A Comprehensive Bench- and Pilot-Scale Investigation of Trace Organic Compound Rejection by Forward Osmosis

SUPPORTING INFORMATION

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S1 – The FO-RO dual barrier system for high efficiency water purification

Our recent study has demonstrated the effective dual barrier characteristics of the FO process when hybridized with seawater RO for treatment of secondary and tertiary treated domestic effluents (Cath et al. 2010). In the process impaired water is first treated by an FO membrane and water is drawn into a seawater draw solution (DS) and the diluted DS is desalinated by RO to produce a stream of purified water. The basic configuration of the hybrid FO-RO process is illustrated in Figure S1. The osmotic dilution approach may provide at least four major benefits related to water and energy resources. These include lower energy and higher recovery seawater desalination, multi-barrier protection of drinking water, reduction in reverse osmosis membrane fouling due to impurities in impaired water, and beneficial reuse of impaired water.

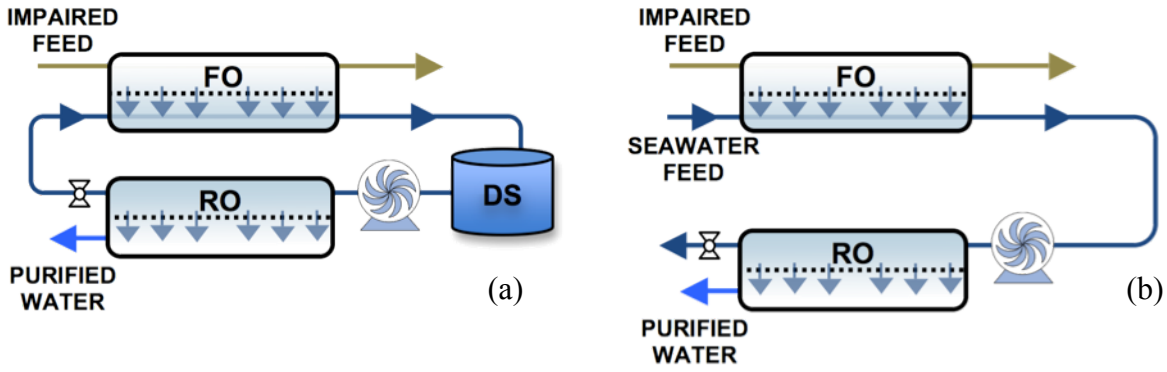

Figure S1. Two configuration of the hybrid FO-RO process: (a) closed loop DS in which the FO recovers water from an impaired stream and the RO reconcentrated the DS for reuse and simultaneously produces purified water, and (b) open loop DS in which the FO recovers water from an impaired stream that dilutes pretreated seawater on the way to a seawater reverse osmosis process.

The rejection of wastewater constituents such as organic carbon, nutrients (i.e., ammonia, nitrate, phosphate), and suspended solids by the two tight barriers (FO and RO) was very high (95-99.9%), the FO membranes protected the sensitive RO membranes from fouling and scaling, and energy saving was calculated.

S2 – Novel spiral wound FO membrane module

For the pilot study the CTA membrane was employed in a novel spiral wound packaging configuration that improves membrane-packing density (i.e., membrane active surface area per module volume) for commercial applications.

However, conventional spiral wound module designs (e.g., spiral wound RO modules) are inadequate for the circulation of two fluids required for FO. In RO spiral wound modules the product water (permeate) is forced out of the membrane envelope by permeating water (Figure S2a); however, in an FO spiral wound module, the DS has to flow through the membrane envelope (Figure S2b) to facilitate mass transfer across the membrane. As illustrated in Figure S2b, an additional glue line is added in the center of the membrane envelope that partially extends toward the outer edge of the membrane envelope, and a plug is placed at the center of the core tube to force the DS to flow inside the membrane envelope. The novel spiral wound FO module that was investigated in the current study is made of a single membrane envelope with an active area of 1.58 m^2 and it was fitted inside a conventional 4040 membrane pressure vessel.

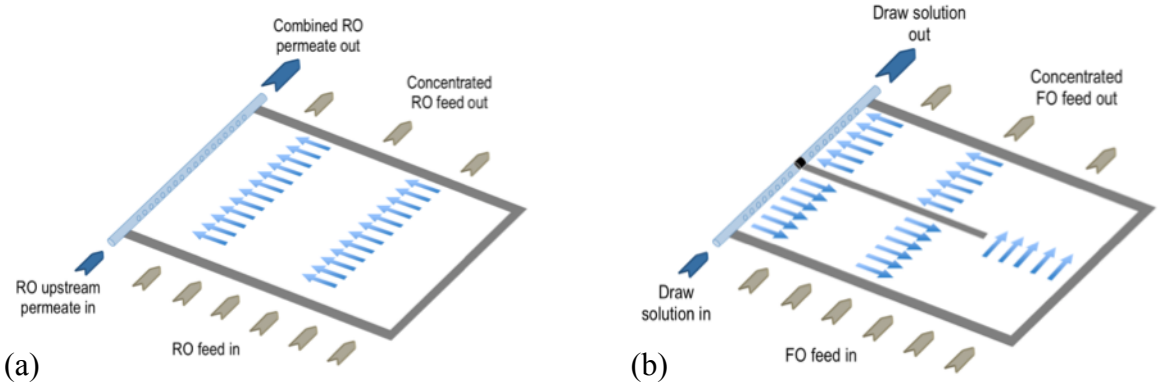

Figure S2. Flow patterns in a spiral wound module used for (a) RO and (b) modified for FO. The feed stream flows tangentially across the exterior of the rolled membrane envelope in both cases; however, the FO DS is forced to flow into the core tube and then through the interior of the membrane envelope before exiting the module.

S3 – Pilot-scale FO-RO system

A pilot-scale FO-RO hybrid system was utilized for the long-term testing of the spiral wound commercial FO membrane. Details about the design and operating conditions and control

of the system are provided in our previous publication (Cath et al. 2010). The major components of the hybrid system are illustrated in Figure S3. The RO subsystem was used for continuous re-concentration and production of DS at constant concentration, and to investigate micropollutant and nutrient removal during the osmotic dilution process. The RO subsystem was configured in a three-stage array (1-1-1) of 2.5"x40" SWRO membrane elements operated in a semi-closed loop. Diluted DS from the FO membrane module returned to the SWRO feed tank and an RO permeate side stream (equivalent to the flowrate of water through the FO membrane) was removed from the system. A high-pressure, variable speed, positive displacement pump (HydraCell M03, Wanner Engineering, Inc., Minneapolis, MN) was used in the RO subsystem.

Sensors were installed in the RO subsystem to measure stage 1 permeate and final concentrate (i.e., FO DS) conductivities, flow rates of all streams, and operating pressures. Permeate and concentrate flow rates and concentrate pressure were measured with rotameters and pressure transducers, respectively. All electronic sensors were connected to the PLC system.

A 4" FO membrane module was acquired from Hydration Technology Innovation (HTI) with a membrane surface area of 1.5 m^2. A constant speed rotary vane pump was used to supply feed at approximately 12 L/min to the FO membrane module. A 50-mesh (279 micron) strainer was installed on the feed line to reduce the loading of suspended solids on the FO membrane.

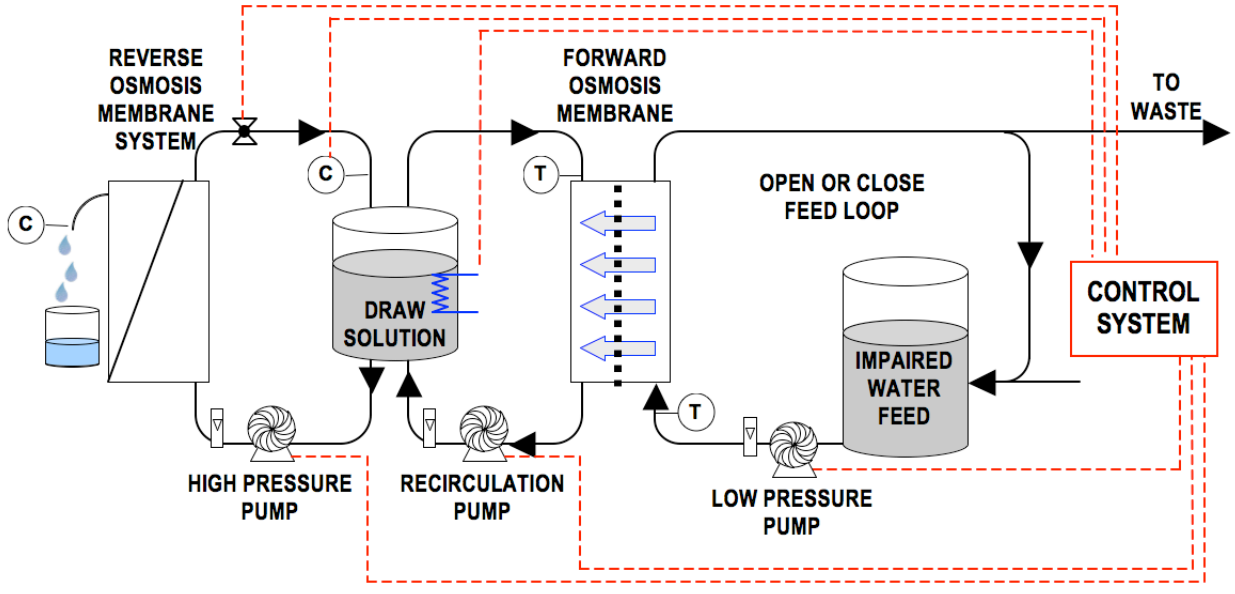

Figure S3. Schematics of the hybrid FO-RO pilot system.

S4 – TOrCs analysis

A total of 69 samples were drawn from the feed, DS, and product water of the FO-RO pilot system during interval B through E and analyzed by isotope dilution LC-MS/MS. Isotope recoveries for TOrCs in each stream are summarized in Table S1. All isotope recoveries exceeded 15 percent for accurate TOrC concentration quantification, and all compounds that overlapped with Vanderford and Snyder were recovered at the same level or higher (Vanderford and Snyder 2006).

Table S1. Isotope recovery for TOrCs detected in feed, DS, and RO product water samples during bench and pilot scale experiments.

Constituent	**Isotope Recovery in stream, %**		
	Feed	**DS**	**RO Permeate**
	ESI+		
Amitriptyline	35.2 ± 6.0	41.5 ± 15.1	65.7 ± 10.9
Atenolol	30.1 ± 6.9	43.6 ± 20.4	55.8 ± 12.8
Benzophenone	68.6 ± 8.9	60.1 ± 10.4	72.5 ± 16.1
Caffeine	19.4 ± 2.5	28.6 ± 10.1	47.9 ± 9.6
Carbamazepine	30.8 ± 2.3	33.2 ± 12.9	73.6 ± 7.8
DEET	32.4 ± 4.2	30.6 ± 10.4	63.9 ± 8.5
Diazepam	35.4 ± 2.9	32.0 ± 10.4	50.3 ± 11.3
Dilantin	54.2 ± 6.1	64.5 ± 20.7	96.7 ± 9.7
Diphenhydramine	22.0 ± 3.0	32.9 ± 12.1	56.4 ± 8.9
Fluoexetine	19.2 ± 1.9	26.4 ± 5.0	34.2 ± 11.4
Hydrocodone	28.0 ± 2.2	37.1 ± 15.1	57.8 ± 7.5
Oxybenzone	28.1 ± 3.7	22.2 ± 5.4	39.6 ± 6.3
Primidone	40.7 ± 3.9	54.4 ± 19.8	86.4 ± 8.8
Sulfamethoxazole	23.4 ± 4.4	31.0 ± 12.0	52.5 ± 11.8
TCEP	27.9 ± 2.2	34.8 ± 18.3	64.3 ± 11.3
Trimethoprim	21.3 ± 2.4	34.5 ± 14.1	74.4 ± 9.9
	ESI-		
Bisphenol A	55.4 ± 8.1	49.8 ± 13.8	63.1 ± 9.4
Diclofenac	55.9 ± 8.8	41.1 ± 6.8	78.5 ± 14.9
Ibuprofen	90.4 ± 5.0	85.6 ± 8.4	94.1 ± 4.3
Methylparaben	49.0 ± 1.8	44.3 ± 19.2	89.6 ± 7.0
Naproxen	65.1 ± 5.0	57.2 ± 8.4	82.2 ± 6.0
Triclocarban	45.7 ± 14.9	42.1 ± 11.4	57.4 ± 16.7
Triclosan	38.9 ± 8.3	58.5 ± 14.3	71.7 ± 12.7

S5 – Calculation of TOrCs rejection in FO

Calculating rejection of any feed constituent during FO is much more complicated than calculating rejection during RO. In the latter, it is very simple to measure the concentration of a constituent in the permeate stream (c_p) and then using the value (in conjunction with the feed concentration (c_f)) to calculate rejection by the membrane [Rejection=1-(c_p/c_f)]. In FO the permeate stream absorbs (and dilutes) directly into the draw solution and therefore its concentration cannot be measured directly – it can only be calculated through a mass balance.

During both the bench- and pilot-scale experiments feed and draw solution samples were drawn at the beginning and end of well-defined and recorded time intervals. The change in concentration of TOrCs in the draw solution during each time interval was used in conjunction with the volume of water that crossed the FO membrane at the same time interval to calculate the concentration of TOrCs in the permeating water. Using the same equation [Rejection=1-(c_p/c_f)], the rejection by the FO membrane was determined. As can be seen in Figure 1 and especially in Figure 3, rejection could not be calculated for some TOrCs that were not detected in specific streams. This is a conservative approach because in many cases we could assume close to 100 percent rejection when a TOrC could not be detected in the DS.

References

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