Under the Patronage of His Excellency **Eng. Abdulrahman bin Abdulmohsen AlFadley**
Minister of Environment, Water & Agriculture

منتدى المياه السعودي
saudi water forum SWF 2024

The Role of Innovation and Modern Technologies in the Desalination Industry

Professor Shane A. Snyder – Georgia Institute of Technology, USA

29 April – 01 May 2024

Hilton Riyadh Hotel & Residences
Riyadh, Saudi Arabia

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Ministry of Environment Water & Agriculture

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المركز الوطني لكفاءة وترشيد المياه
NATIONAL WATER EFFICIENCY AND CONSERVATION CENTER
MAEE


Population of over 5.8 million
Density of 7,810 people per km^2
Land area : 728 km^2

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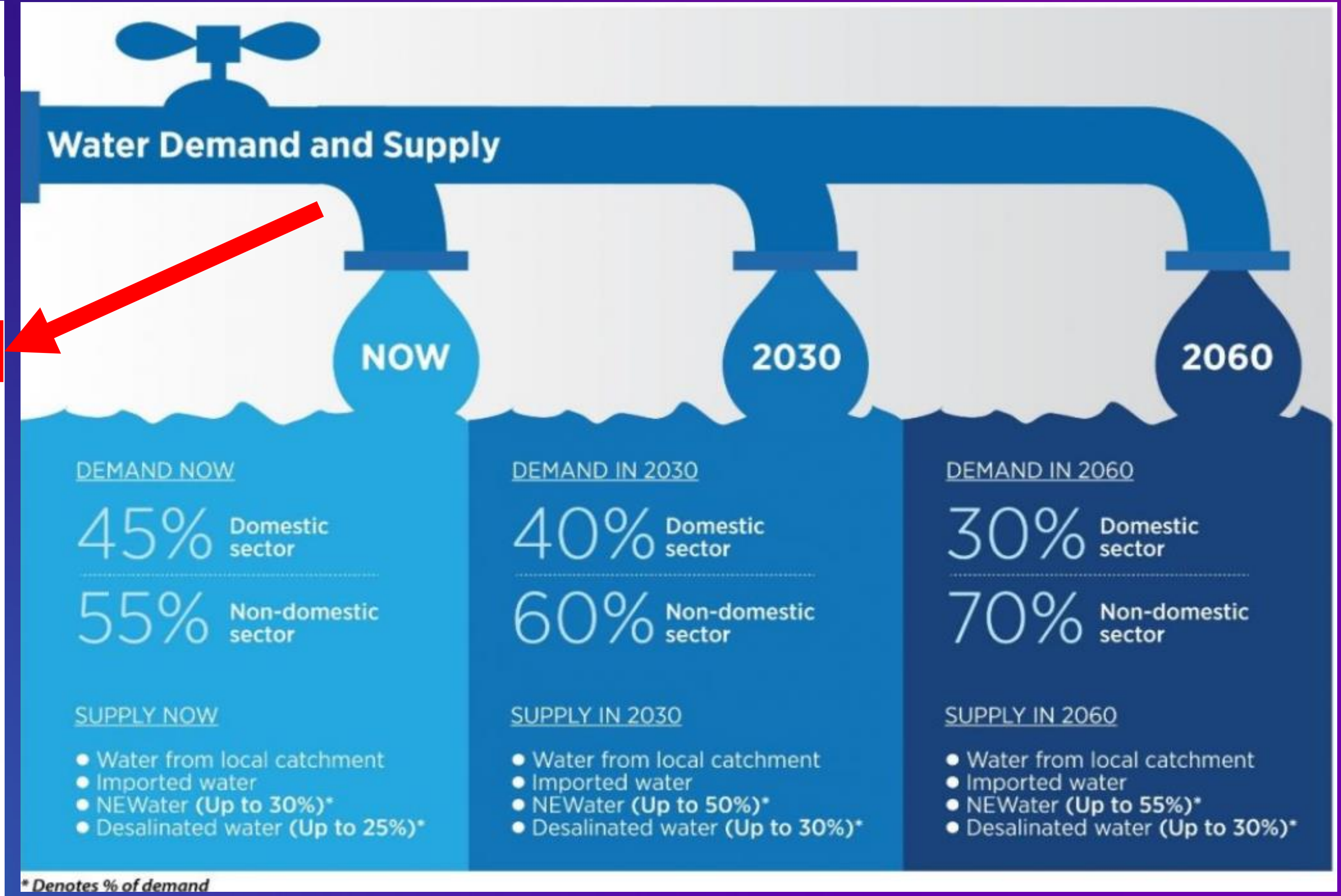
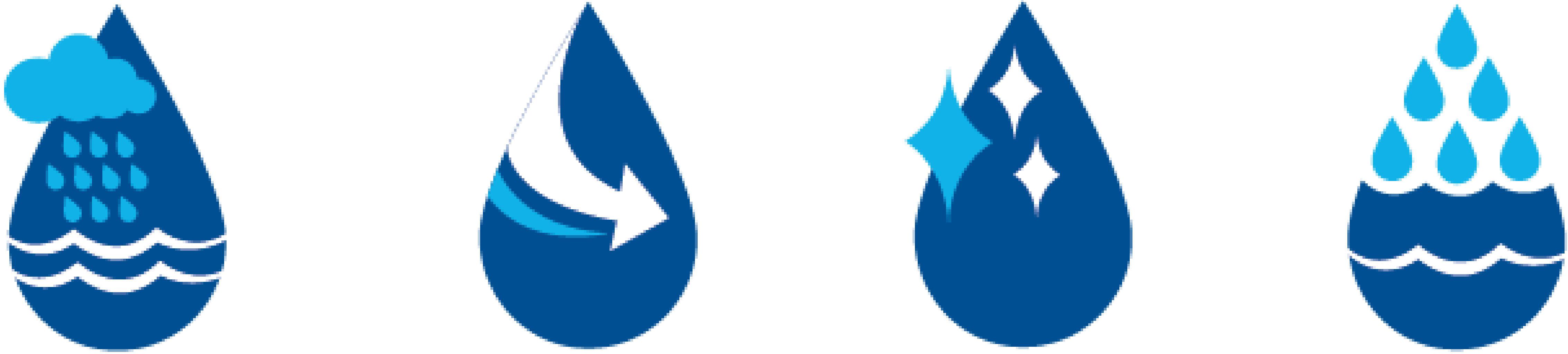
Water Story in Singapore…..

World's Top Water-Stressed Countries in 2040

RANK	NAME	ALL SECTORS
1	Bahrain	5.00
1	Kuwait	5.00
1	Qatar	5.00
1	San Marino	5.00
1	Singapore	5.00
1	United Arab Emirates	5.00
1	Palestine	5.00
8	Israel	5.00
9	Saudi Arabia	4.99
10	Oman	4.97
11	Lebanon	4.97
12	Kyrgyzstan	4.93
13	Iran	4.91
14	Jordan	4.86
15	Libya	4.77
16	Yemen	4.74
17	Macedonia	4.70



Singapore’s Four National Taps



WATER FROM LOCAL CATCHMENT

IMPORTED WATER

NEWATER

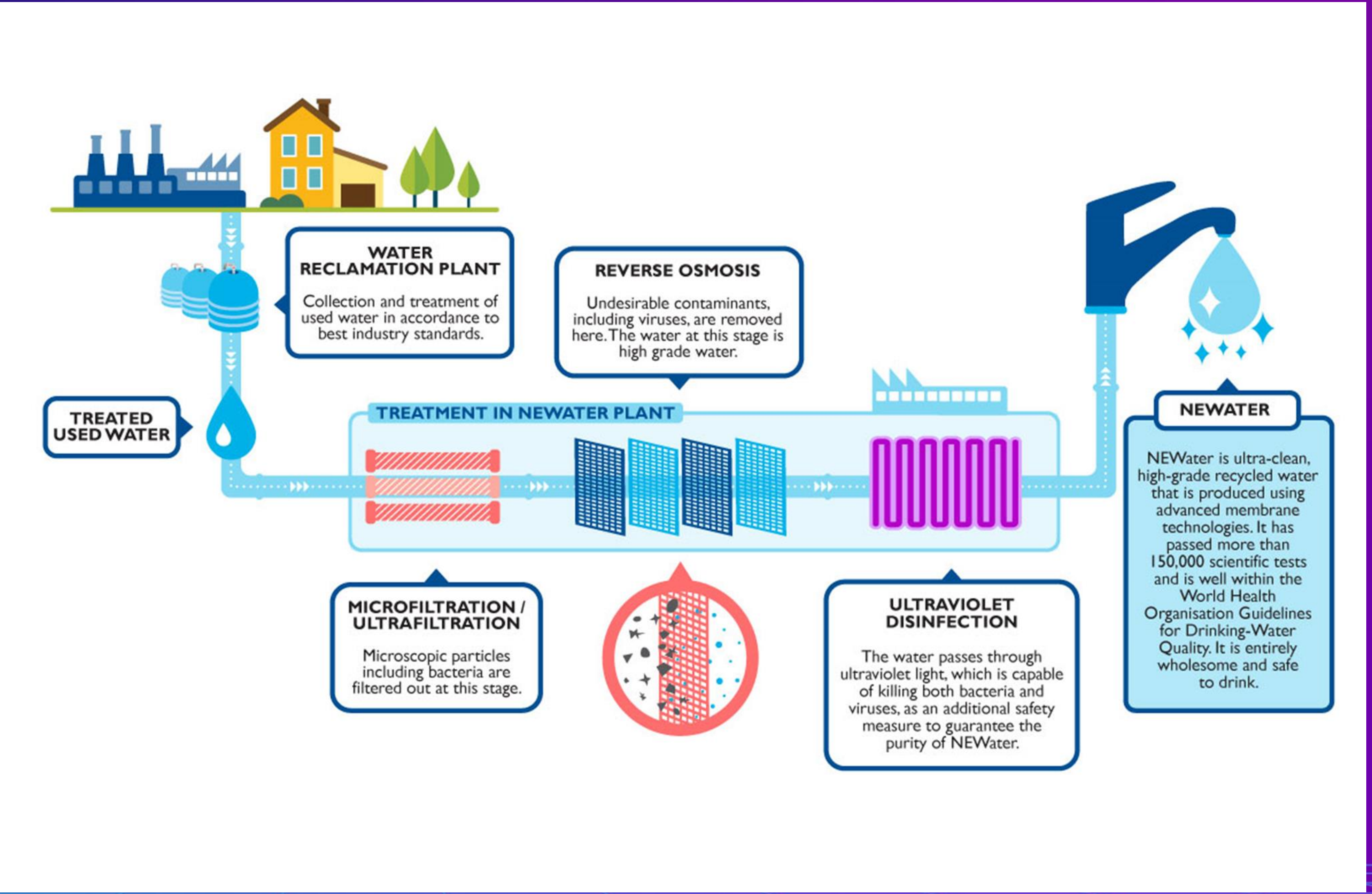
DESALINATED WATER

Singapore’s water demand is forecasted to double by 2065

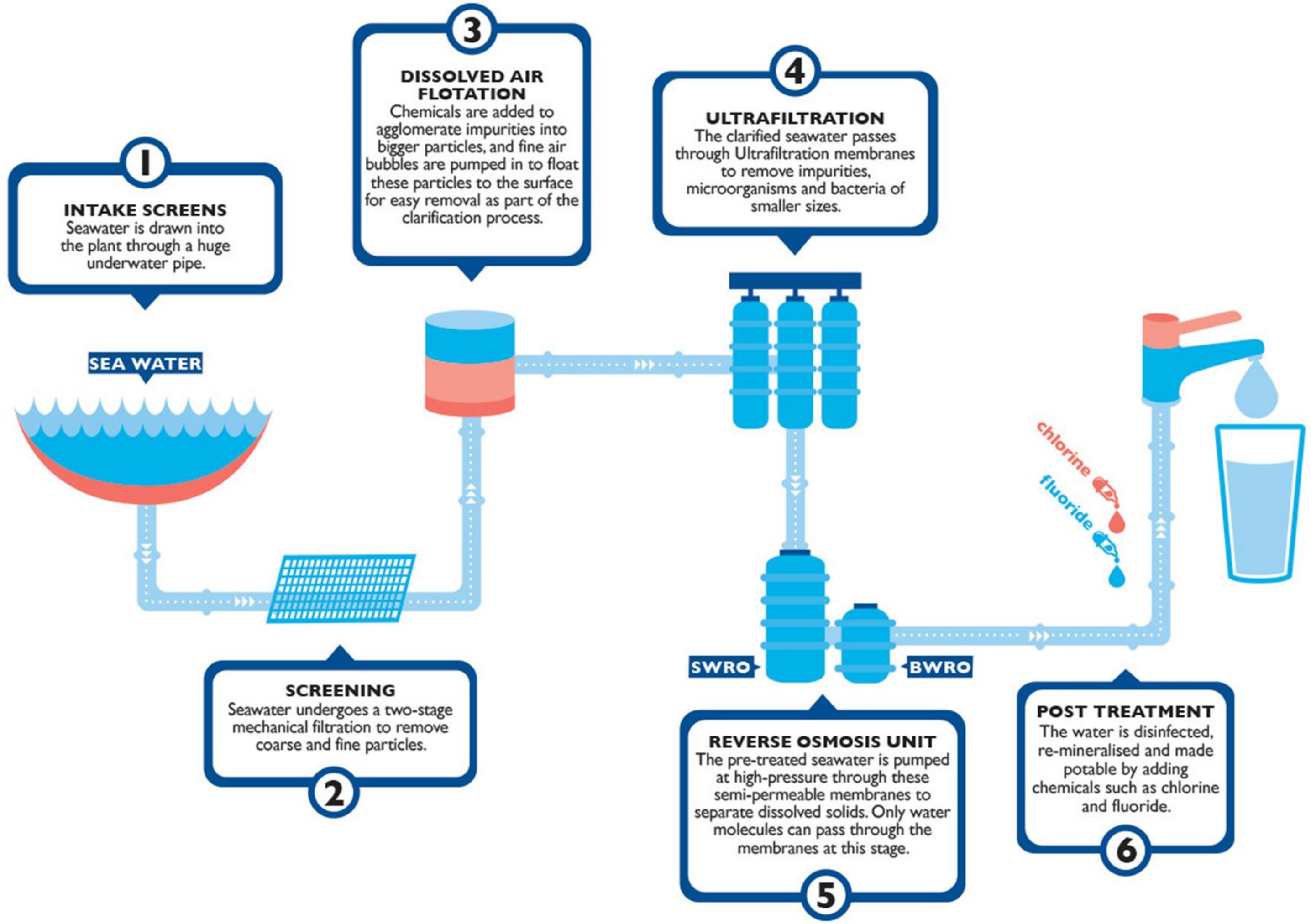
Singapore: Local Catchment (Marina Barrage)

Singapore: Imported Water (from Malaysia)

Singapore: Recycled Water (NEWater)



Singapore: Seawater Desalination



Singapore: Seawater/Freshwater treatment (Keppel)

BY THE NUMBERS

KMEDP is Singapore's **4th** desalination plant

The plant can produce up to **30 million gallons** of fresh drinking water daily

1st water treatment plant to use Ultraviolet as the primary disinfection process

Equipment and processes occupy an area of **2.4ha**

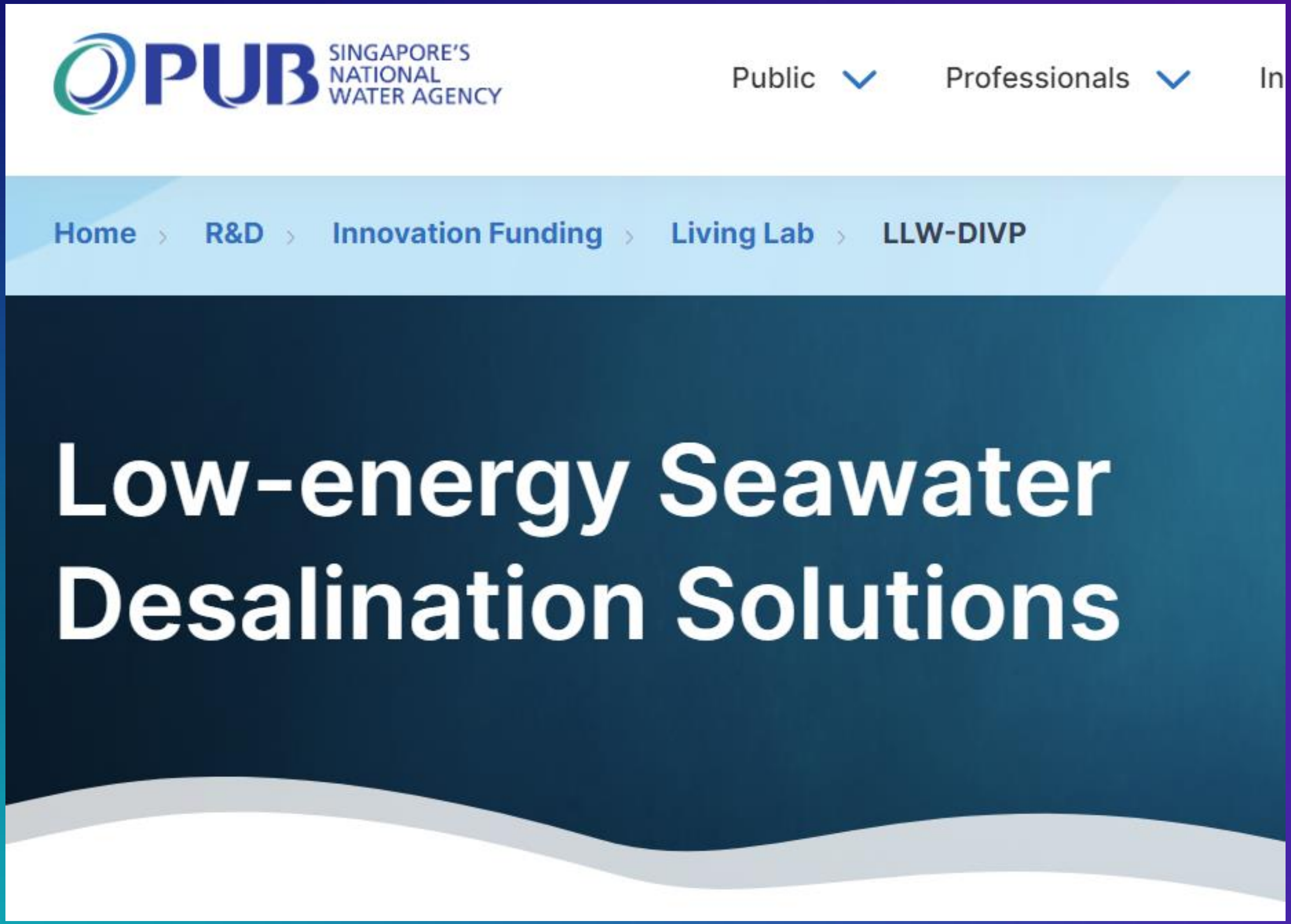
Will supply drinking water to PUB over a **25-year** concession period from 2020 to 2045

The auto strainer is an automatic self-cleaning disc filter that removes particles greater than **100 micrometres** in size, which is the diameter of a strand of hair

Energy saved every hour using the Energy Recovery Device (ERD) is sufficient to power **28** 4-room HDB flats for a month

Uses the UVC system which renders **99.99%** of all viruses harmless in a fraction of a second

Singapore: Desalination Energy Efficiency



https://www.pub.gov.sg/Industry/RandD/InnovationFunding/Living-Lab/LLW-DIVP

"Seawater desalination is an energy-intensive treatment process. With the anticipated growing dependence on this resource, improving the energy efficiency for desalination has been a key research priority for Singapore. PUB's goal is to reduce the energy consumption for seawater desalination to less than 2 kWh/m3 at the system level through technology and process innovation."

Singapore: Desalination Integrated Validation Plant (1 MGD)

➢ Integrated Validation Program Activities:
- Design and Operationalize an Integrated Validated Platform
- One-stop Plug & Play field validation of promising desalination technologies

INTEGRATED VALIDATION PLANT

Pre-treatment technologies → Seawater Desalination → Energy Recovery/Polishing

Pre-treatment technologies
- Low-pressure NF
- Ceramic membranes
- Ceramic-polymer hybrid membranes
- Mixed matrix membranes

Seawater Desalination
- Bio-mimetic RO membranes
- Re-inforced RO membranes

Energy Recovery/Polishing
- Energy Recovery Devices
- PRO/RED (for energy offset)
- Capacitive deionization

➢ Objectives: To identify and validate technologies that lead to overall
- Desalination energy savings (lower operational cost)
- Higher recovery/efficiency

Upcoming Technologies (RFP)

Co-Developed Technologies

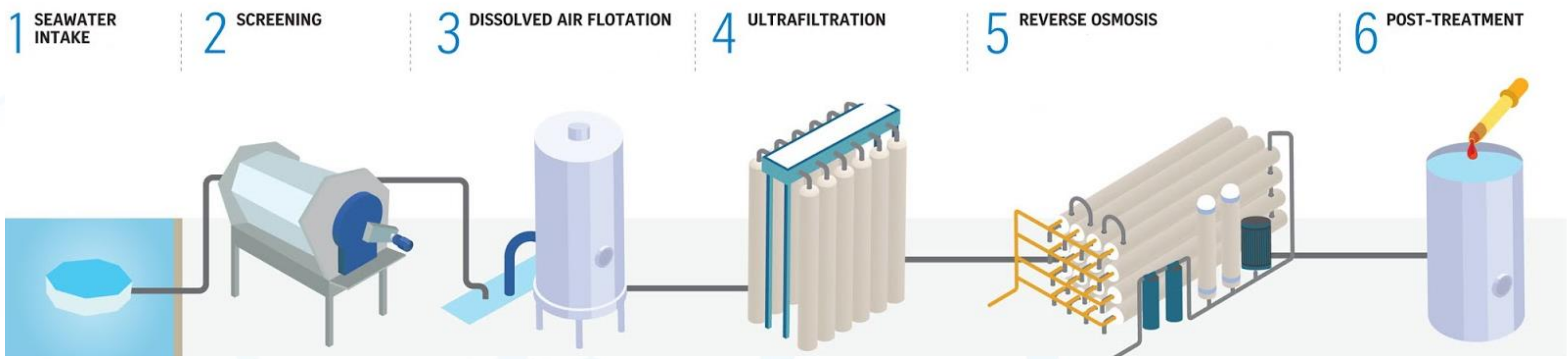
Future Technologies

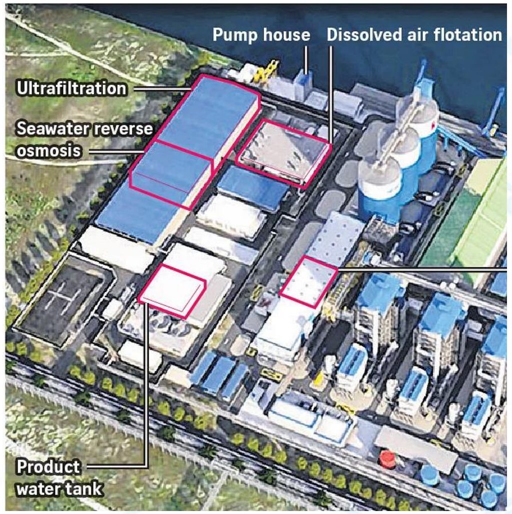
Plant Takeover + Licenses → Verification of Existing Systems → Baseline Run → Best-in-Class

Seawater Desalination: Pre-Treatment (Ceramic Membranes)

Challenges:

- Variable seawater quality
- Algal Bloom
- Require combination of different technologies (high cost/large footprint)





Dissolved Air Floatation
+
Polymeric UF
→ **Ceramic UF**

Fig 1: *Aerial view of Jurong Island desalination and power plat, showing the footprint of pre-treatment (UF+DAF)*

https://www.straitstimes.com/singapore/singapores-fifth-desalination-plant-opens-on-jurong-island

Seawater Desalination: Pre-Treatment (Ceramic Membranes)

Advantages:

- Long life expectancy (>20 years)
- Mechanical and Chemical Resistance
  - → Cleaning with strong oxidants (ozone, chlorine) and extreme pH possible
  - → No risk of leaking of contaminants (e.g., nanoplastics, polymer additives)
- Good dissolved organic carbon (DOC) removal with in-line coagulation

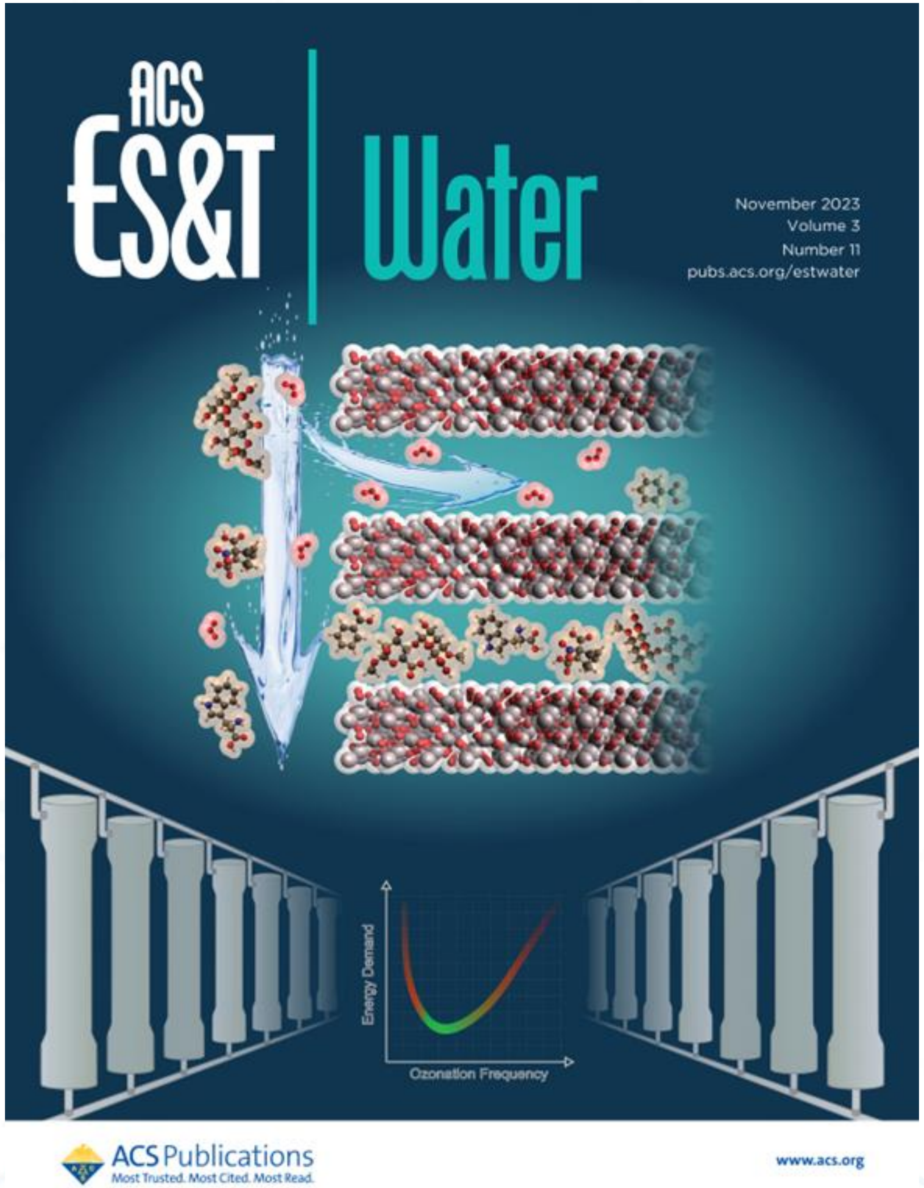
Successful pilot-plants have been demonstrated

Altman et al., Desalination (2023)

Challenges/room for process advancement:

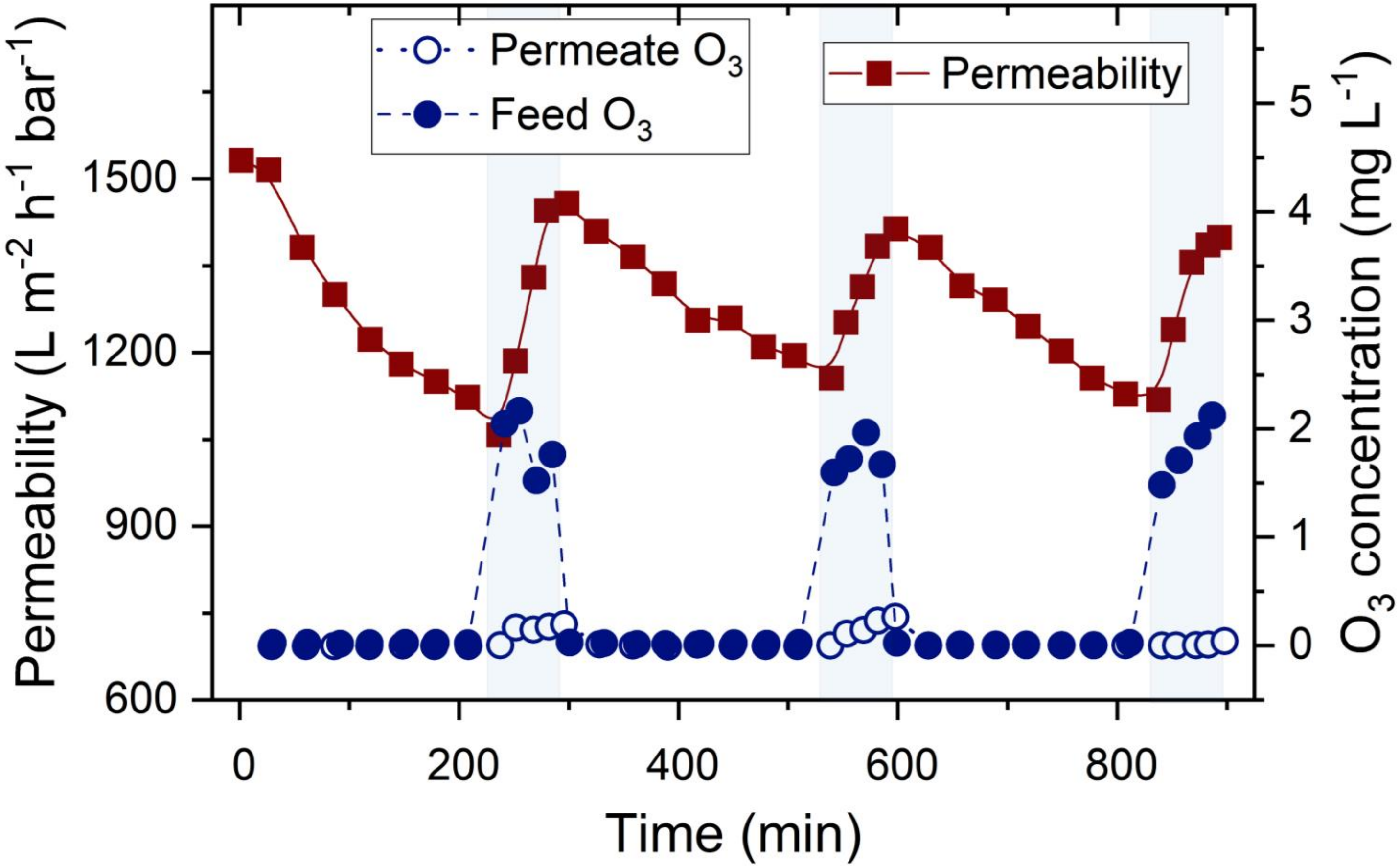
- Many operational conditions to select (coagulant dose/type, cleaning agents and frequency)
- Operations highly dependents on specific seawater characteristics and seasonal variations

Seawater Desalination: Pre-Treatment (Ceramic Membranes)

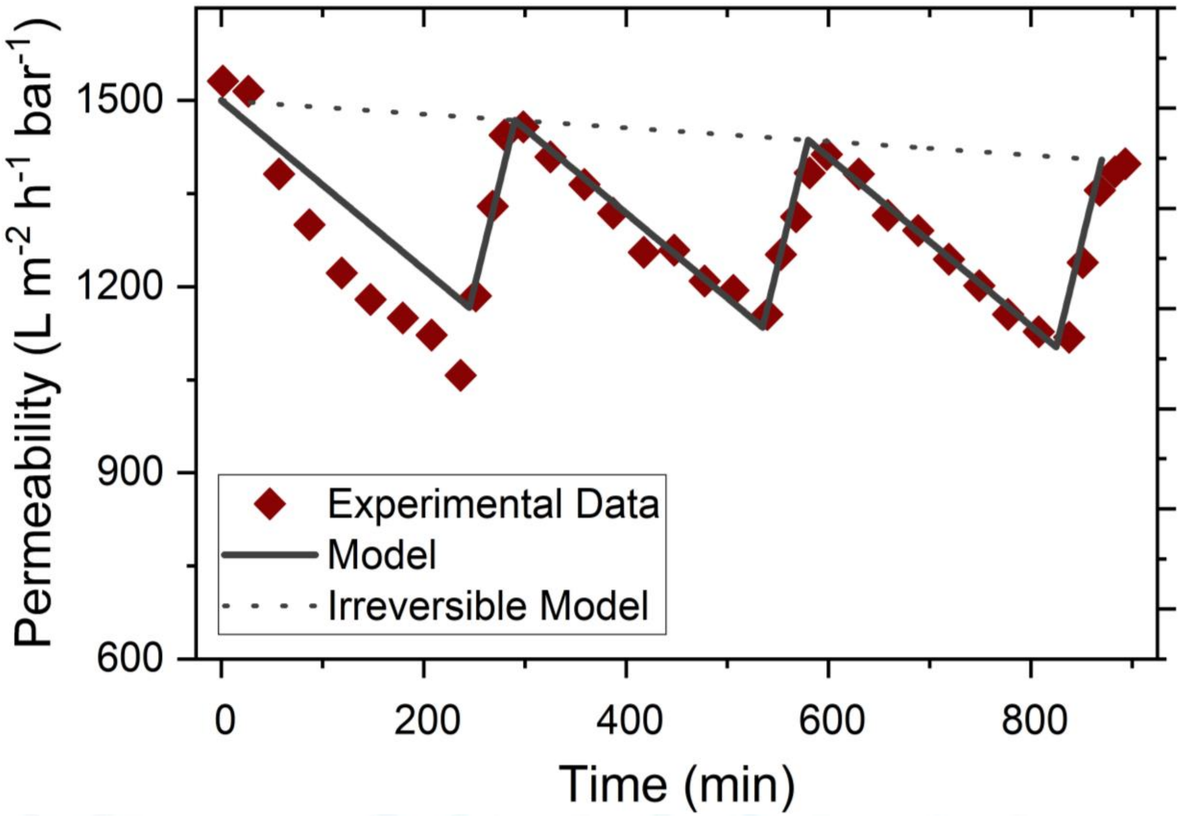


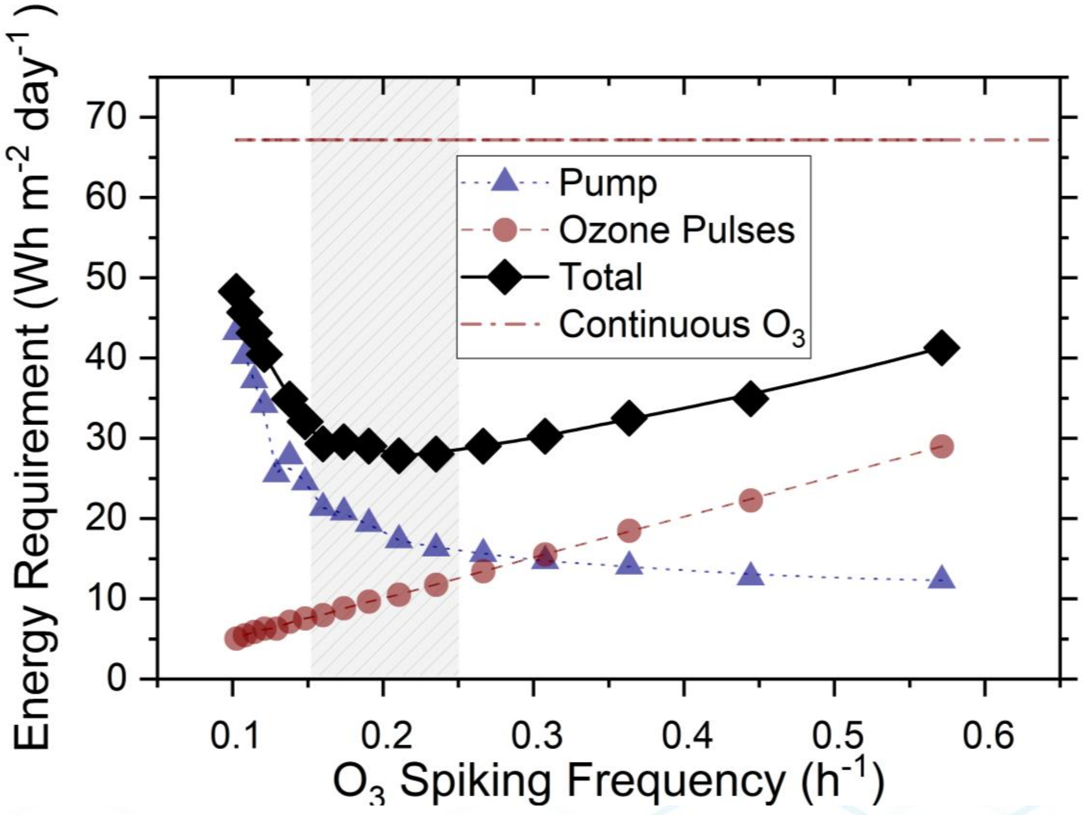
M Tagliavini, S Leow, J Clement, G Galjaard and SA Snyder*

"Experimental Investigation and Numerical Optimization of Periodic In Situ Ozonation to Control Fouling in Ceramic Ultrafiltration



Seawater Desalination: Pre-Treatment (Ceramic Membranes)





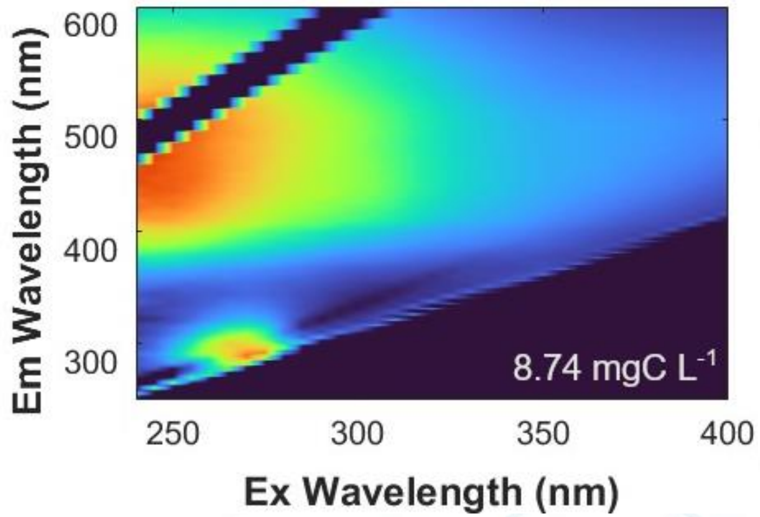
- The model was first calibrated on experimental (lab-scale) data
- Simulate energy consumption at different ozone spiking frequency

- Balancing additional pumping energy (due to membrane fouling) and ozone energy requirement **saves 40-55% of energy** compared to continuous ozonation

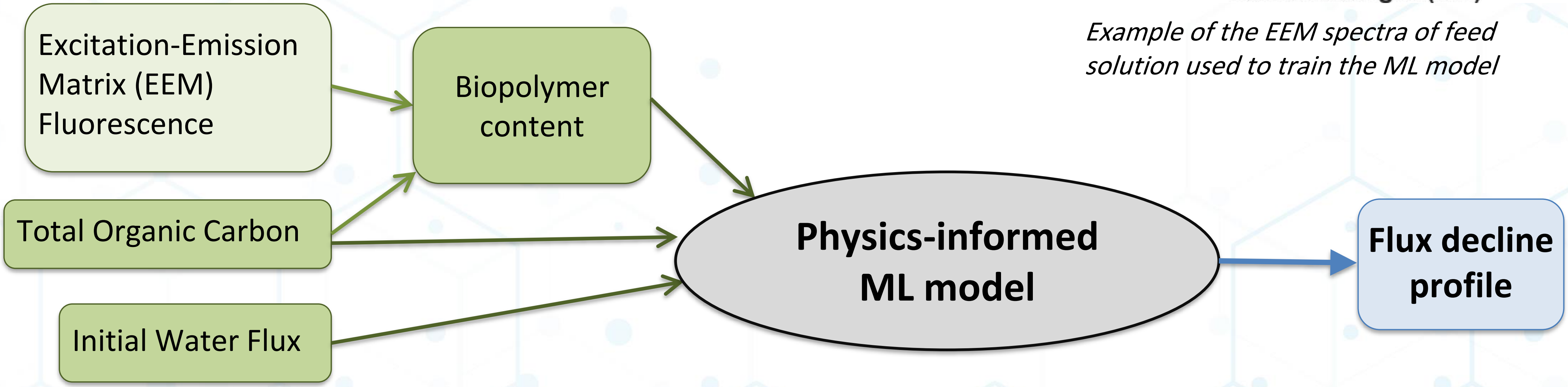
Seawater Desalination: Pre-Treatment (Ceramic Membranes)

- Realistically complex model seawater (composed by Humic Acid, Bovine Serum Albumin, Amino acids and Alginate)

- Alginate biopolymer used to mimic *algal bloom*
  (Alshahri et al., Science of the Total Environment, 2022)



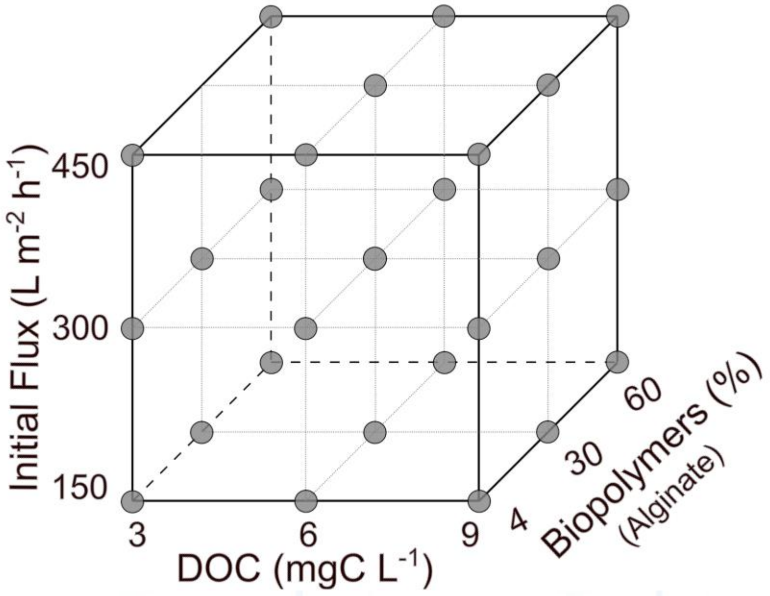
Example of the EEM spectra of feed solution used to train the ML model



Machine Learning to Predict Ceramic UF Flux Decline

Model Training

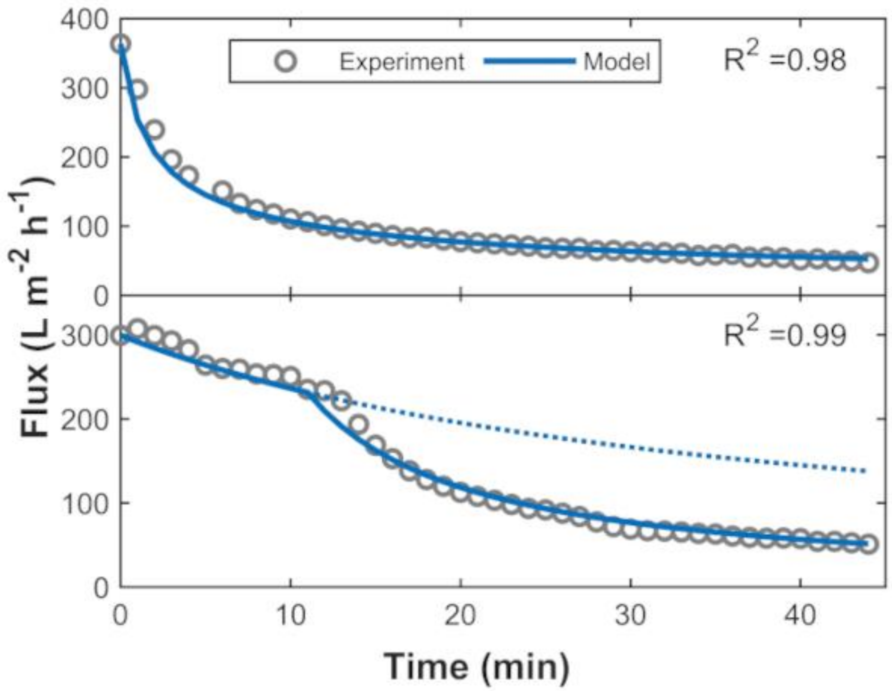
- ML model was trained on 30 experiments performed varying initial flux, TOC and content of biopolymer



Design of the 30 experiments used to train the machine learning model

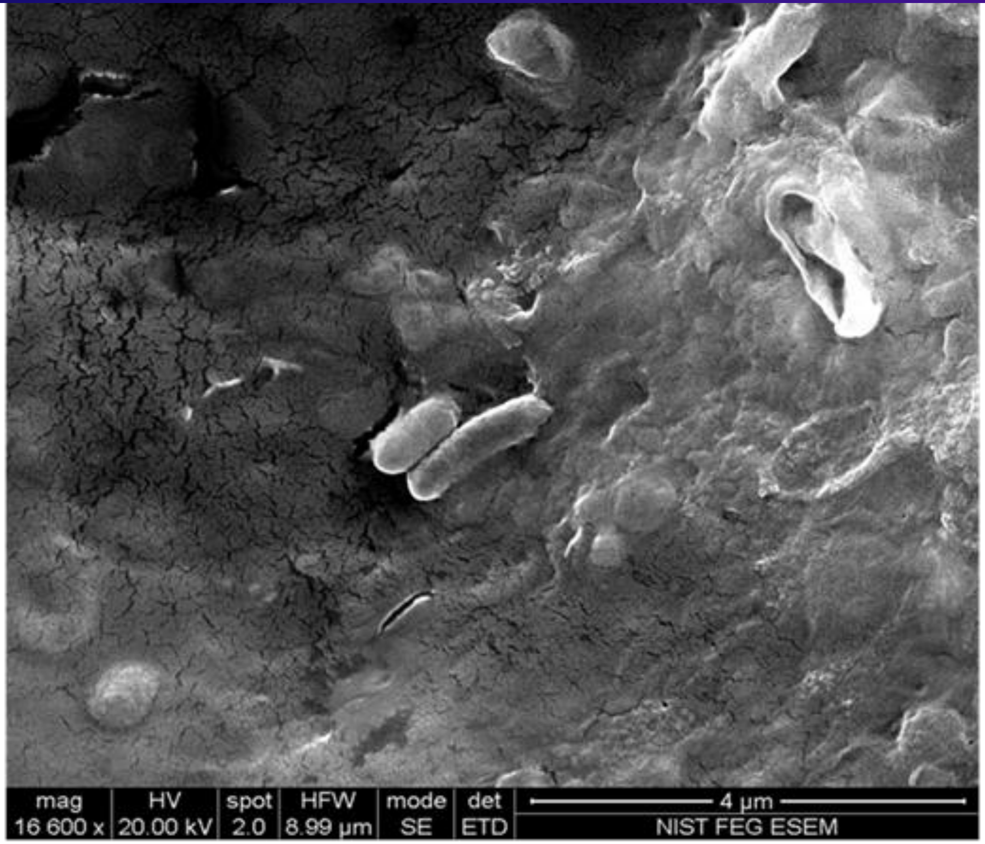
Model Validation

- Model validity was tested for 8 unknown experiments (e.g., feed compositions the model was not trained on)

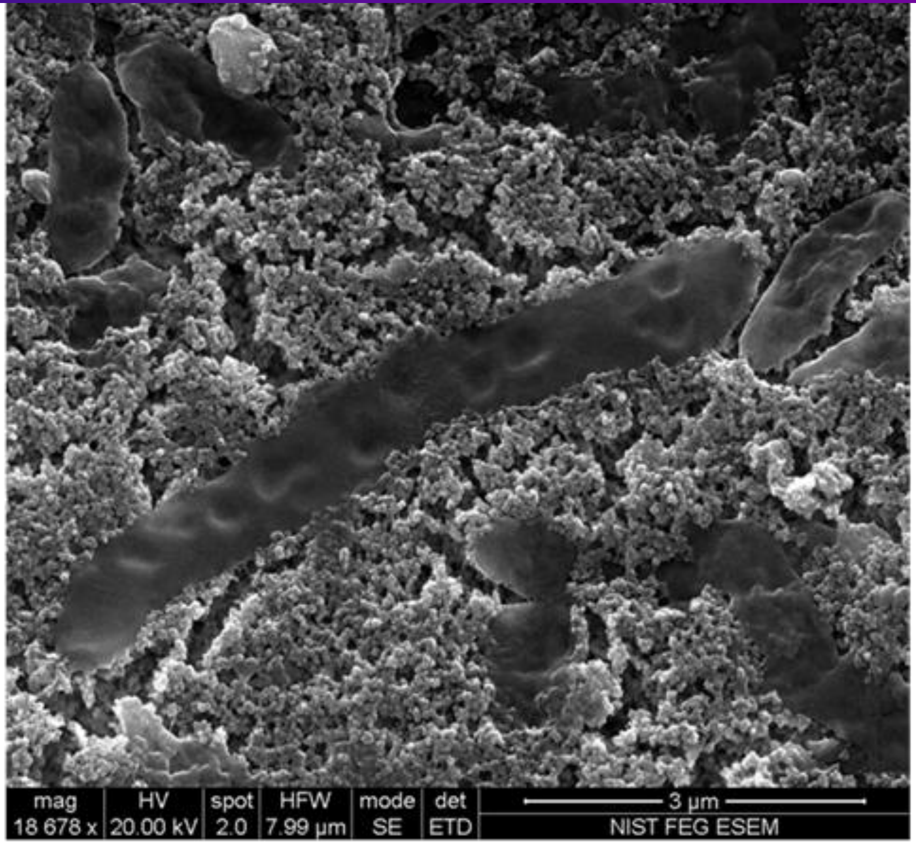


Example of validation of the trained model on unknown data (unpublished data)

Polymeric Membrane Fouling Reduction: Pre-Ozonation



MBR-RO control



MBR-Ozone-RO (3 mg/L)

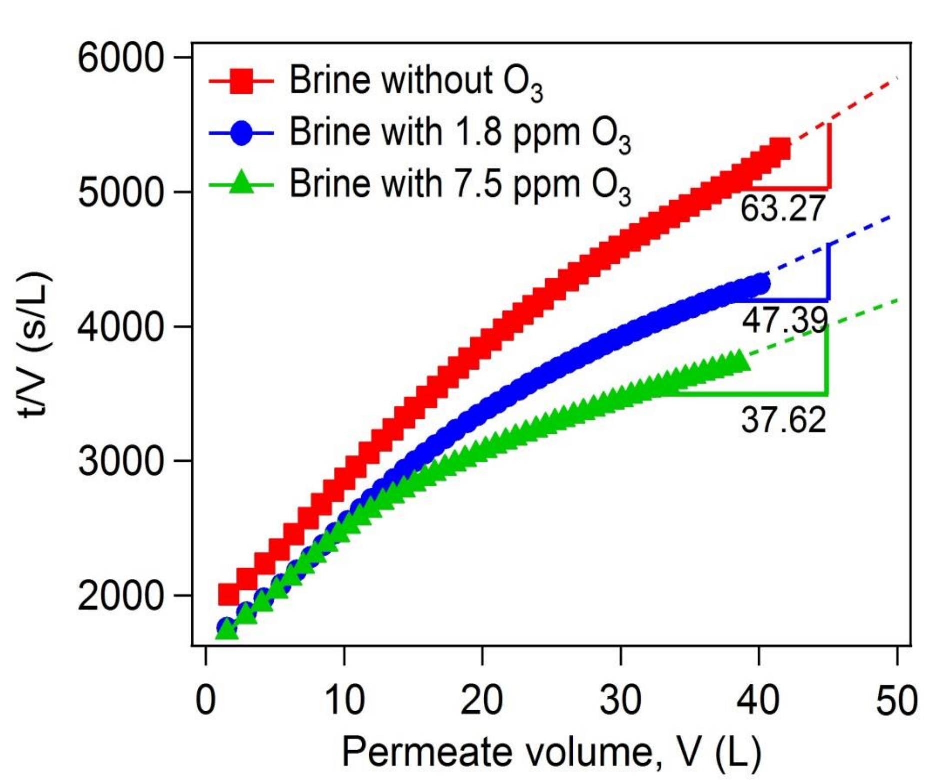
Stanford, B. D.; Pisarenko, A. N.; Holbrook, R. D.; Snyder, S. A., Preozonation Effects on the Reduction of Reverse Osmosis Membrane Fouling in Water Reuse. *Ozone-Sci. Eng.* **2011,** *33* (5), 379-388.

Membrane Fouling Reduction: Ozonation RO Brine

Ozone reduced MFI value about 1.7 fold

$$\frac{t}{V} = \frac{\eta R_m}{A\Delta P} + \underbrace{\frac{\eta I}{2\Delta P A^2}}_{MFI} V$$

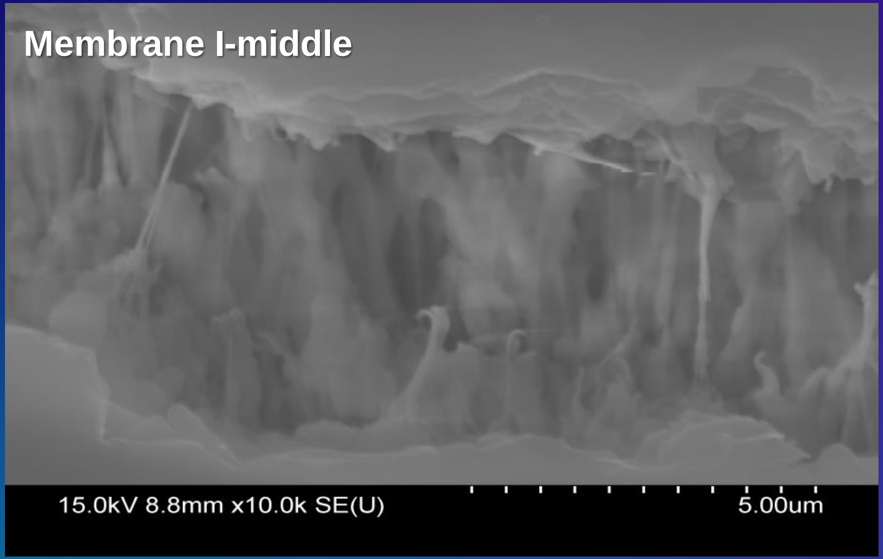
Matrix	MFI (s/L^2)
Brine w/o O_3	63.27
Brine w/ 1.8 ppm O_3	47.39
Brine w/ 7.5 ppm O_3	37.62

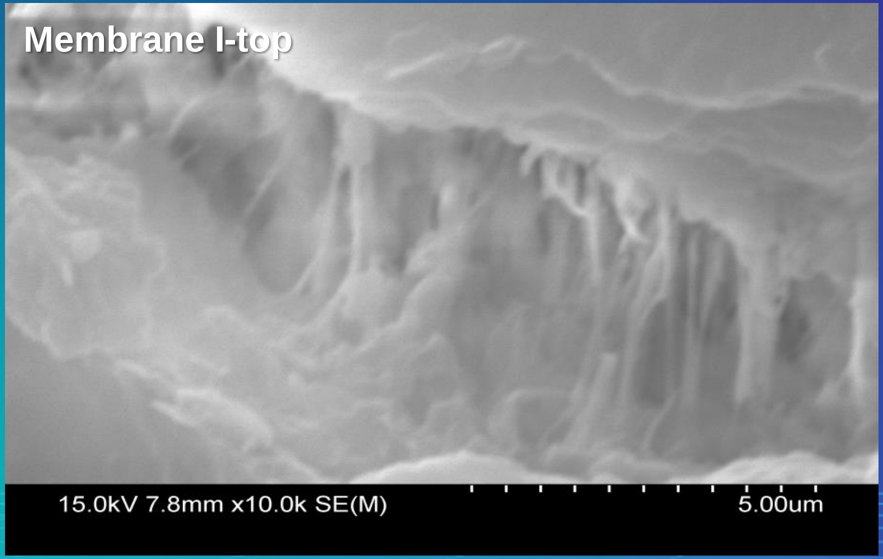


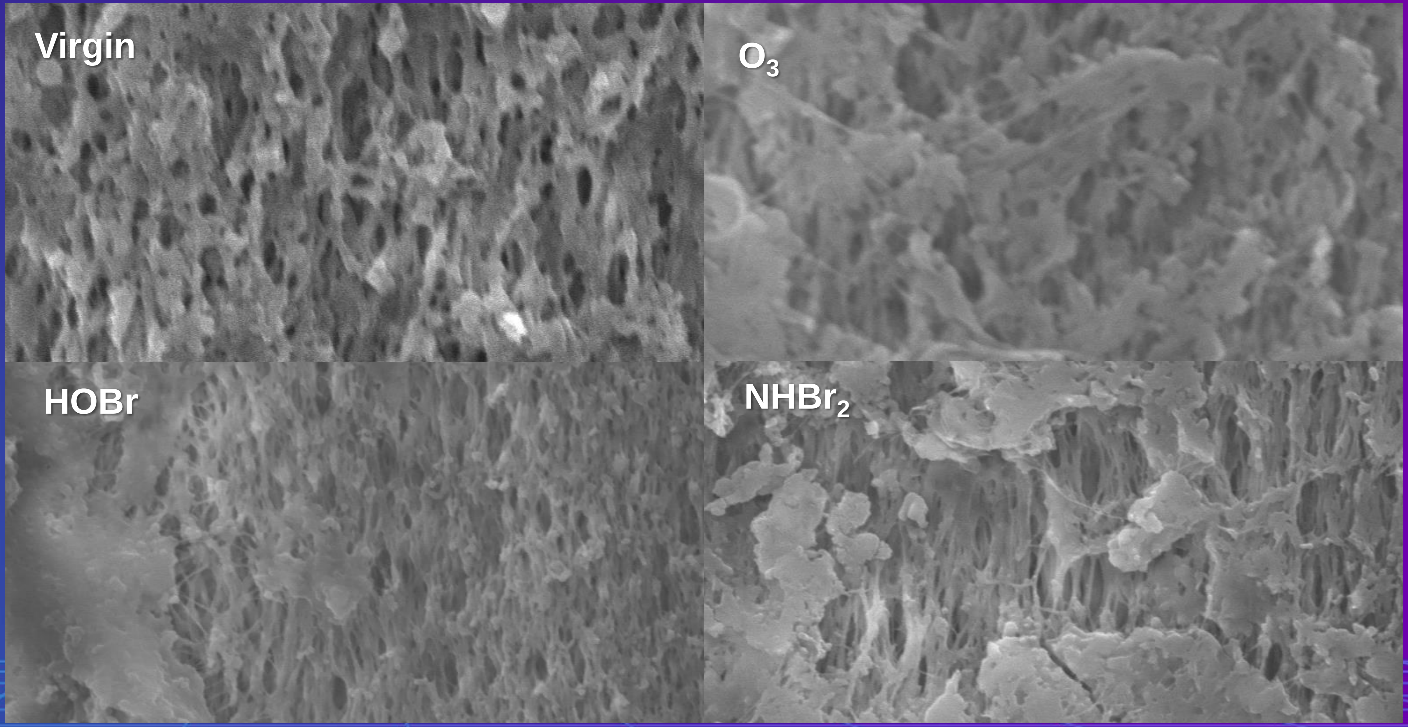
Park M, Anumol T, Simon J, Zraik F, Snyder SA. ***J. Mem. Sci.*** 2017 (523):255-263.

Membrane Fouling Reduction: Ozonation MF/UF Damage

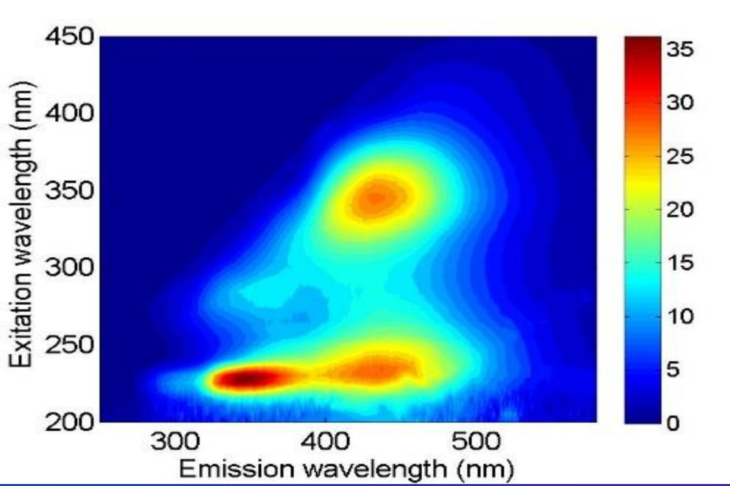
- Pre-O_3 caused membrane failure
- Tensile strength greatly diminished
- O_3 >HOBr>>$NHBr_2$
- O_3 at sub-residual doses required
- Alternative surrogate needed



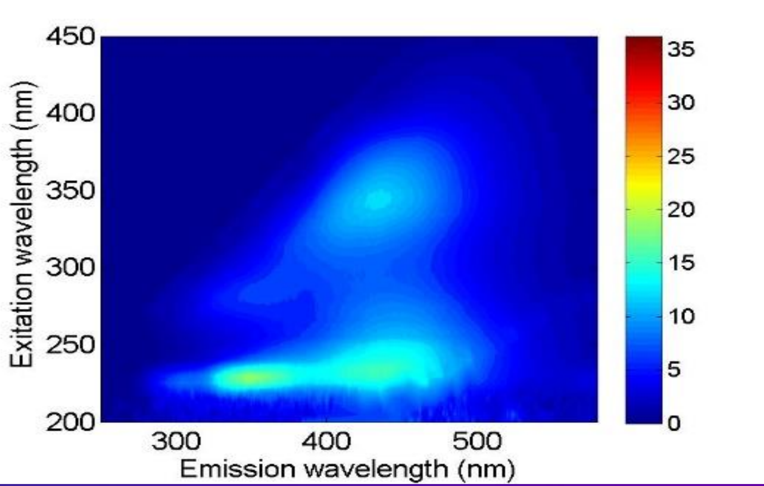




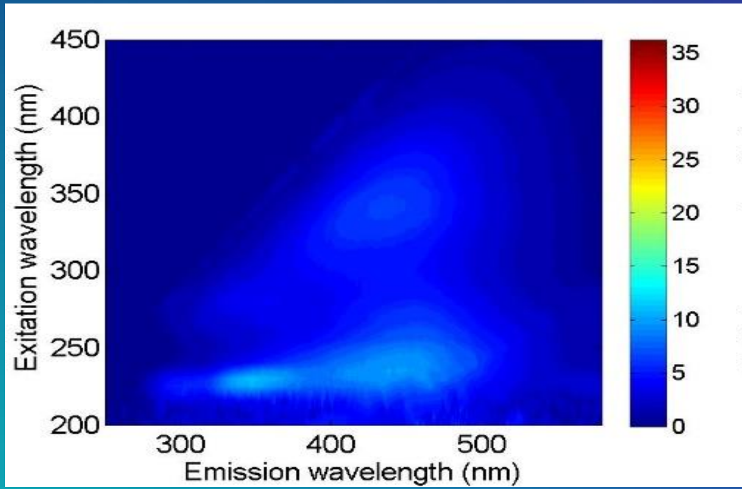
Membrane Fouling Reduction: Ozonation Control



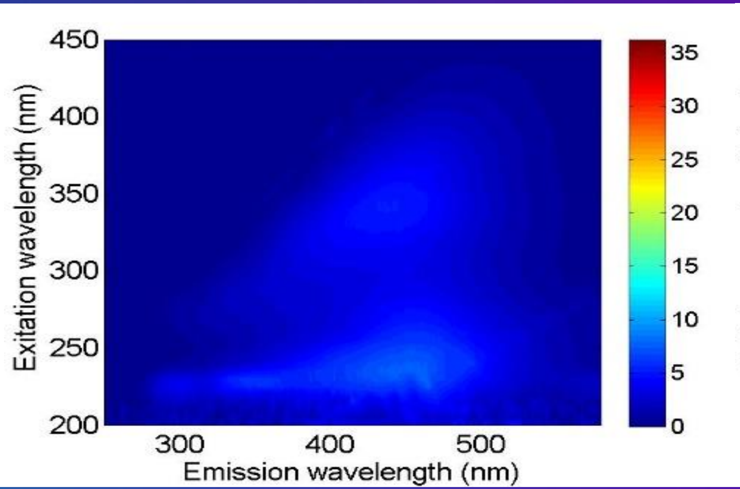
Control



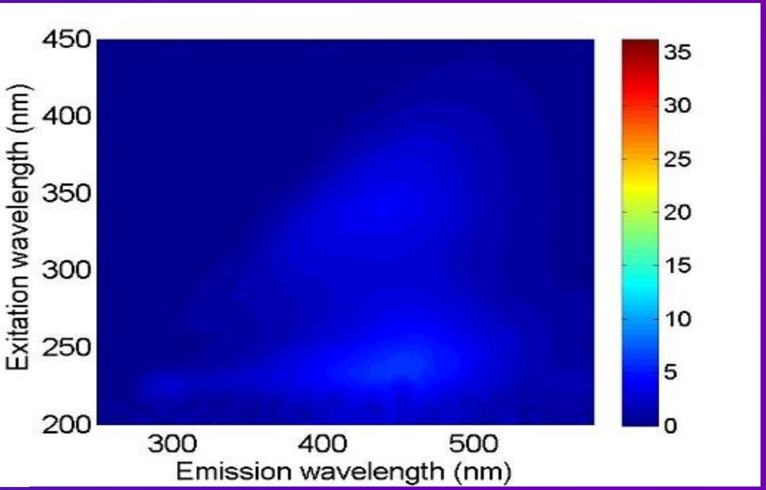
1.5 ppm



3 ppm



4.5 ppm

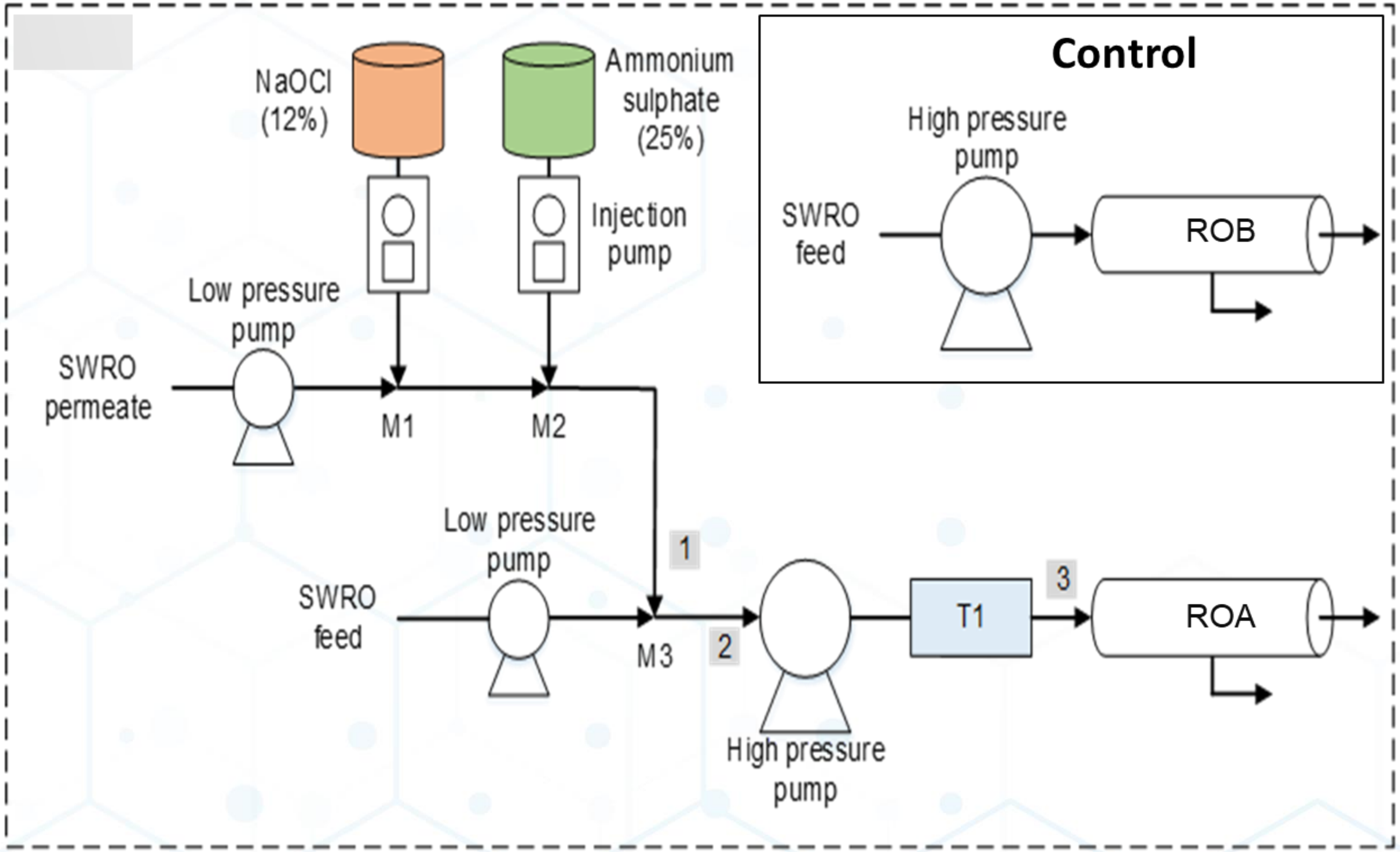


6 ppm

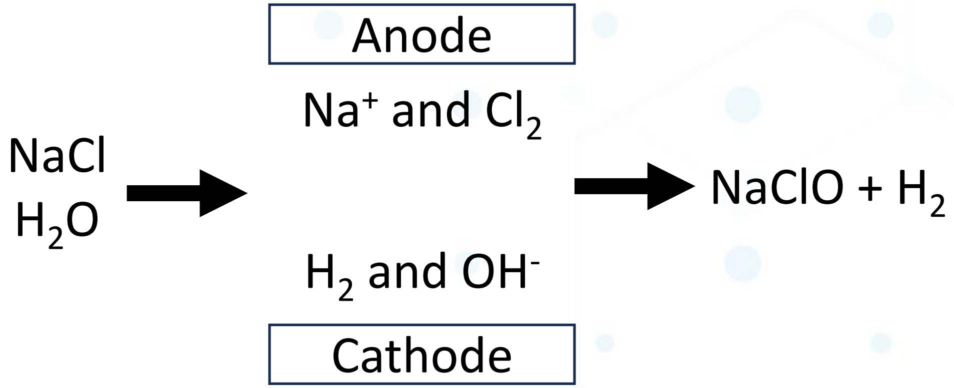
Merel S, Anumol T, Park M, Snyder SA. *J. Hazard. Mater.* 2015 282:75-85

SWRO Membrane Fouling Reduction: Chloramination

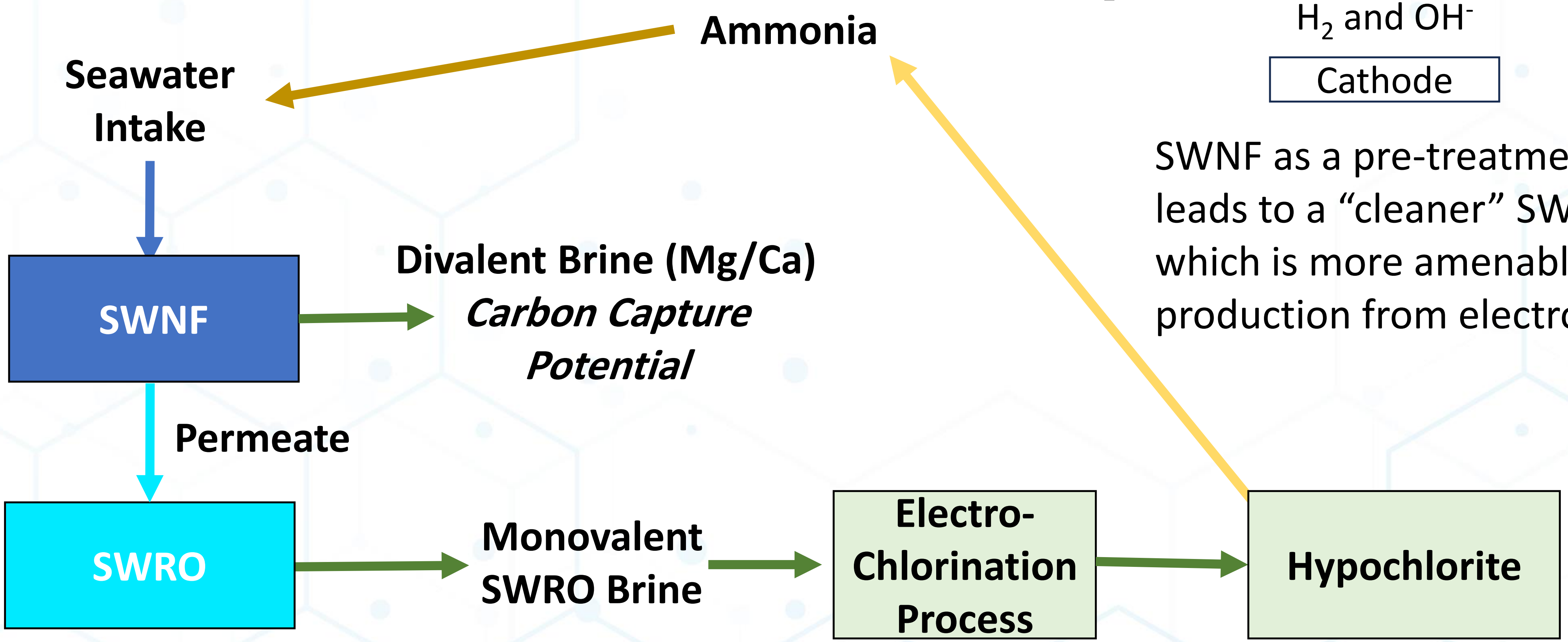
*Schematic of inline pre-formed NH_2Cl system and SWRO desalination system (**pilot test – 50 days**).*



SWRO Membrane Fouling Reduction: Chloramination



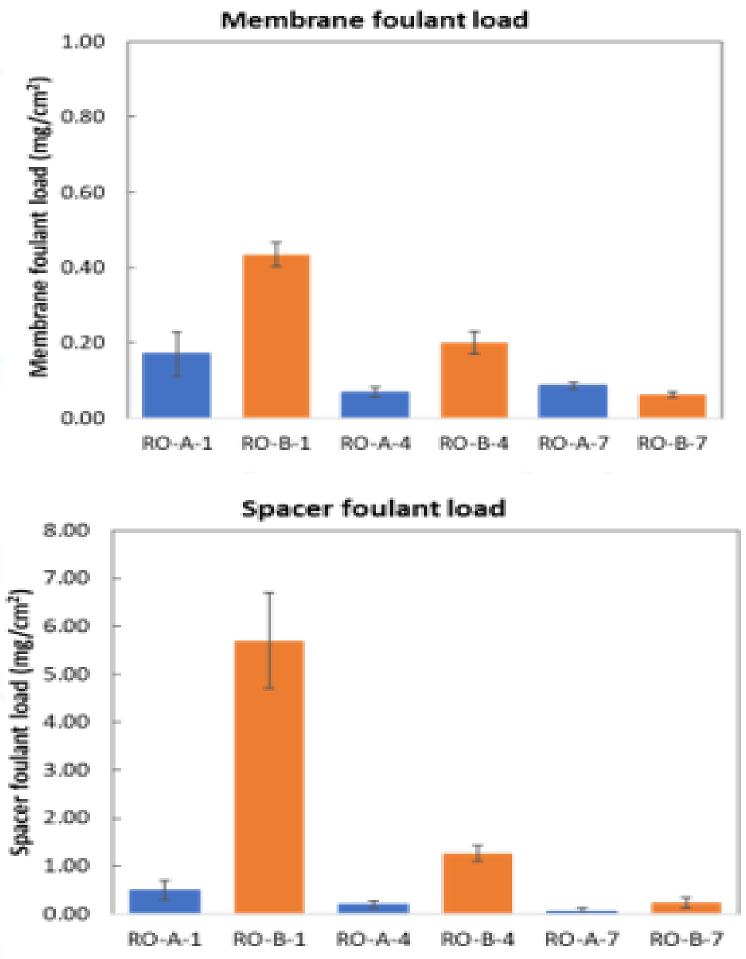
SWNF as a pre-treatment to SWRO leads to a “cleaner” SWRO brine which is more amenable to HOCl production from electrolysis.



SWRO Membrane Fouling Reduction: Chloramination

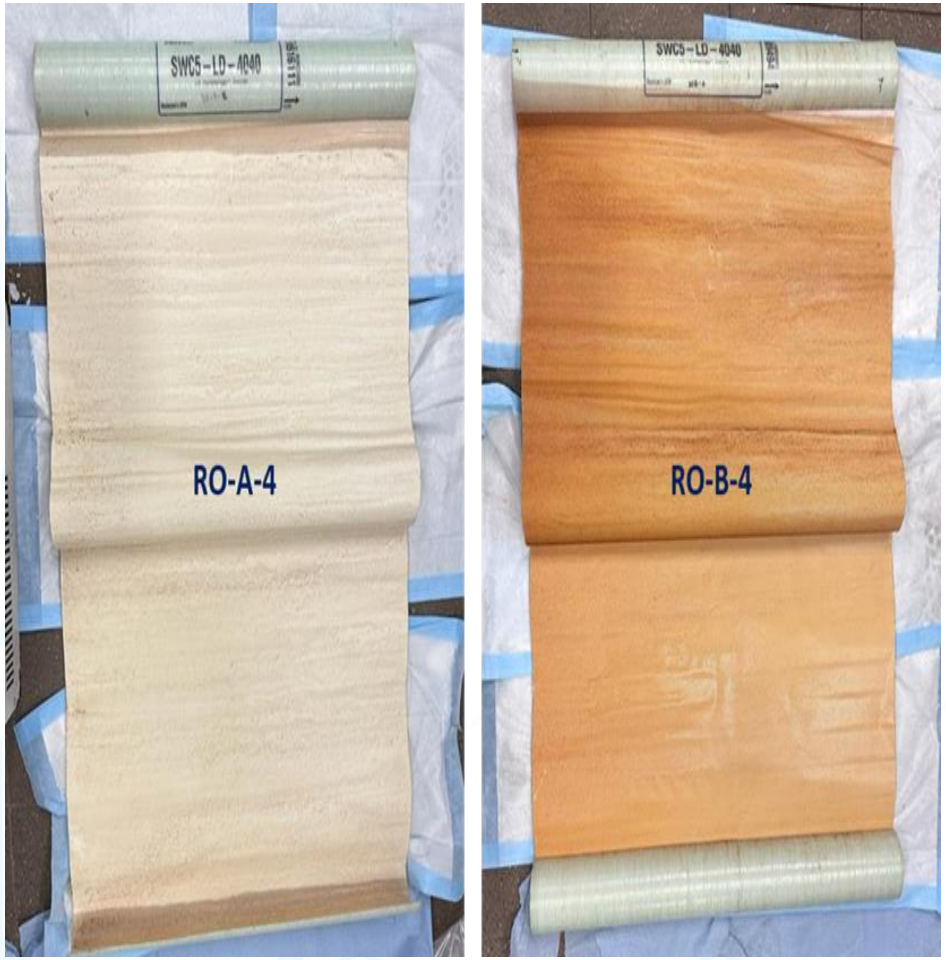
Comparison of RO trains: ROA (2 mg/L NH_2Cl dosage) with the control ROB (No NH_2Cl)

Membrane/spacer foulant load*

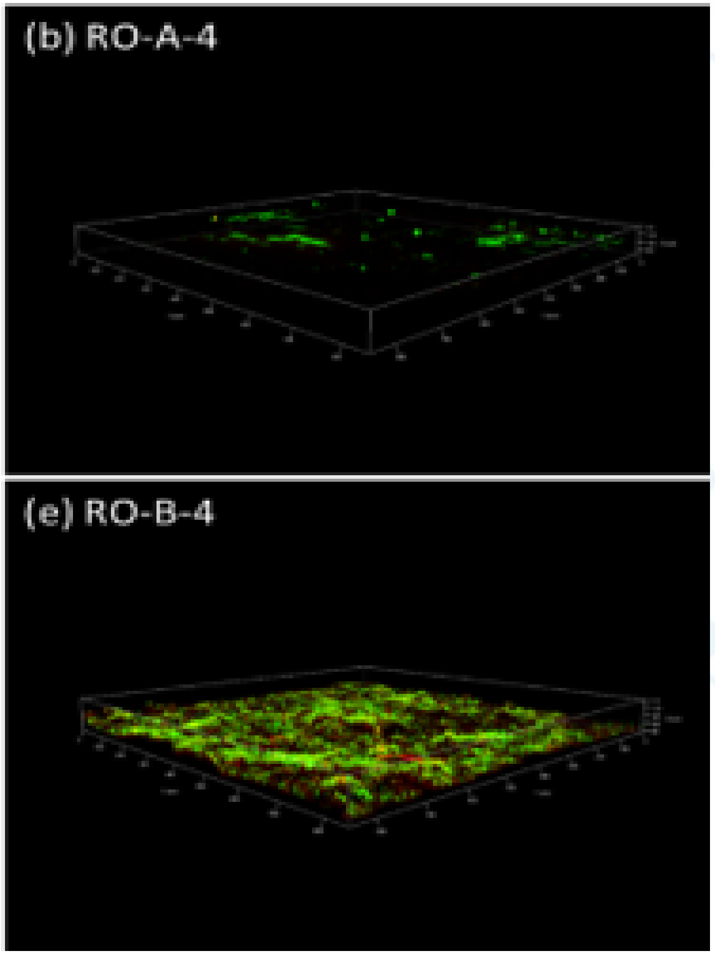


* (1)- first, (4)-middle, and (7)-last elements of the trains

Membranes visual comparison



CLSM images of live/dead cells*



*Live cells – green fluorescence, dead cells – red fluorescence

Seawater Desalination & Carbon Capture

WTE Incineration

Desalination plants

Incineration bottom ash (IBA)

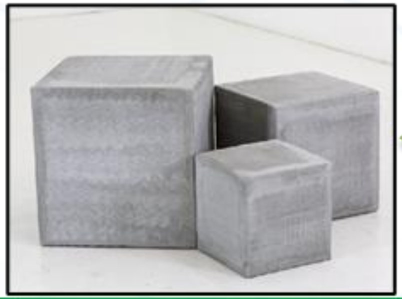
Al	~30,000 mg/kg
Ca	~100,000 mg/kg
Fe	~50,000 mg/kg
K	~10,000 mg/kg
Mg	~10,000 mg/kg
Na	~20,000 mg/kg
pH	~12

Seawater desalination brine

Ca	822	mg/L
Mg	1,924	mg/L
Na	12,443	mg/L
K	638	mg/L
Cl	25,699	mg/L
pH	8.2	

Raw chemicals

Construction materials



Carbonates

Carbonated IBA

Integrated CCSU system with wastes

$CaO + CO_2 \rightleftharpoons CaCO_3$

$Mg(OH)_2 + CO_2 \rightleftharpoons MgCO_3 + H_2O$

$NaOH + CO_2 \rightleftharpoons NaHCO_3$

$KOH + CO_2 \rightleftharpoons KHCO_3$

*https://www.todayonline.com/singapore/singapores-greenhouse-gas-emissions-top-50m-tonnes-report

Conclusions:

- **Diverse water portfolios greatly increase water security**
  - Synergy between water reuse and SWRO systems can be realized
  - Combined systems can reduce infrastructure/costs/energy
- **Membrane fouling is a major limitation for RO efficiency**
  - Pre-ozonation can greatly reduce RO & MF/UF fouling
  - Ceramic membrane pre-treatment robust and effective
  - Machine Learning/AI offers optimization benefits
  - Fluorescence is a promising surrogate for low O3 concentration
- **Chloramination is a cost-effective biocide for SWRO**
  - Even monochloramine can result in some membrane oxidation
  - Disinfection byproduct formation should be more closely evaluated
- **Seawater desalination can enable CO2 capture & resource recovery**

Under the Patronage of His Excellency **Eng. Abdulrahman bin Abdulmohsen AlFadley**
Minister of Environment, Water & Agriculture

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THANK YOU!

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29 April – 01 May 2024

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