	90.5	100			2000					500			
verapamil (455)	750	750													
nonionic															
caffeine (194)	750	750	32.2	50	2000	9.6	2000								
DEET (191)	750	750	38.8	50											
1,4-dioxane (88)							9								
hydrocodone (299)			14.3	20											
paracetamol (151)	750	750			2000	8.3									
pentoxifyline (278.31)					2000										
phenazone (188)					2000	7.6									
primidone (218)	750	750	1.6		2000		2000								
meprobamate (218)	750	750													
methylparaben (152)			23.7	30											
metronidazole (171)						7.5									

impacts of membrane fouling on TOrC rejection, Milli-Q water was adjusted for both ionic strength and fouling potential by introducing humic acid,^{62,63} sodium alginate,⁵⁶ and bovine serum albumin;⁵⁶ in a specific case, calcium was added to promote various degrees of membrane fouling via complexation with humic acid.⁶³ Feed solution pH was commonly maintained near neutral, which is common for most domestic wastewaters; however, in two cases, the feed solution pH was adjusted to near pH 3 and pH 8.^{59,64}

All but two studies were conducted at the bench scale, using flat sheet tests cells with <620 cm² of membrane area. One pilot-scale investigation used a flat sheet test cell of 2660 cm² active area,⁵⁵ whereas the other used a commercial spiral wound membrane element with an active area of approximately 1.5 m². Interestingly, all studies used the CTA membrane manufactured by HTI. Despite recent advancements in FO membrane development, only two studies compared the TOrC rejection of the HTI CTA membrane to that of emerging polyamide TFC FO membranes; one study used a membrane that was synthesized in their laboratory,⁵⁹ and the other used a commercially available TFC membrane manufactured by Oasys Water (Boston, MA, USA).⁶⁵

2.3. TOrCs and Concentrations Previously Investigated. Overall, a total of 70 TOrCs have been investigated to date for their rejection by FO membranes (Table 2). These compounds were classified as charged (positive or negative), hydrophobic nonionic, or nonionic on the basis of their physiochemical properties at near neutral pH. High-performance liquid chromatography (HPLC),^{52,53,62–64} ultrafast liquid chromatography (LC),⁵⁹ and liquid chromatography–mass spectrometry (LC-MS and LC-MS/MS)^{55,57,65} were the common analytical techniques and instruments used to quantify TOrC concentrations in the different studies. Feed TOrC concentrations were highly variable, ranging from environmentally relevant concentrations measured in domestic wastewater (<960 ng/L) to concentrations greater by 3 orders of magnitude (250 µg/L).

3. TORC REJECTION IN FORWARD OSMOSIS: RESULTS FROM RECENT STUDIES

3.1. Effects of Membrane Fouling. Although membrane fouling propensity is considered low in osmotically driven membrane processes, various degrees of fouling and cake layer formation can occur, depending on the type of feedwater, complexation with multivalent cations, and reverse salt flux.^{62,63,72} Several studies investigated the impacts of membrane fouling on TOrC rejection; however, only six have explicitly compared the rejection of TOrCs between clean and fouled FO membranes.^{54,56,57,60,62,63}

Several studies have shown that carboxylic and hydroxyl functional groups, abundantly found in natural organic matter,^{60,63} can alter the membrane surface charge.^{4,11} It has been suggested that membrane fouling can increase the negative charge at the membrane boundary layer. An increasingly negative charge at the membrane surface can increase the electrochemical interaction between feed stream compounds and the membrane active layer. Xie et al.⁶³ reported that the rejection of negatively charged TOrCs increased as a result of enhanced electrostatic repulsion between the FO membrane and solutes, which is consistent with the substantial decrease in the membrane salt (NaCl) permeability coefficient. The highly hydrated fouling layer also provides an additional filtration barrier and is claimed to enhance TOrC rejection by fouled membranes.^{54,57,60,62,63} The rejection of nonionic compounds by clean membranes is largely dictated by size exclusion, but this may not accurately predict TOrC rejection by fouled membranes. In the presence of a fouling layer, polymeric membranes may swell due to elevated electroneutrality, increasing the effective molecular weight cutoff (MWCO) of the membrane.^{43,48} Therefore, rejection of hydrophilic nonionic TOrCs might decrease after a membrane is fouled, despite common claims that the additional filtration barrier enhances membrane sieving. The rejection of hydrophobic nonionic compounds might also depend on sorption and compound–foulant interactions.⁴⁸ In the short term, rejection of hydrophobic nonionic TOrCs can increase due to enhanced sorption to the fouled membrane; however, rejection might decrease over time⁶⁰ because of enhanced

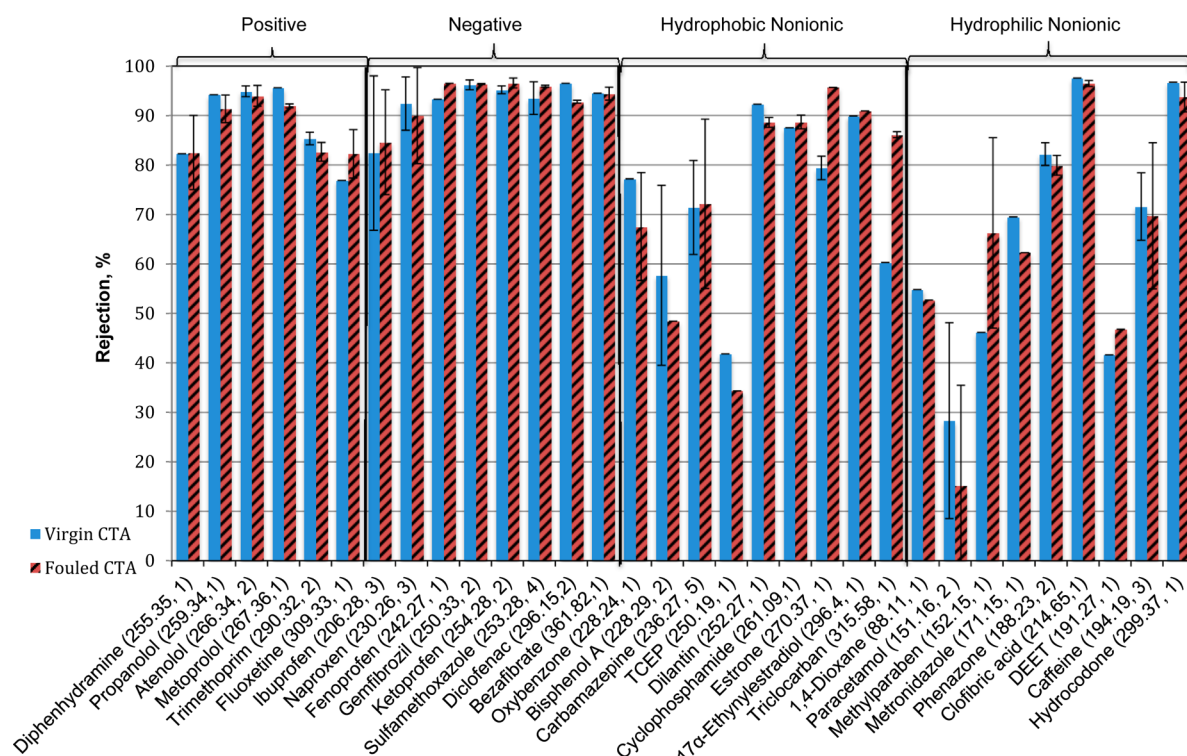


Figure 1. Average rejection of TOxTs by virgin and fouled FO CTA membranes tested at the bench scale. Only those results from experiments that used NaCl or seawater draw solution are shown. TOxTs are grouped on the basis of their physiochemical composition near neutral pH and are ordered by increasing molecular weight (MW, no. of studies). Error bars represent the standard deviation between multiple sample results for individual studies and between sample results reported by multiple studies.

diffusion resulting from cake-enhanced concentration polarization.⁸⁰

The main fouling agent used in most studies was humic acid (Sigma-Aldrich, St. Louis, MO, USA (50 mg/L)) mixed with inorganic ions in synthetic feed solution; however, some investigations focused on other fouling agents in the feed and their effect on TOxT rejection. Linares et al.⁶⁰ used secondary wastewater effluent feed, and Hancock et al.⁵⁷ used membrane bioreactor (MBR) effluent dosed with activated sludge, elucidating the impacts of natural versus synthetic feed solutions. Cartinella et al.⁵⁴ investigated the impacts of foulants found in a hygiene wastewater (e.g., detergents) in life support systems on TOxT rejection. D'Haese et al.⁵⁶ investigated three different foulants, sodium alginate, bovine serum albumin (BSA), and settled activated sludge, and compared the rejection of 20 TOxTs in the presence of these different foulants. In one study,⁶³ the degree of membrane fouling was systematically controlled by varying the concentration of calcium in the synthetic wastewater with a goal of understanding the role of calcium complexation on fouling layer formation and the associated impacts on TOxT rejection. This study showed that increasing calcium concentration in the feed stream increased the deposition of humic acid on the membrane surface, resulting in a positive correlation of increased TOxT rejection.⁶³

Two studies focused on the role and impact of reverse salt flux on TOxT rejection in the presence of a fouling layer.^{62,63} Xie et al.^{62,63} investigated multiple-draw solutions, including MgSO_4 and glucose, with the intention of elucidating the effects of reverse salt flux on fouling layer formation and the rejection of model TOxTs. The authors reported that higher reverse salt flux ($\text{NaCl} > \text{MgSO}_4 \approx \text{urea} \approx \text{glucose}$) led to increased fouling

through elevated ionic strength at the feed-membrane surface and, therefore, to higher TOxT rejection. It is interesting to note that the formation of the fouling layer did not drastically decrease water flux in the majority of the studies. Xie et al.⁶³ suggested that additional hydration sites available on the humic acid fouling matrix facilitated diffusion of water molecules across the membrane.

The average rejection of 32 TOxTs was calculated for studies that investigated rejection of TOxTs by both fouled and clean FO membranes (Figure 1). For the comparison, we have used results only from experiments that used NaCl or seawater draw solution and the HTI CTA membrane at the bench scale. The chosen TOxTs are grouped on the basis of their physiochemical characteristics near neutral pH and are ordered by increasing molecular weight.

Overall, the data presented in Figure 1 are in agreement with the rejection mechanisms described in previous studies.^{43,60} In most cases, rejection of charged compounds was higher for fouled membranes. D'Haese et al.⁵⁶ found that the different foulants did not change rejection significantly with the exceptions of phenazone, cyclophosphamide, and gemfibrozil, with rejections that significantly decreased when the membrane was fouled with BSA, as compared to sodium alginate. The authors did not thoroughly discuss the results and did not offer sufficient explanations for these observations. Rejection of negatively charged TOxTs clearly shows a positive correlation between increasing molecular weight and rejection. Negatively charged compounds were also more readily rejected by the FO membrane due to electrostatic repulsion by the negatively charged membrane surface. Rejection of nonionic compounds decreased in all but two cases, as proposed by Linares et al.;⁶⁰ however, rejection of hydrophobic nonionic compounds varied

greatly. This may be for a variety of reasons, including the molecular shape of the TOrC,⁶⁴ variation in draw solution concentration and reverse salt flux,^{62,63} compound and foulant hydrophobicity,^{54,57,60} and cake-enhanced concentration polarization. The duration of experiments could also affect the long-term rejection of TOrCs. Many of the bench-scale experiments with nonfouled membranes lasted for 2–10 h, whereas many of the fouling experiments lasted much longer, in some cases up to 5 days.⁶⁰ Similarly to RO and NF, as TOrCs adsorb to the fouling layer over time, an initial increase in rejection occurs; however, as time progresses, an increased concentration differential across the membrane would induce permeation of the TOrCs into the membrane, diffusion through the membrane, and desolubilization into the draw solution.^{62,80} Therefore, longer experiments may decrease the observed overall rejection of TOrCs in studies of fouled membranes.

3.2. Effects of Solution Chemistry: pH. The effects of feed solution chemistry, and specifically pH, have been investigated for pressure-driven membrane processes.^{43,45,67,81} Physicochemical properties (e.g., hydrophobicity and charge) of TOrCs and membrane surface charge are directly affected by changes in solution pH; bench-scale studies by Jin et al.⁵⁹ and Xie et al.⁶⁴ obtained similar results when assessing the performance of clean FO membranes under different pH values.

Jin et al.⁵⁹ evaluated the rejection of four pharmaceutical compounds at pH values of 3, 6, and 8 using both clean CTA and hand-cast polyamide TFC membranes. No significant change in TFC membrane performance as a function of feed solution pH was observed. A thorough discussion of TFC membrane performance is provided in section 3.8. When evaluating results from the CTA membrane, the authors concluded that the rejection of carbamazepine (236 Da) and diclofenac (296 Da) was high (typically >95%) and did not vary with feed solution pH. Carbamazepine is nonionic at neutral pH, and therefore rejection was predominantly dictated by size exclusion. A similar conclusion was proposed for diclofenac, despite its negative charge above a pH of 4.08.⁵⁹ In contrast, the rejection of ibuprofen (206 Da) and naproxen (230 Da), two negatively charged compounds (pK_a values of 4.47 and 4.20, respectively) of low molecular weight, changed with respect to variations in pH. When the pH decreased from 6 to 3, rejection of both compounds increased by at least 10%. The authors noted that both compounds are neutrally charged at pH 3 and their hydrophobicity increases with decreasing pH. Therefore, they hypothesized that increased rejection was due to enhanced sorption to the membrane surface, prior to diffusion through the membrane structure that is expected in the long term. When the pH increased from 6 to 8, rejection of both compounds again increased by at least 10%. The authors attributed this increase in rejection to electrostatic repulsion between the increasingly negatively charged membrane surface and negatively charged compounds at elevated pH.

Xie et al.⁶⁴ also investigated the rejection of two pharmaceutical compounds, including carbamazepine, at pH values ranging from 3.5 to 7.5 using a CTA membrane. The results were consistent with those previously presented⁵⁹ for FO rejection of carbamazepine with respect to feed solution pH, for which approximately 90% rejection was observed in all tests. Rejection of sulfamethoxazole (253 Da) was significantly affected by feed solution pH. At pH below 5.8, this compound is neutral and rejection is dictated by size exclusion. Interestingly, the authors note that despite a molecular weight

similar to that of carbamazepine, rejection of the nonionic sulfamethoxazole was significantly lower under similar testing conditions. The authors suggested that the presence of dipole moments and the molecular shape of the compounds can influence these TOrCs' rejection and must be taken into consideration. No discussion regarding increased sorption was provided. At pH above 5.8, sulfamethoxazole is negatively charged and was therefore better rejected as the pH increased. The authors' conclusions are similar to those of Jin et al.:⁵⁹ that charged compounds at increasing pH are better rejected due to increasing electrostatic repulsion. It should be noted that both studies also investigated the impact of feed solution pH on water flux through the FO membranes. Jin et al.⁵⁹ concluded that no significant change in water flux was observed with respect to pH, whereas Xie et al.⁶⁴ reported a slight increase in water flux with increasing pH. Increased water flux was attributed to conformational changes to the cross-linked membrane polymer structure and increasing membrane hydrophilicity, which can change significantly with increasing pH and feed solution buffering capacity;^{64,82} however, no attempt was made to correlate TOrC rejection to this observation.

3.3. Effects of Draw Solution Solutes and Concentrations. FO performance strongly depends on draw solution composition and concentration;^{83–94} however, until recently no studies had directly investigated the effects of draw solution solute and concentration on TOrC rejection. Hancock et al.⁵⁷ were the first to comment on the impacts of draw solution chemistry on TOrC rejection in FO, comparing FO performance using NaCl and synthetic seawater at similar osmotic pressures. The authors concluded that the type of draw solution used did not affect TOrC rejection. Although their conclusion is naturally intuitive given that seawater is predominantly NaCl, this study opened the door for further research to investigate the impacts of various draw solution concentrations using the same solute.

Jin et al.⁵⁹ investigated the rejection of four pharmaceutical compounds as a function of increasing water flux (using NaCl draw solution) through clean CTA and TFC FO membranes. Superior TOrC rejection by the TFC membranes was observed, and no significant changes were detected with increasing water flux. Insignificant change in carbamazepine and diclofenac rejection was observed when using the CTA membrane; however, the authors noted a significant increase in ibuprofen and naproxen rejection with increased water flux. Regrettably, the authors did not discuss these findings, paying greater attention to the impacts of feed pH on TOrC rejection (section 3.2). Similarly, Alturki et al.⁵³ did not discuss changes in observed TOrC rejection as a function of draw solution concentration. Using 0.5 and 2 M NaCl draw solutions, the authors compared the rejection of a clean CTA membrane operating in three different modes: FO, RO, and pressure-retarded osmosis (PRO) (section 3.5). Although the authors offered several explanations for the variations in TOrC rejection between each mode of operation, no explanation was provided for changes in TOrC rejection as a function of draw solution concentration in FO mode only.

Xie et al.^{62,63} have since conducted the most thorough investigations of the impacts of draw solution solutes on TOrC rejection. In three separate studies the authors explored TOrC rejection using NaCl,^{62,63} MgSO₄,^{62,63} glucose,^{62,63} and urea⁶³ as draw solutions at similar osmotic pressures. The authors concluded that forward diffusion of TOrCs could be hindered

by the reverse diffusion of solutes from the draw solution into the feed, especially with clean membranes. This claim is supported by the increased rejection of TOrCs with increased reverse diffusion of NaCl compared to the lower reverse diffusion observed with the other three draw solutes. These results provide a likely explanation for the results observed by Jin et al.,⁵⁹ where greater rejection of compounds at higher NaCl draw solution concentration might be attributed to greater reverse diffusion of solutes into the feed solution.

3.4. Effects of Transmembrane Temperature Difference. In a recent study by Xie et al.⁶⁵ the impacts of system temperature (defined as no temperature difference between the feed and draw solution) and transmembrane temperature difference on TOrCs rejection was investigated using CTA (HTI) and TFC (Oasys Water) FO membranes. Several studies have already reported the correlation between solution temperature and changes in water flux and solute permeability in FO;^{95–98} however, no study before had correlated these findings to changes in TOrC rejection.

The authors investigated nine pharmaceutical and three PCP compounds.⁶⁵ The rejection of charged compounds was greater than that of nonionic compounds and was minimally affected by solution temperature; however, changes in solution temperature did affect rejection of nonionic TOrCs. When the system temperature was increased, an increase in solute partitioning and diffusion was observed as predicted by the solution–diffusion model.⁹⁹ For example, the sorption of linuron (249 Da) and triclosan (289 Da) increased by 1 order of magnitude when feed and draw solution temperatures were increased by 20 °C (from 20 to 40 °C).⁶⁵ The diffusion coefficient of each compound also increased, which further explained the decrease in rejection with increased system temperature. In comparison, introducing a thermal gradient across the membrane boundary layer influenced water flux and reverse solute diffusion,^{95–97} which in turn have been shown to impact TOrCs rejection. Increasing temperatures resulted in a decrease of feed solution viscosity, thereby increasing both the rate of diffusion of water through the membrane¹⁰⁰ and the subsequent dilution of TOrCs permeating into the draw solution. Reverse solute diffusion can also hinder the forward diffusion of solutes and TOrCs from the feed into the draw solution. The solute diffusivity coefficient increases at elevated draw solution temperature, and solute resistivity of the membrane decreases.¹⁰⁰ Therefore, increased reverse solute diffusion due to higher draw solute diffusivity, induced by transmembrane temperature differences, can further hinder the diffusion of nonionic TOrCs across the membrane into the draw solution. The study concluded that changes in CTA and TFC membrane TOrC rejection were similar at different solution temperatures.

3.5. Effects of Membrane Orientation: Forward Osmosis versus Pressure-Retarded Osmosis. In osmotically driven membrane processes membranes are orientated and operated in either FO mode (active layer facing feed) or PRO mode (active layer in contact with draw solution). Whereas the PRO orientation is suitable for separation and rejection of feed constituents, this orientation is specifically used for harvesting energy when a salinity gradient is available (e.g., estuaries and desalination plants).^{71,101–103} It is otherwise rarely investigated for treatment of difficult waste streams due to severe fouling that can occur in the porous support layer of the membrane. The merit of investigating TOrC rejection by FO membranes operated in PRO mode is therefore

questionable. Regardless, three studies investigated the rejection of TOrCs by FO membranes while oriented in PRO mode (nonpressurized draw solution). Alturki et al.⁵² were the first to evaluate TOrC rejection of a CTA membrane operated in PRO mode in an osmotic membrane bioreactor (OMBR). A total of 50 TOrCs, representing pharmaceutical compounds, pesticides, steroid hormones, and other EDCs, were evaluated for their rejection and persistence after 7 days of operation. The authors concluded that the OMBR demonstrated high rejection (below detection limits) of most compounds with a molecular weight (MW) >266 Da. It was suggested that such excellent removal efficiency was likely attributed to the increased TOrC retention in the OMBR, which facilitated further biological uptake and degradation; however, trimethoprim (290 Da) and diclofenac, both with MW >266 Da, were poorly rejected (<35% rejection). The authors cited previous studies that noted poor biological uptake and degradation of these two compounds. Therefore, the feed concentration of both TOrCs increased in the feed solution over the testing period, which increased their diffusion across the membrane. Rejection of compounds with molecular weight <266 Da was highly variable, ranging from no removal to complete rejection. High rejection of compounds below 266 Da was not anticipated, and therefore TOrC rejection was attributed largely to biological degradation.

Alturki et al.⁵² provided a thorough review on the rejection of 50 different compounds, but did not discuss the effects of membrane orientation on membrane fouling or TOrC rejection. Surface charge and hydrophobicity of the membrane support layer can be significantly different when those of the active layer,^{104,105} which might affect electrostatic repulsion and the sorption capacity of the membrane. The authors also did not discuss the effects of cake-enhanced and internal concentration polarization, water flux, and reverse salt flux, all of which are expected to increase during operation in PRO mode. The study also did not compare between TOrC rejection of the FO membrane when operated in PRO mode and FO mode. Therefore, Alturki et al.⁵³ published an additional study that further investigated the rejection of 40 TOrCs by a clean CTA membrane as a function of draw solution concentration and membrane orientation. The authors' conclusions agreed with previous findings that the rejection of charged and nonionic compounds generally increases with MW. When the rejection of charged compounds was compared to draw solution concentration, it was found that increased rejection occurred at lower concentration. The authors proposed that higher draw solution concentration increased the reverse diffusion of solutes into the membrane support layer; this in turn increased the local ionic strength, which may have affected electrostatic repulsion or compressed the double layer surrounding the charged solutes and contaminants. This is despite the similar surface charge that was observed on the CTA membrane active layer and support layer during membrane characterization.⁵³ The rejection of nonionic TOrCs was largely dictated by compound size and MW, and draw solution ionic strength had minimal impact on compound rejection. In both cases, the authors concluded that membrane orientation significantly affected TOrC rejection, with compounds showing poorer rejection in PRO than in FO mode. In PRO, internal concentration polarization (ICP)⁸⁷ can increase the diffusive driving force of contaminants from the porous support layer into the draw solution, thus leading to a decline in effective TOrC rejection.

Xie et al.⁶⁴ further probed these findings by exploring the rejection of two pharmaceutical compounds as a function of membrane orientation and feed solution chemistry using a clean CTA membrane. For nonionic compounds, such as carbamazepine, increased concentrations in the membrane support layer increased the concentration gradient across the membrane boundary layer, which increased compound diffusion and decreased rejection when compared to FO. Furthermore, because the compound is nonionic, no significant impacts to rejection were observed with changes in solution pH. Similar to carbamazepine, sulfamethoxazole was also less rejected in PRO than in FO for pH <5.5; however, sulfamethoxazole is a negatively charged compound, and increasing rejection was observed with increasing feed solution pH. These results suggested that rejection of charged TOrCs could be enhanced by electrostatic repulsion when operated in PRO, despite concentrative ICP. It should also be noted that with increasing pH, water flux through the FO membrane slightly increased, which can increase the selectivity and apparent rejection of the membrane despite reduced rejection due to ICP.

3.6. Hybrid Forward Osmosis–Reverse Osmosis Membrane Systems. The use of FO as advanced pretreatment prior to RO, NF, or thermal distillation has been well documented in previous studies.^{55,57,68,106–108} Most commonly, FO is coupled with RO, where water first permeates from an impaired feed stream through the FO membrane and dilutes the draw solution. The diluted draw solution is then treated with RO, producing high-quality product water while reconcentrating the draw solution for reuse in the FO process.^{55,70–72,109–111} Three studies have explored the rejection of TOrCs using the hybrid FO–RO treatment scheme.

Cath et al.⁵⁵ were the first to investigate the combined rejection of TOrCs by an FO–RO system using flat sheet CTA FO membranes (HTI) and spiral wound polyamide RO membranes (SW30-2540, DOW Filmtech). Their main objective was to explore the mass transport phenomena of osmotic dilution ahead of seawater desalination; however, the study examined a limited number of TOrCs. Hancock et al.⁵⁷ later explored the rejection of 32 TOrCs from MBR permeate over 40 days of continuous operations using a 4 in. diameter spiral wound CTA FO membrane (HTI) coupled with spiral wound seawater RO membranes (SW30-2540, DOW Filmtech). Linares et al.⁶⁰ published a study simultaneously with Hancock et al.⁵⁷ in which they investigated the rejection of 13 compounds by a flat sheet CTA FO membrane (HTI) coupled with low-pressure RO (LPRO) membranes (BW30, DOW Filmtech).

Results from the three studies were in agreement, concluding that a hybrid FO–RO treatment scheme provides exceedingly high TOrC rejection and can serve as a suitable dual barrier to contaminant transport when impaired feed waters are treated. Cath et al.⁵⁵ observed TOrC rejection in the final RO permeate below analytical detection limits of all compounds studied. Hancock et al.⁵⁷ reported >99% rejection of most TOrCs despite operating the FO draw solution in a closed loop, which can lead to exceedingly high TOrC concentrations in the draw solution and can increase the concentrative external concentration polarization (ECP) at the RO membrane surface. Rejection of nonionic compounds was generally greater with increasing MW, which is in agreement with findings discussed throughout section 3. The authors also concluded that charged

TOrCs were well rejected, citing agreement with previous investigations. Interestingly, results published by Linares et al.⁶⁰ were consistent with those of Hancock et al.⁵⁷ despite testing TOrC concentrations of >2 orders of magnitude higher. Additionally, compared to a standalone LPRO system, hybrid FO–LPRO increased the rejection of all compounds, including two compounds with MW lower than or equal to the molecular weight cutoff of the chosen RO membrane.

3.7. Pilot-Scale Testing. Two pilot-scale studies have investigated the rejection of TOrCs by the FO process, both focusing on FO–RO hybrid treatment systems. The first was conducted by Cath et al.,⁵⁵ who used a system of flat sheet membrane coupons (2660 cm² active area) coupled with three 2.5 in. diameter by 40 in. long spiral wound SWRO membranes that was operated continuously for 8 days. In the second study,⁵⁷ a commercial spiral wound CTA membrane (HTI, 4 in. diameter by 40 in. long) was used, and the coupled FO–RO system was operated for 40 days. Six TOrCs were investigated by Cath et al.⁵⁵ and 32 TOrCs by Hancock et al.⁵⁷ Results from these studies were discussed under section 3.6. Cath et al.⁵⁵ commented on the improved performance of an FO–RO hybrid treatment system versus a standalone FO system for rejection of TOrCs; however, the authors did not directly comment on system performance as a function of scale. Hancock et al.⁵⁷ concluded that TOrC rejection observed at the pilot scale was greater than that observed for all conditions tested at the bench scale. The authors hypothesized that this can be attributed to FO membrane compaction, increased membrane fouling, and improved hydrodynamic conditions expected when operating treatment systems at a larger scale.

3.8. Polyamide Thin-Film Composite Membranes. Surging interest in the development of polyamide TFC FO membranes followed the first review on FO published in 2006.⁶⁸ Three subsequent reviews^{70–72} have since described the rapid development of these membranes, both commercially and by several research groups in academia; however, only two studies have investigated TOrC rejection using polyamide TFC membranes specifically synthesized for osmotically driven membrane processes. One study compared TOrC rejection of a TFC membrane to that of a CTA membrane operated in PRO mode, but it was an NF membrane (NF90, DOW Filmtech) designed specifically for pressure-driven membrane processes and is therefore not discussed.⁵³

In 2012, Jin et al.⁵⁹ were the first to compare the performance of two hand-cast TFC membranes¹¹² to that of HTI's CTA membrane; the TFC membranes exhibited superior water permeability and TOrC rejection. The higher rejection by the TFC membranes was attributed to electrostatic repulsion by the more negatively charged membrane active layer and the reduced solute permeability and higher water flux (at similar osmotic pressure driving force) of the polyamide membrane compared to the CTA membranes. For the relatively large molecular weight compounds (200–300 Da), the authors also noted that feed solution pH had minimal impact on TOrC rejection, indicating that size exclusion was likely the dominant removal mechanism versus electrostatic repulsion or adsorption.

In 2013, Xie et al.⁶⁵ were the first to explore the rejection performance of a commercially available FO TFC membrane (Oasys Water) while investigating changes in FO TOrC rejection with respect to transmembrane temperature differences. Whereas changes in TFC membrane performance and rejection were similar to those observed in the CTA membrane,

in general, the authors' findings agreed with those presented by Jin et al.⁵⁹ TOrC rejection by the TFC membrane was significantly greater than that of the CTA membrane, likely due to size exclusion related to the smaller B value (solute permeability) of the membrane active layer. The authors also noted the more negatively charged surface of the TFC membrane, concluding that electrostatic repulsion of charged compounds resulted in higher rejection than that observed for neutral compounds.

4. DISCUSSION AND OUTLOOK

Results from FO studies to date demonstrated that FO alone, or in combination with RO, can be used to reject a broad range of TOrCs. At least 70 compounds were tested under various operating conditions in 14 studies, and the majority were well rejected (>90% rejection) by the different FO membranes.

Like in NF and RO, the rejection mechanisms of TOrCs by FO involve a complex combination of mechanisms, including steric hindrance, electrostatic repulsion, solubility and diffusivity in the membrane, and hydrophilic–hydrophobic forces between the solutes and membrane. These, in conjunction with the highly dependent performance of FO on operating and physiochemical conditions on both sides of the membrane, require careful consideration in planning experiments and interpreting the results. For example, reverse solute diffusion, internal concentration polarization, and transmembrane temperature gradient are phenomena that occur in FO and not in RO or NF. These might affect the transport and rejection of TOrCs in FO processes.

In general, the rejection of hydrophilic nonionic TOrCs is controlled by physical sieving of compounds larger than the membrane's MWCO. For hydrophobic nonionic TOrCs, the initial adsorption onto membranes may be an important factor in the rejection of TOrCs; the rejection decreases with increasing saturation of the solute in the membrane. Although the CTA FO membranes can be less negatively charged than TFC NF, RO, and FO membranes, the rejection of negatively charged TOrCs is enhanced by electrostatic repulsion. The rejection of positively charged compounds follows the general principle of size exclusion; however, it exhibits lower rejection than negatively charged compounds and hydrophilic nonionic compounds due to slight electrostatic attraction to the negatively charged membrane surface. In addition, the solution chemistry in FO systems and membrane fouling might have considerable influence on rejection of TOrCs.

Data summarized in Table 1 clearly show the wide variability of testing conditions used in the 14 FO TOrC studies. Most notable is the broad range of TOrCs tested and their concentrations in the feed solution. Whereas it is important to test many TOrCs with a variety of chemical characteristics, the feed concentrations must be within an environmentally relevant range. In some of the reviewed studies, experiments were conducted with feed streams having very high TOrC concentrations, which are unrealistic for most water treatment applications. The dependence of solute mass transport through membranes on concentration gradient, the effects of external concentration polarization (higher solute concentration at the feed–membrane interface), and the potential accumulation of TOrCs in the draw solution when using RO for closed-loop reconcentration of the draw solution can negatively affect the apparent rejection of TOrCs in FO.

Furthermore, the duration of experiments and conditioning of the FO membrane might have substantial effects on the

accuracy of the results. Low and medium molecular weight and uncharged TOrCs slowly diffuse through the membranes under the influence of various driving forces. Conditioning the membrane by exposing it to the feed solution for an extended time before the experiment (at least 24 h without draw solution on the support side)⁵⁷ and conducting long-term experiments (>10 h) will ensure that the results capture steady state transport and rejection conditions and not transient conditions.

Moreover, membrane sorption capacity is largely dependent on the hydrophobic properties of the chosen TOrCs, the membrane polymer chemistry, and the type and degree of membrane fouling. In many studies rejection of hydrophobic nonionic compounds increased in the presence of membrane fouling; however, experiments in these studies were conducted for a very short time (a few hours). Due to cake-enhanced concentration polarization, previous studies are likely reporting TOrC rejection during a transitional period when the concentration of TOrCs is increasing at the membrane surface prior to enhanced diffusion across the polymer matrix. The long-term, steady state rejection of these TOrCs might decrease significantly when compared to short-term results. Therefore, experiments conducted to investigate TOrC rejection by fouled FO membranes should be conducted for durations exceeding 24 h, preferably several days. Future studies may also benefit from adopting more standardized testing conditions such as those recently published,⁹⁸ especially if implemented as a control experiment prior to changing operating conditions.

Other operating conditions might substantially affect TOrC rejection results in FO. For example, a small number of studies reported TOrC rejection results from testing in PRO mode. For most FO applications, FO membranes will always be operated with the dense active layer facing the feed solution and not in PRO orientation. When the membranes are operated in PRO orientation, it is usually for the purpose of energy generation and not for water treatment. Furthermore, although operating in PRO mode might increase water flux through the FO membrane, concentrative internal concentration polarization might actually increase TOrC diffusion through the membrane and decrease TOrC rejection. Therefore, testing TOrC rejection in PRO mode is discouraged for testing of TOrC rejection or rejection of any other constituents by the FO process.

The majority of studies investigated TOrC rejection at the bench scale. Only a few evaluated TOrC rejection at the pilot scale, and even fewer compared TOrC rejection between bench and pilot scales. Whereas it is appropriate and important to test TOrC rejection at a laboratory scale, results from pilot studies might be more relevant because commercially packaged membranes have different performances and hydraulics and because, in most cases, the feed solution is more environmentally relevant.⁵⁷ This also highlights the importance of testing and standardizing the composition and cosolutes tested in the feed streams. Dissolved and suspended organic and inorganic constituents in the feed streams will substantially affect the performance of FO membranes and their rejection of TOrCs.

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Notes

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