

Rejection of malathion by nanofiltration and reverse osmosis membranes exposed to foulant and two clean-in-place procedures

Anne M. Mikelonis^{a,*†}, Christopher J. Orme^{b,†}, Amit S. Nilkar^b, Jeffrey G. Szabo^c and Stephen J. Reese^d

^a Homeland Security and Material Management Division, Center for Environmental Solutions & Emergency Response (CESER), Office of Research and Development (ORD), U.S. Environmental Protection Agency (U.S. EPA), Research Triangle Park (RTP), NC 27711, USA

^b Chemical Separations Group, Material Separations & Analysis Department, Idaho National Laboratory, Idaho Falls, ID 83415, USA

^c Homeland Security and Material Management Division, Center for Environmental Solutions & Emergency Response (CESER), Office of Research and Development (ORD), U.S. Environmental Protection Agency (U.S. EPA), Cincinnati, OH 45268, USA

^d Geothermal Energy & Subsurface Systems Group, Power & Energy Systems Department, Idaho National Laboratory, Idaho Falls, ID 83415, USA

*Corresponding author. E-mail: mikelonis.anne@epa.gov

†These authors contributed equally to this work.

 AMM, 0000-0002-0835-5530

ABSTRACT

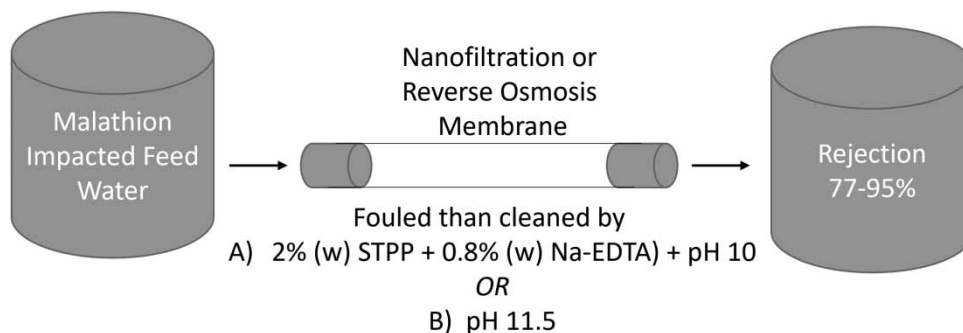
This research tested the treatment efficacy of an Energy Savings Nanofiltration 1 Low Fouling (ESNA 1-LF) nanofiltration (NF) and an Energy Saving Polyamide 2 (ESPA2) reverse osmosis (RO) membrane for removing malathion from water. Both membranes are of composite polyamide construction. The study included measuring malathion rejection using both pristine membranes and membranes exposed to a simulated secondary wastewater effluent foulant before and after two types of clean-in-place procedures. Across all conditions studied, malathion rejection ranged from 84 to 95% for the ESNA1-LF NF membrane and 77 to 94% for the ESPA2 RO membrane. Contact angle measurements were also collected for each membrane exposure condition. While the contact angle measurements indicated changes to the hydrophobicity of the selective layer of the membranes, they did not correlate to changes in the performance of malathion rejection. As expected, it was observed that malathion rejection improved with the introduction of foulant. Also, the clean-in-place procedures helped restore flux while maintaining malathion rejection.

Key words: clean-in-place, malathion, nanofiltration, pesticide, reverse osmosis

HIGHLIGHTS

- ENSA-1LF and ESPA2 membranes removed 77–95% of malathion from the waters studied.
- Malathion rejection improved with the introduction of simulated secondary wastewater effluent foulant.
- Clean-in-place procedures helped restore flux while maintaining malathion rejection.

GRAPHICAL ABSTRACT



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1. INTRODUCTION

Malathion is one of the most prevalent organophosphate pesticides (Atwood & Paisley-Jones 2017; Badr 2020). It is an active component of products used for controlling mosquitos, other insects harmful to agriculture, and head lice (National Pesticide Information Center 2010). Malathion was designed to minimize toxicity to mammals and nontarget insects, but there are environmental and health concerns at concentrations exceeding regulatory limits. These include the degradation of aquatic ecosystems, suggestive evidence of carcinogenicity to humans, and toxicity to nontarget beneficial insects such as bees (Newart 2006; Hertz-Picciotto *et al.* 2018). High aqueous concentrations stem from over/misapplication and insecticide manufacturing waste streams. Malathion is also commonly used as a surrogate for the nerve agent VX (Figure 1) due to similarities in physical-chemical properties (Bartelt-Hunt *et al.* 2008; Costa 2018). The research reported here aims to document the treatment efficacy of a nanofiltration (NF) and a reverse osmosis (RO) membrane for removing malathion from water. The study includes testing of malathion rejection using both pristine membranes and membranes exposed to foulant before and after two types of clean-in-place procedures. Water utilities and emergency responders may utilize malathion treatability and membrane cleaning information following the accidental/intentional release of malathion or a homeland security incident.

While malathion concentrations in most waters are low to nonexistent, malathion has been detected at high concentrations in a variety of different water sources internationally. In an assessment of 1,098 journal articles (selected through a targeted keyword search in Scopus, Embase, and PubMed databases with inclusion criteria including the reporting of malathion in water resources, articles published in English, and that they were cross-section studies), the mean values of malathion in highly contaminated drinking waters were 26,684.64 $\mu\text{g/L}$, ground waters 397.75 $\mu\text{g/L}$, and surface waters 9,310.78 $\mu\text{g/L}$ (Vasseghian *et al.* 2022). The meta-analysis also found that in these highly contaminated waters, exposure to malathion residues in drinking water sources was above recommended levels of carcinogenic risks in some locations. The United States Environmental Protection Agency currently does not regulate malathion in drinking water, but it is listed on the drinking water contaminant candidate list (2022) and has a health advisory level of 0.2 mg/L (U.S. EPA 2018). The U.S. guidelines for malathion limits in surface waters that range from 0.1 to 140 $\mu\text{g/L}$ depend on the state (Agency for Toxic Substances & Disease Registry 2003).

Several different water treatment processes have been found effective at removing malathion. Advanced oxidation processes involving hydrogen peroxide in combination with iron, ozone, or iron with ultraviolet irradiation have been found to remove 60–99, >99, and 94.3% of malathion, respectively (Roche & Prados 1995; Roe & Lemley 1997; Huston & Pignatello 1999). Ozone at a dose of 5 mg/L and 10 min of contact time also removed 99% of malathion from water (Roche & Prados 1995). Additionally, adsorption has proved to be an effective method for treating malathion-contaminated waters (Gupta *et al.* 2002; Chatterjee *et al.* 2010; Jusoh *et al.* 2011; Marican & Durán-Lara 2018; Sabbagh *et al.* 2021). While there are proven treatment technologies, not all water treatment scenarios will have the equipment and funds available to implement additional advanced oxidation processes or sorbents, and therefore, it is necessary to consider additional treatment technologies as well.

RO membranes were developed for water treatment applications in the 1970s (Warsinger *et al.* 2018). They are composed of support and a top polymer layer that permeates water. The polymer layer has sub-nanometer pores and is most often made from polyamide or cellulose acetate materials (Lee *et al.* 2011). Pressure is applied to drive water through the membrane leaving rejected contaminants on the feed side. Due to their high salt rejection, RO is the most used desalination technology in the

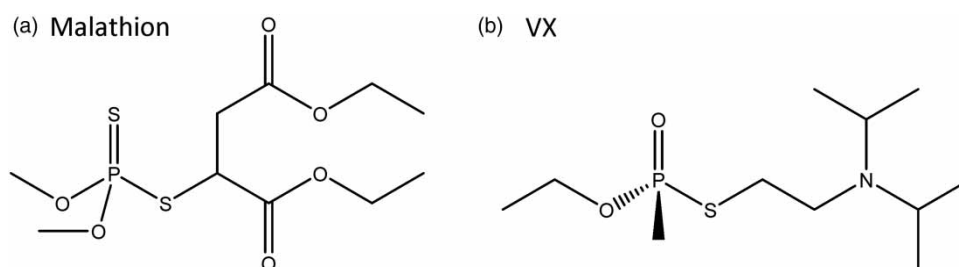


Figure 1 | Molecular structure of (a) malathion and (b) chemical warfare agent VX.

water treatment industry and has also been successfully used to separate low-molecular-weight organic compounds such as pesticides (Chian *et al.* 1975). NF membranes were introduced approximately 20 years later as an alternative to RO with higher water permeability and therefore lower operating pressures and energy costs. This stems from NF membranes having a higher molecular weight cutoff (MWCO) of approximately 100–5,000 Da compared to RO's MWCO of <100 Da (Peter-Varbanets *et al.* 2009). Malathion has a MWCO of 330.4 Da, a molecular width of 0.510 nm, and a log *n*-octanol/water partition coefficient of 2.36 (Kiso *et al.* 2000), so rejection by sieving is expected to be successful for RO membranes and most, but not all, NF membranes. NF membranes are also more commonly designed to remove specific organic contaminants than RO (Bellona *et al.* 2004). Several membrane-based studies have indicated effective treatment of malathion using RO or NF membranes (Chian *et al.* 1975; Kiso *et al.* 2000; Zhang & Pagilla 2010; Sorour & Shaalan 2013). However, there are gaps in these studies because only a subset of pristine membrane material types and feed solutions were tested. At a conventional water treatment plant, membrane processes follow multiple pre-treatment unit treatment processes such as screening, coagulation, flocculation, and settling basins. In emergency mobile water treatment applications, minimal pre-treatment occurs prior to treatment of the malathion. Both RO and NF membrane processes become fouled when feed streams contain dissolved inorganic and organic matter. This can either increase or decrease separation efficiency but causes a reduction of membrane flux that requires cleaning to restore normal performance (Agenson & Urase 2007). This is particularly applicable in potable reuse and mobile treatment applications. The research presented in this paper uniquely contributes to the field by expanding the membranes tested and by including foulants before and after cleaning.

2. EXPERIMENTAL

2.1. Membranes and crossflow test unit

An ESNA1-LF NF membrane (Hydranautics, Oceanside, CA) and a low-pressure ESPA2 RO membrane (Hydranautics, Oceanside, CA) were used as model membranes for this research. These membranes were selected after consultation with members of the American Water Works Association Membrane Processes and Research Committee about perceived market prevalence. ESNA1-LF NF membranes are marketed to remove pesticides, bacteria, viruses, hardness, iron, and total organic carbon. They have also been shown to remove arsenic (Yu *et al.* 2013) and trace organic solutes (Drewes *et al.* 2005). ESPA2 RO membranes are marketed for salt rejection when lower feed pressures are needed. They have also been shown to remove N-nitrosamines (Fujioka *et al.* 2013a) and disinfection byproducts (Doederer *et al.* 2014). Both membrane materials were composite polyamide. According to Hydranautics' product sheets, the ESNA1-LF NF membrane has an expected performance of 88–97% CaCl₂ rejection at 500 ppm CaCl₂, 0.52 MPa, 25 °C, and 6.5–7.0 pH. It has a smooth surface topography to minimize sites for debris trapping and its surface charge has been reduced compared to the original ESNA1 membrane (Bartels & Casey 2006). The membranes were cut from flat sheets to fit a 42 cm² active area stainless-steel coupon holder (Item # CF042SS, Sterlitech, Auburn, WA) and stored in deionized (DI) water when not in use. Additionally, a 34 mm feed and permeate spacer material provided by Hydranautics was used during the treatability/cleaning portions of this work. Experiments were performed using a custom-built laboratory-scale crossflow unit consisting of a feedwater tank with pump (Item # M-03S 1.8 GPM, WANNER HYDRA-CELL, Minneapolis, MN) flowing solution through two membranes in parallel (Figure 2). Pressure measurements were collected before and after each membrane using 0–1,000 psi pressure transducers (Item # UX-68075024, Cole-Parmer, Vernon Hills, IL), flow measurements were collected on each feed return using 0.5–5 L/min flow meters (McMillan Flow, Cole-Parmer, Item # EW-32718030, Vernon Hills, IL), and mass measurements were collected of each membrane's permeate using 3,100 g × 0.1 g top loading balances (Item # PGL2002, Adam Equipment, Oxford, CT).

2.2. Test sequence

For each membrane type, a two-phase series of experiments was performed (Figure 3) using the membrane skid. In brief, the process involved fouling a subset of membranes, testing the percent rejection of malathion on pristine and fouled membranes, performing clean-in-place procedures using one of two cleaning solutions, and then re-testing the percent rejection of malathion. Following tests using the membrane skid, the contact angle was collected for each membrane. Specifics of each experimental step are described in greater detail below. The choice of test conditions was based on the operating range of the crossflow coupon test unit and manufacturer specifications for the membranes (e.g., pressure, temperature, and cleaning procedures).

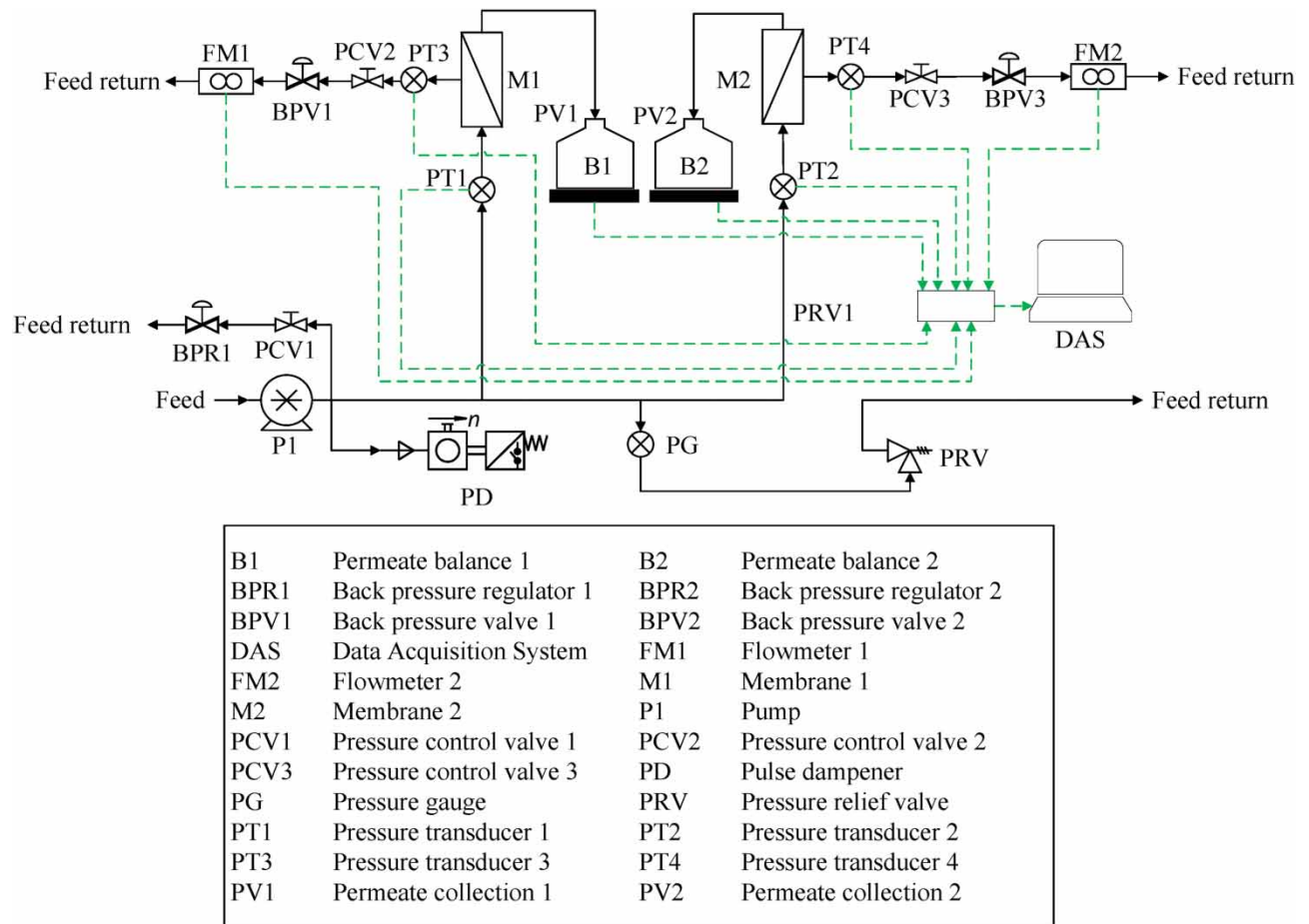


Figure 2 | Schematic of the membrane test skid.

2.3. Accelerated fouling experiments

Accelerated fouling experiments were conducted to condition the membranes to a state that would trigger clean-in-place procedures during typical operations. According to the manufacturer, routine cleaning is advised when the normalized permeate flow has decreased by 10–20%, the normalized permeate quality decreased by 10–20%, or the normalized pressure has dropped by 15–30% (Hydranautics 2020). Fouling was performed through a multi-step process. Membranes were compacted and equilibrated under a target pressure of 1.72 MPa by running DI water through the system until flux plateaued (approximately 20–45 min). After the DI water step, a 2,000 mg/L solution of NaCl (Product Number S271-3, Fischer Scientific, Waltham, Massachusetts) was fed through the system at a target pressure of 1.72 MPa until flux plateaued (approximately 20–45 min). Salt rejection was quantified by using conductivity (Model 19820-10 TDS/Conductivity Meter, Cole-Parmer, Vernon Hills, IL) with percentage rejection calculated by subtracting the permeate concentration from the feed concentration and dividing by the feed concentration. Finally, a simulated secondary wastewater effluent foulant solution comprised of 20 mg/L alginate (Product Number 180947-100G, Sigma Aldrich, St. Louis, Missouri) and 20 mg/L total organic carbon (Suwannee River NOM, Catalog Number 2R101N, International Humic Substances Society, Denver, CO) was recirculated at a target pressure of 250 psi until flux dropped by at least 20% (approximately 2 h). The conditioned membrane coupons were stored moist (in approximately 1 mL of DI water) until used in cleaning experiments.

2.4. Malathion treatability experiments

During Phase II experiments, new and fouled membranes were tested for their ability to remove malathion. A 10 mg/L solution of malathion was prepared using Spectracide Malathion Insect Spray Concentrate (Product Number 071121109002, Spectrum Brands, Inc., Madison, WI). This was selected to represent a highly contaminated drinking

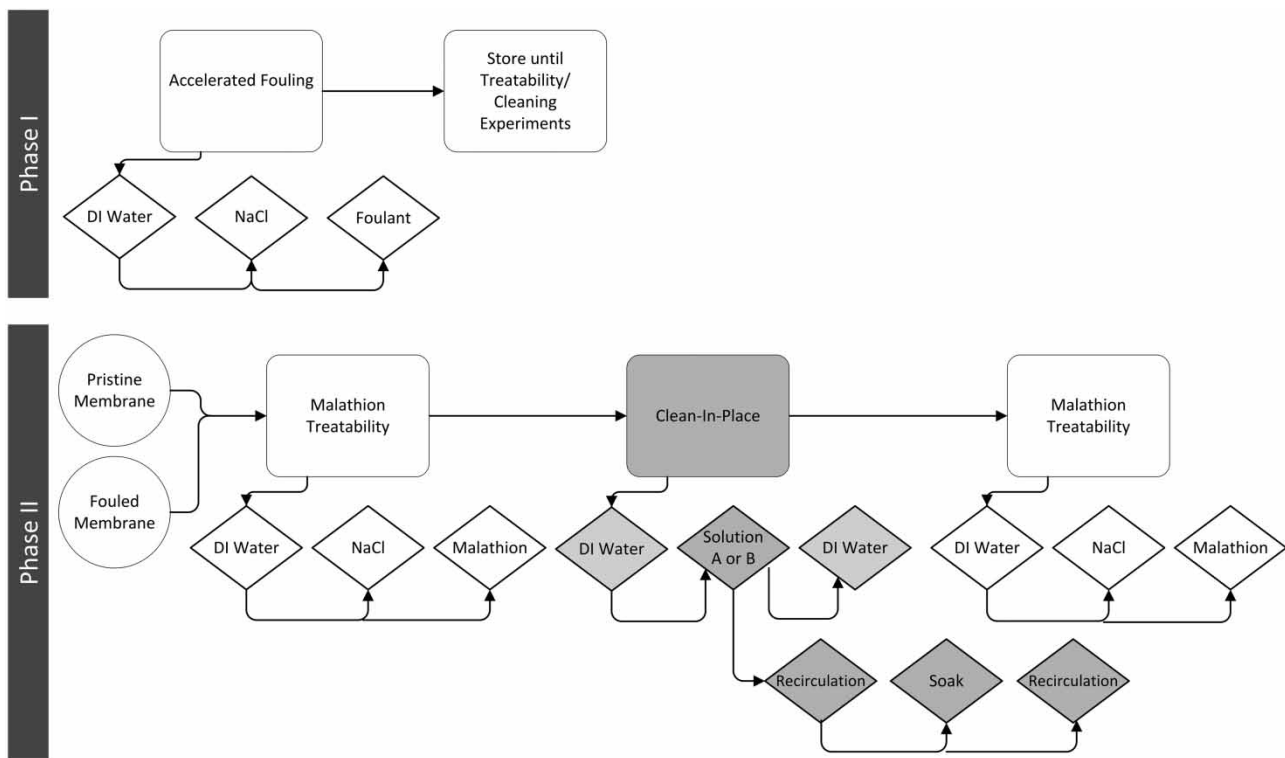


Figure 3 | Sequence of experiments performed using the membrane skid.

water source. Spectracide contains 44% of the solvent naphtha (petroleum). No attempt to boil off the naphtha was attempted. DI water was recirculated for at least 10 min followed by the recirculation of 2,000 mg/L NaCl for at least 10 min (note that one experimental run, ESNA1 with cleaning solution A, did not include the 2,000 mg/L NaCl step, but the DI water step was recirculated for 20 min instead of 10). Following the equilibration with water/salt, the malathion feed solution was recirculated through the membranes for 60 min with paired samples collected from the feed tank and the permeate tanks for both membranes at 20, 40, and 60 min. The crossflow velocity during sample collection ranged from 0.04 to 0.12 m/s and averaged 0.08 m/s across all experiments pre- and post-cleaning. Rejection was calculated as a percentage difference at each time point of the feed minus the permeate concentration divided by the feed concentration and averaged for reporting the overall rejection in this paper. This experimental sequence (DI, salt, malathion) was then repeated post-cleaning. Malathion concentrations were quantified using EPA method 622 (EPA 1992), which is a gas chromatographic analytical method.

2.5. Cleaning experiments

Two cleaning solutions were investigated in this research. Solution A was a gentle cleaning solution from Nitto Hydranautics Technical Service Bulletin 107.72 recommended for light to moderate levels of organic foulants. It contained 2% (w) sodium tripolyphosphate (STPP) (Product Number 238503-500G, Sigma Aldrich, St. Louis, MO), 0.8% (w) the sodium salt of ethylenediaminetetraacetic acid (Na-EDTA) (Product Number E9884-500G, Sigma Aldrich, St. Louis, MO), and pH adjusted to 10 using hydrochloric acid (Product Number 258148-2.5L, Sigma Aldrich, St. Louis, MO) (Hydranautics 2020). Solution B was a high pH cleaning solution that used NaOH (Product Number S318-1, Fischer Scientific, Waltham, MA) to adjust pH to 11.5. No detergent was added to solution B (0.03% [w] sodium dodecyl sulfate is recommended in TSB 107.72) to test a simpler option for use during emergency response field operations. The cleaning procedure was a six-step process. First, the permeate valve was opened. Next the membranes were flushed for 3 min with DI water at 0.34 MPa and 200 mL/min. After the DI water flush, the cleaning solution was recirculated at 0.34 MPa for 30 min. A slow ramp up of the flowrate was used to avoid clogging the system by the foulant removal and was 200 mL/min for 5 min, then 400 mL/min for 5 min, and finally 600 mL/min for the remaining 20 min. The coupons were then left in the test skid saturated in cleaning

solution for a 30 min soak, followed by the recirculation of the cleaning solution for another 30 min at 0.34 MPa and the same ramp of flowrates as in the initial recirculation. The final step was a 3-min flush with DI water at 0.34 MPa and 200 mL/min.

2.6. Contact angle experiments

After Phase II experiments were completed, captive bubble contact angle measurements were collected using a standard goniometer (Model No. 250-U1, ramé-hart instrument co., Succasunna, NJ) with environmental fixture (Product # 100-14, ramé-hart instrument co., Succasunna, NJ). The instrument was calibrated using a combo calibration device (Product # 100-27-31-U, ramé-hart instrument co., Succasunna, NJ), and Teflon was used as a reference measurement prior to analysis of the membranes. Each membrane was cut to approximately 0.64 cm × 1.9 cm, adhered to the stage using double-sided tape, and submerged in ultrapure water. A 20 μ L bubble was generated using an inverted stainless-steel needle (sd = 3.6 μ L). Image analysis was performed using ImageJ software v. 1.53.

3. RESULTS AND DISCUSSION

3.1. Phase I accelerated fouling experiments

The ESNA1-LF NF membranes had an average DI water flux of 86 kg/m²-h and a 2,000 ppm NaCl flux of 65 kg/m²-h. During the fouling procedure, the membrane in cell 1 started at a flux of 69 kg/m²-h, and the membrane in cell 2 started at 74 kg/m²-h (Figure 4(a)). Over the course of being exposed to the foulant, the fluxes were reduced to 45 and 49 kg/m²-h, respectively (averaged from the 80–115-min mark of the experiment). This corresponded to a 35 and 34% reduction in flux for the two membranes. The ESPA2 RO membranes had an average DI water flux of 46 kg/m²-h and a 2,000 ppm NaCl flux of 68 kg/m²-h. During the fouling procedure, the membrane in cell 1 started at a flux of 57 kg/m²-h and the membrane in cell 2 started at 75 kg/m²-h (Figure 4(b)). Over the course of being exposed to the foulant, the fluxes were reduced to 45

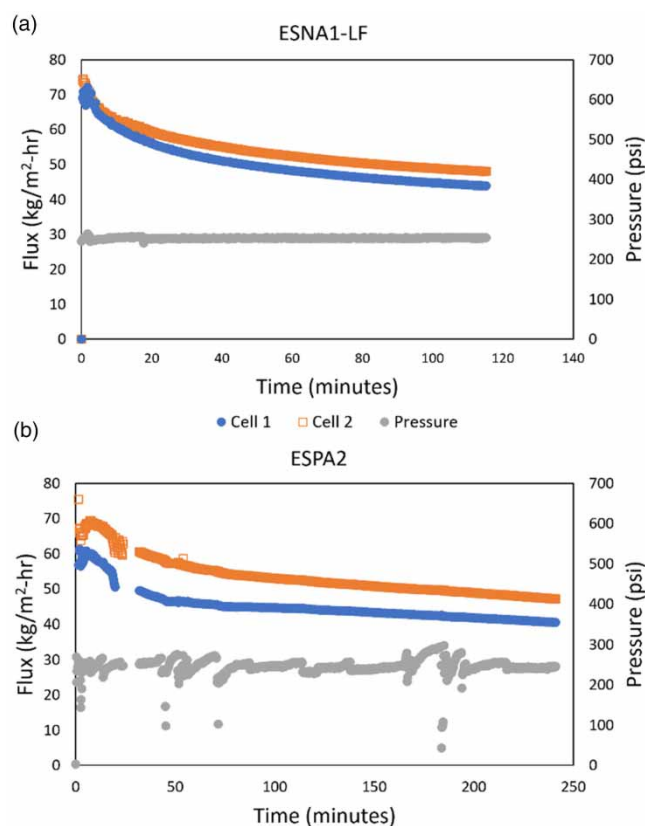


Figure 4 | Flux and pressure data from accelerated fouling experiments for two (a) ESNA1-LF NF membranes and (b) ESPA2 RO membranes. To produce replicates for the treatability experiments, both cells were fouled using the same feed solution of 20 mg/L alginate and 20 mg/L total organic carbon natural organic matter.

and 56 kg/m²-h, respectively (averaged from the 80–115-min mark of the experiment). This corresponded to a 22 and 25% reduction in flux for the two membranes.

3.2. Phase II salt solution

Salt rejection and solution flux averaged 89% and 85 kg/m²-h for ESNA1-LF NF pristine membranes and 92% and 52 kg/m²-hr for ESPA2 RO pristine membranes prior to the cleaning routines (Figure 5). Others have reported EPSA-2 RO Na⁺ rejection of 98.6% (Cao *et al.* 2018). The membranes exposed to foulants averaged 93% and 51 kg/m²-h salt rejection and flux for ESNA1-LF NF and 88% and 52 kg/m²-h for ESPA2 RO prior to the cleaning routines. Assuming a $\pm 5\%$ natural variability in the performance of membrane coupons since membrane properties are not always uniform in a membrane sheet, salt rejection was the same before and after being exposed to the foulant regardless of the membrane type. However, the ESPA2 RO membrane's flux remained constant, while the ESNA1-LF NF's flux dropped substantially after exposure to the foulant. The combination of sodium alginate and Suwannee River natural organic matter represents organic foulants that may be experienced in secondary effluent from advanced water reclamation (Ang *et al.* 2006). In short, the RO membranes were challenging to foul in relation to the salt solution performance using the method used in this research. In an actual operation

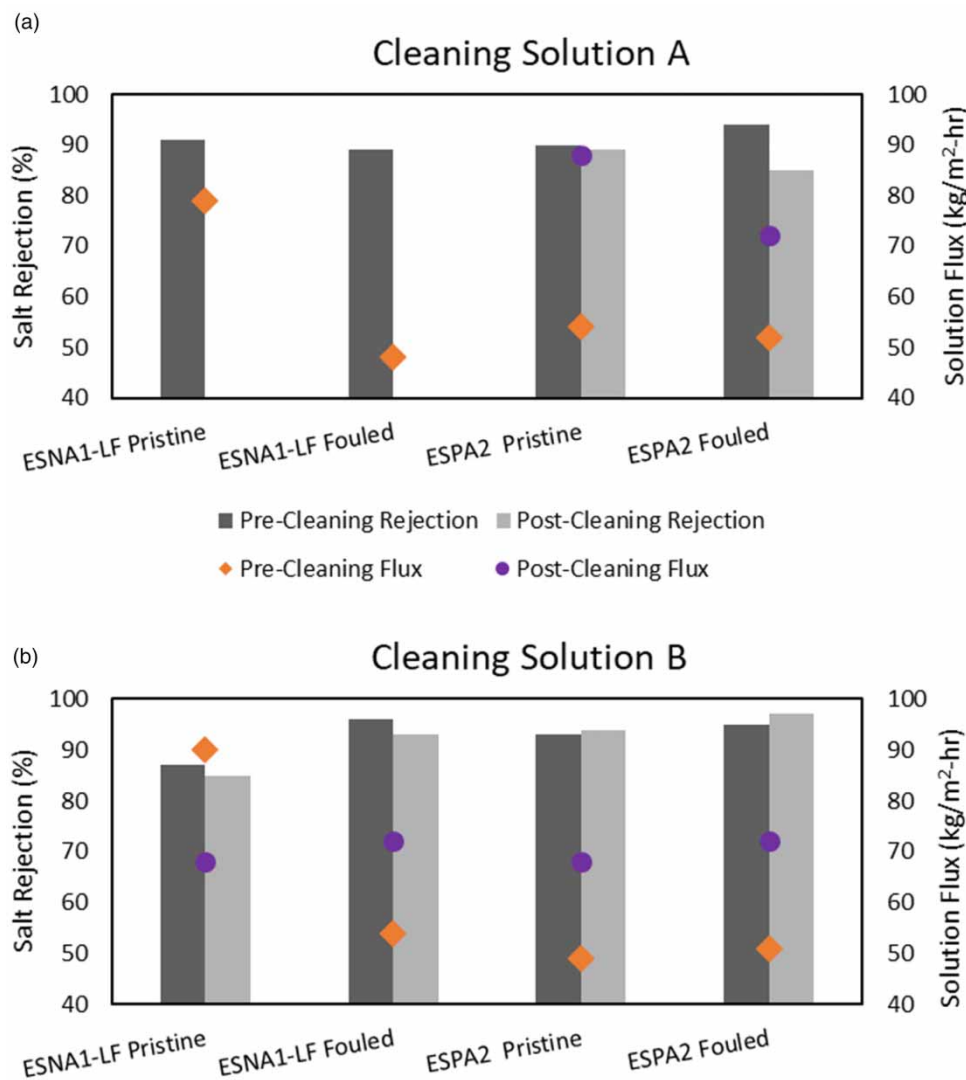


Figure 5 | Salt performance data (% rejection and water flux) for pristine and fouled ESPA2 RO and ESNA1-LF NF before and after cleaning with (a) 2% (w) of STPP, 0.8% (w) of Na-EDTA, and pH adjusted to 10 and (b) pH adjusted to 11.5 using NaOH. Note that salt solution flux was not measured for the ESNA1-LF pre-cleaning test with cleaning solution A.

using a salt-based performance metric, the RO membrane would not yet trigger clean-in-place procedures. Testing proceeded to assess if the cleaning solutions themselves impacted malathion rejection. Interestingly, after cleaning with either solution A or solution B, the ESPA2 RO pristine and foulant exposed membranes' salt rejection stayed approximately the same, but the flux increased to levels comparable with the ESNA1-LF NF membrane.

3.3. Phase II malathion solution

Malathion rejection and solution flux averaged 90% and 73 kg/m²-h for ESNA1-LF NF pristine membranes and 83% and 58 kg/m²-h for ESPA2 RO pristine membranes prior to the cleaning routines (Figure 6). The higher malathion rejection of the NF is presumably due to the reduced electrostatic interaction between the malathion and the membrane. The membranes exposed to foulants averaged 94% and 52 kg/m²-h malathion rejection and flux for ESNA1-LF NF and 94% and 54 kg/m²-h for ESPA2 RO prior to the cleaning routines. The improvement in rejection is not surprising as ESPA2 RO membranes have demonstrated the improved rejection of organic molecules when fouled by tertiary wastewater effluent (Fujioka *et al.* 2013a). After cleaning, the malathion solution flux increased for the ESNA1-LF NF membranes cleaned using solution A, but the flux stayed the same or got worse after the use of cleaning solution B. A large rebound in flux was not observed for the ESPA2 RO membranes. After using solution A, the malathion rejection of all membrane types did not significantly change except for the ESPA2 RO membrane exposed to foulant, its rejection was 7% lower than before cleaning. After using solution B, pristine

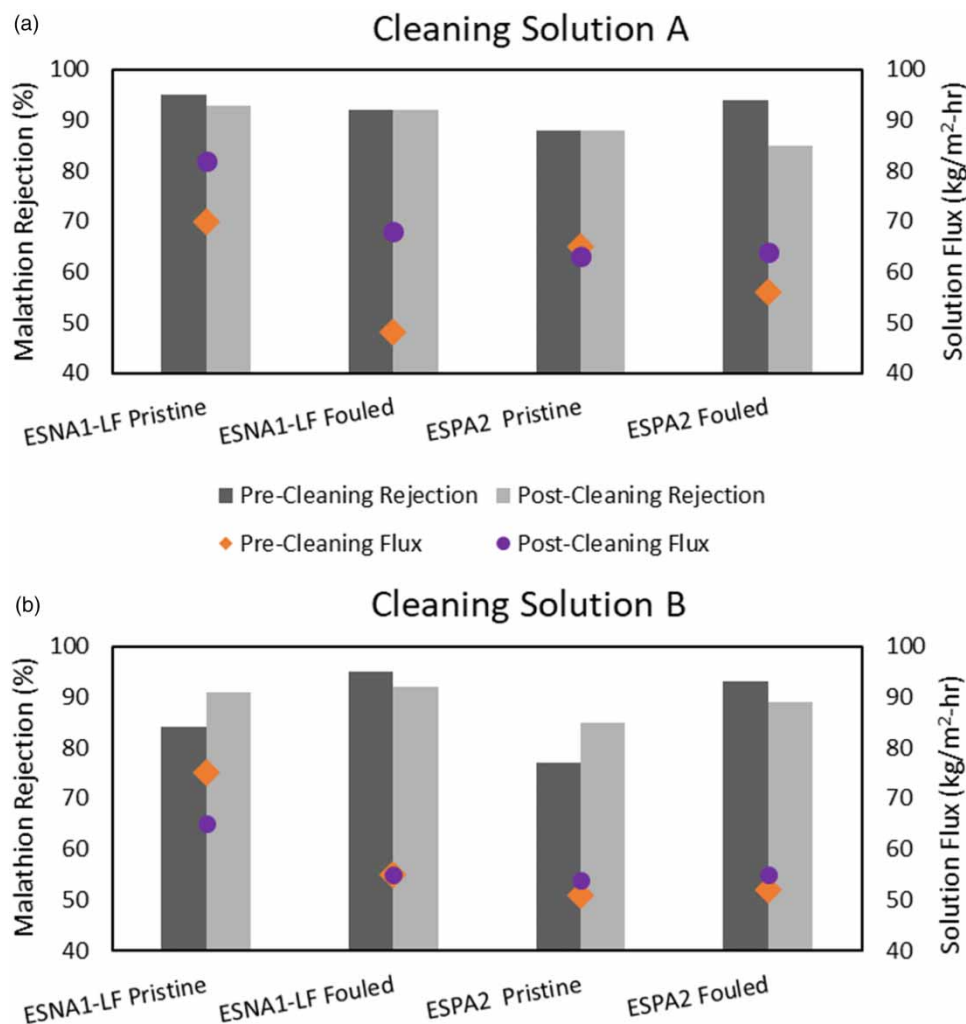


Figure 6 | Malathion performance data (% rejection and water flux) for pristine and fouled RO and NF before and after cleaning with (a) 2% (w) of STPP, 0.8% (w) of Na-EDTA, and pH adjusted to 10 and (b) pH adjusted to 11.5 using NaOH.

membranes' malathion rejection improved (7% for ESNA1-LF NF and 8% for ESPA2 RO), while membranes exposed to foulant's malathion rejection slightly decreased (3% for ESNA1-LF NF and 4% for ESPA2 RO). Post-cleaning rejections were within 4% of each other regardless of if cleaning solutions A or B were used.

Across all conditions, malathion rejection ranged from 84 to 95% for the ESNA1-LF NF membrane and 77 to 94% for the ESPA2 RO membrane. These results are comparable to malathion rejection using different types of water treatment membranes. For example, when malathion rejection was assessed using a NF ceramic membrane and feed concentrations of malathion of 5.1–17.1 mg/L, performance was 93.5–99.4% removal of malathion (Sorour & Shaalan 2013). Zhang and Pagilla studied malathion rejection of two NF polyamide thin-film composite membranes and one NF poly(piperazine amide) thin-film composite membrane and observed rejections ranging from approximately 55–99% depending on the transmembrane pressure and membrane pore size (Zhang & Pagilla 2010). They observed a size exclusion mechanism where the highest rejection was observed for the membrane with the lower pore size. This correlation was not observed in our study as others have reported similar pore sizes of 0.439 nm for the ESNA1-LF NF membrane (Tanne *et al.* 2019) and 0.289 nm for the ESPA2 RO membrane (Fujioka *et al.* 2013b). Kiso *et al.* studied four different membranes (3 NF and 1 RO); two were made from poly(vinyl alcohol)/polyamide and two were sulfonated polyethersulfone-based. Their malathion rejection ranged from 41 to 99.14%, with the RO membrane having the highest rejection. The sulfonated polyethersulfone NF membrane with the lowest NaCl rejection had the worst malathion rejection. Furthermore, they observed adsorption of pesticide on the membranes, with more absorption occurring on the sulfonated polyethersulfone than the poly(vinyl alcohol)polyamide (Kiso *et al.* 2000). In our work, salt rejection was high for both types of membranes, so no such correlation between desalting capabilities and malathion rejection was observed. Another study also found a considerable amount of pesticide adsorbed onto RO membranes, but the polymers of the membranes were cellulose acetate and a cross-lined polyethyleneimine, which presently represent a smaller market share of actively used membranes (Chian *et al.* 1975). The rejection of malathion for both types of membranes in Chain *et al.* was greater than 99%. The use of foulants and clean-in-place procedures in our study may have mitigated some adsorption that provided additional treatment in previous studies (Chian *et al.* 1975; Kiso *et al.* 2000). In our study, contact angle measurements do not indicate a uniformity in surface properties that might occur if a large amount of chemical remained on the surface. However, the rebound of the salt solution flux after cleaning, but not the malathion solution flux indicates potential changes in the membranes' selective layer that had a different impact on solutions containing smaller ions than longer organic molecules. The impact of the naphtha contained in the Spectracide was not investigated in this study. Not observed in this study, others have found that emulsified oils foul RO membranes (Kasemset *et al.* 2013).

3.4. Contact angle

The ESNA1-LF NF membrane had a contact angle of 30° and the ESPA2 RO membrane of 35° prior to any experimentation (Table 1). Regardless of exposure to cleaning solution A or B, the pristine membranes' contact angles remained relatively unchanged ($\pm 2^\circ$). The fouled membranes exposed to cleaning solution A saw a modest increase in the contact angle (+5° for ESNA1-LF NF and +3° for ESPA2 RO). The fouled membranes exposed to cleaning solution B were relatively unchanged for ESNA1-LF NF but saw a decrease of 10° for ESPA2 RO. The contact angle measured for ESNA1-LF NF was very similar to contact angles measured using the captive bubble technique in the literature (Muthu *et al.* 2014), but captive bubble contact angle measurements have been previously reported as higher for ESPA2 RO at 61.3° (Varin *et al.* 2013). From the data provided by Varin *et al.* no clear indication arose as to the discrepancy, although there have been several iterations of ESPA2 products, so perhaps it was a different generation of the membrane. Contact angle measurements collected in this work do not appear to correlate to any changes in membrane performance (which stayed relatively constant in this study). They

Table 1 | Contact angle measurements for a variety of membrane exposure conditions

Exposure conditions	Contact angle (°)	
	ESNA1-LF NF	ESPA2 RO
Not used in experiments	30	35
Pristine, cleaning solution A	29	33
Fouled, cleaning solution A	35	38
Pristine, cleaning solution B	29	36
Fouled, cleaning solution B	29	25

do suggest minor material changes when fouled and different changes due to the interactions of cleaning solutions but within the uncertainty of the measurement. If rejection does begin to suffer, contact angle measurement may be a useful qualitative tool for diagnosing if changes to the membrane surface are contributing to a decline in performance.

4. CONCLUSIONS

This study adds data to the limited existing literature that indicates polyamide-based NF and RO membranes are able to remove high percentages of malathion from water. The study introduced foulant representative of secondary wastewater effluent and observed that malathion rejection improved. This foulant applies to potable reuse facilities that are being increasingly implemented in water-stressed regions. The membranes were also exposed to two different clean-in-place procedures that helped restore flux while maintaining malathion rejection. While this project was limited in scope/funding, future research should be conducted to obtain a comprehensive exploration of different operating parameters (e.g., pressure, pH, and temperature) and extended fouling experiments with different types of foulants (e.g., different types of scale and biological material). The data presented here suggest that polyamide-based NF and RO membranes are an effective tool for utilities and emergency responders to treat malathion-contaminated waters. After an accidental or intentional release of pesticides or chemical weapons, an understanding of emergency water treatment capabilities is necessary so that an effective remediation strategy can be launched as soon as possible.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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