Membrane Research Activities in Singapore

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On behalf of MEMSIS
ICOM2023, Chiba, Japan

Urban Solutions and Sustainability

Key drivers:

i. Understanding, mitigating and adapting to **climate change**,

ii. Developing Singapore as a city that nurtures citizens' **health and well-being**,

iii. Transforming our built environment to become more **sustainable**, while optimising our limited manpower and resources.

SGMEM
Singapore Membrane Consortium

Singapore Membrane Consortium – Ecosystem

Research

NUS | NTU | SUTD | SIT

Innovation

START @NTUitive | EWTCOI @NP

Enterprise

Shell Singapore, sembcorp, ST Engineering, evoqua, Kurita, SepPure, Veolia Water, Aquaporin Asia, JFE, Memstar, BASF, BlueOcean Memtech, TriTech, Century Water, DuPont, demem, ecosoft, Suntar, DIVIGAS, Ceraflo, Arkema, NALA Membranes, Namiton, Liquinex, firmbase, Baxter, Memsift Innovations, PepsiCo

Partners

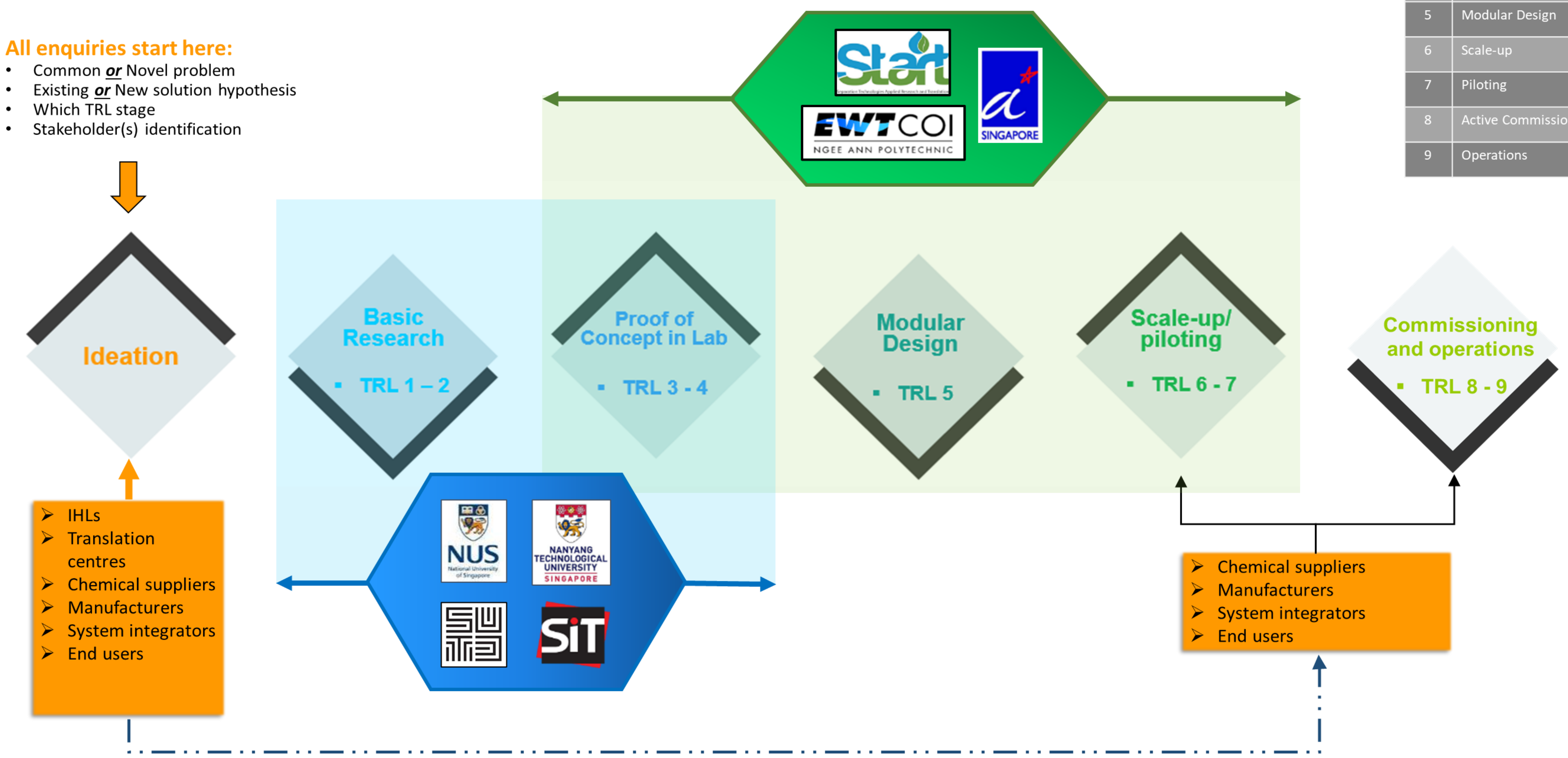
PUB Singapore's National Water Agency, EDB Singapore, Enterprise Singapore, Imagine H2O Asia, Agency for Science, Technology and Research Singapore, ripple2wave Incubator

Sponsor

National Research Foundation
Prime Minister's Office
Singapore

SG MEM Engagement Model

TRL	Stage
1	Basic principles
2	Invention and Research
3	Proof of Concept
4	Bench Scale
5	Modular Design
6	Scale-up
7	Piloting
8	Active Commissioning
9	Operations



START (Separation Technologies Applied Research and Translation) Capabilities

Flat-sheet Membranes

Phase Inversion

Thin Film Composite

Commercial Scale Elements

Industrial Scale RO Elements Testing

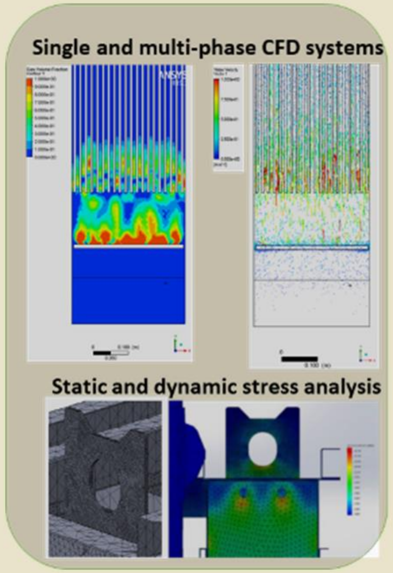
- Unique Fabrication Lines in Singapore of 1m width
- Lab-scale coupons to Commercial scale Elements Fabrication and Testing
- Piloting Efforts

PUB Water for All: Conserve, Value, Enjoy | Start | NTUitive

START Capabilities

- Pilot Scale membrane fabrication facility
- 1-Inch to 8-inch Modules Fabrication and Testing
- Piloting Efforts

SYSTEM DESIGN



- Engineering Design
- Process development, process units design,
- Scale-up and optimization.

Focus areas:

- 3D computer-aided design (CAD) modelling
- Finite Element Analysis (FEA)
- Computational Fluid Dynamic (CFD)

Featured Software:

SOLIDWORKS SIMULATION ANSYS FLUENT

Research Activities at the Singapore Membrane Technology Centre (SMTC)

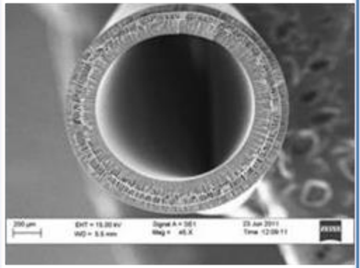
- Established since **2008** at Nanyang Technological University (NTU), Nanyang Environment and Water Research Institute (NEWRI)
- **Mission** of SMTC
  - **Research & Development**: research with links to industry and international community;
  - **Education & Training**: to produce PhDs and Researchers in membranes technology;
  - **Industry & Application**: to act as incubator for novel membrane technology.

Prof. Wang Rong, Director

A/P Chong Tzyy Haur, Deputy Director

Asst/P She Qianhong

Novel Membranes

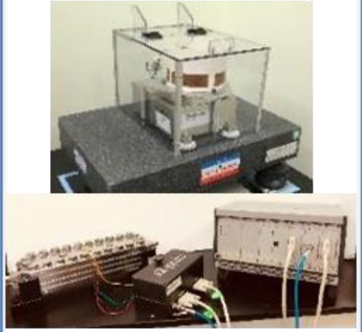


(e.g. FO/PRO, low pressure NF, MD, biomimetic)

Enhanced Module & System Design

(e.g. Multi-stage approach, 3D-Printed spacer & module)

Fouling Control & Sensors



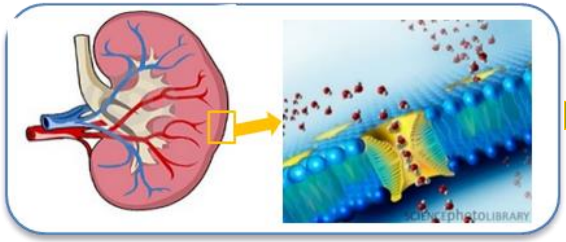
(e.g. Preventing membrane damage, optimizing performance)

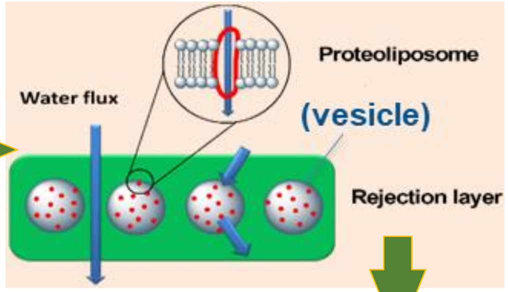
Novel Membrane Bioreactors (MBRs)

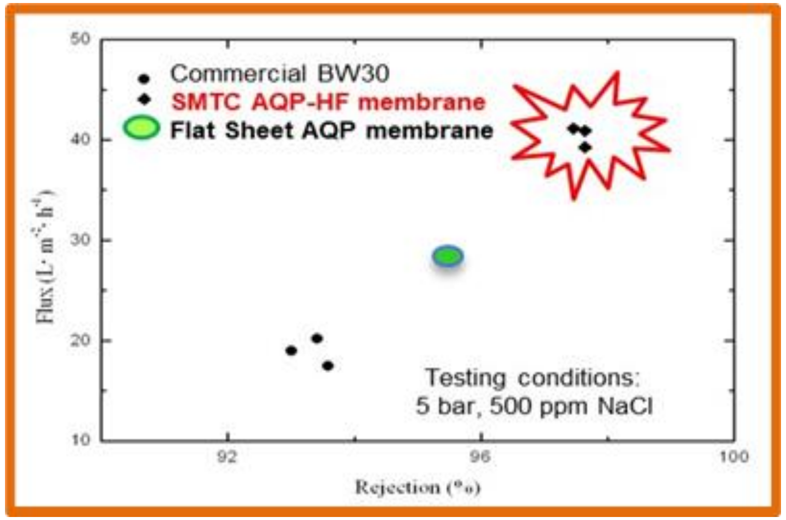
(e.g. AnMBR, extractive MBR, fluidized bed MBR)

Bio-programmable Membrane (BPM) for Low Energy Water Desalination and Reclamation

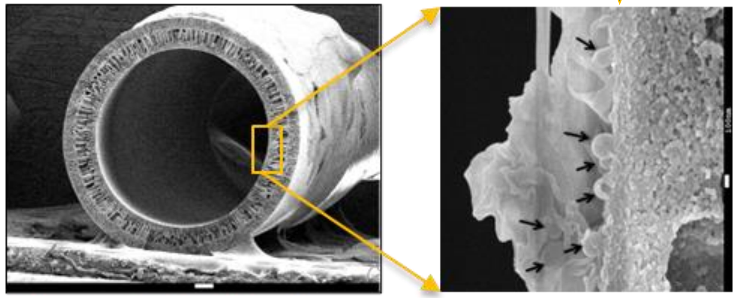
- Challenge: Reverse osmosis (RO) membranes have **low water permeability → High energy cost** for operation
- Solution: Learn from nature – 1st approach: **Aquaporin (AQP)-based biomimetic membrane**







JMS 494 (2015) 68

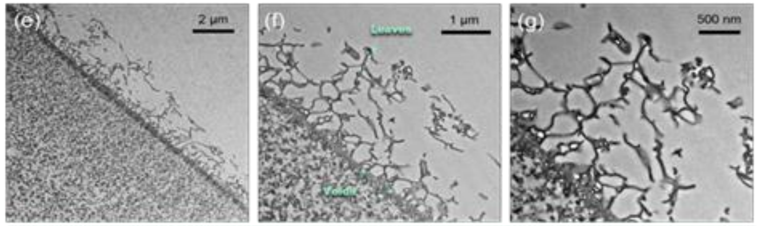


First AQP-Hollow fiber membrane

Prof. Wang Rong, NTU

Bio-programmable Membrane (BPM) for Low Energy Water Desalination and Reclamation

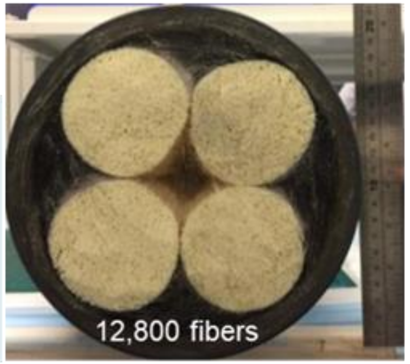
- 2nd approach: **Bio-Programmable Membrane (BPM)** without AQPs
  - Inspired by the AQP-RO, one type of **biomolecules** was identified to replicate the effect of AQP vesicles at a lower cost



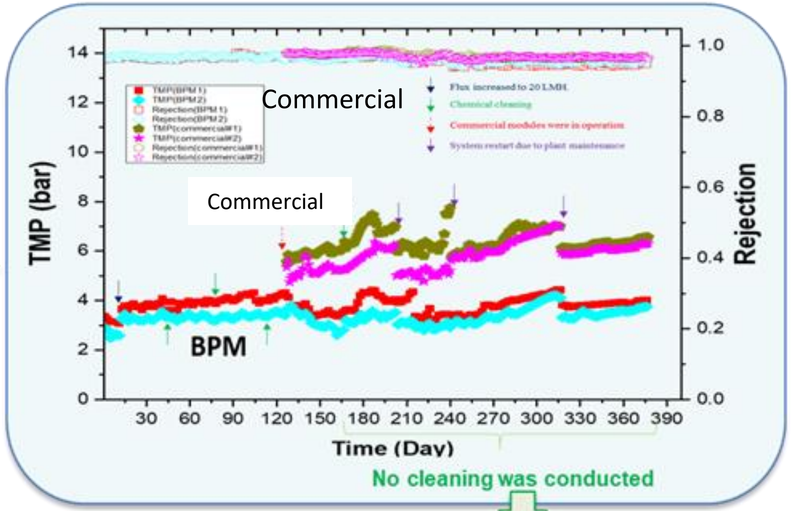
BPM-RO: effective surface area is ~**3X** of that of control

Scale-up of BPM-RO

2", 4", **8"** module



Pilot Test at UPWRP: 14 m^3/d (Phase 1) to 100 m^3/d (Phase 2)



cost saving and high throughput

~ 50% pumping energy saving (0.198 kWh/m^3)

Prof. Wang Rong, NTU

BPM-RO Hollow Fiber Membrane Commercialization

Ong Tze Guan

Founder & CEO

Forward Osmosis (FO) Technology for Cold Concentration

Technology Readiness

Patent: **Forward Osmosis Hollow Fiber (HF) Membrane**

PCT-EP(DE); PCT-EP(FR); PCT-EP(GB); PCT-SG

- Started to have contracts since June 2019.
- >20 contracts with revenues >S$250K by far

2013 (Patent Filing) — **2021 (Granted)**

Year

2013 — **Singapore MND R&D Award**

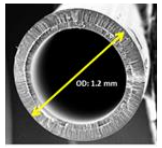
2016 — **Alternative Water Resources Prize,** PSIPW Saudi Arabia

2018 — **For Niche Application in the F&B Industry** (Aromatec)

2019 – 2020 — **Scale-up & translation (TRL4 → TRL6*)**

2020 — **Investment** (Sunbo Partners Pte Ltd, Korea)

2021 —— 2023 — **Phase 1:** Industrial validation **(TRL7~8)**



ARO-FO-4040 TFC HF membranes

Bench-top

Suitcase demo set

Pilot-scale (750 L/day)

Prof. Wang Rong, NTU

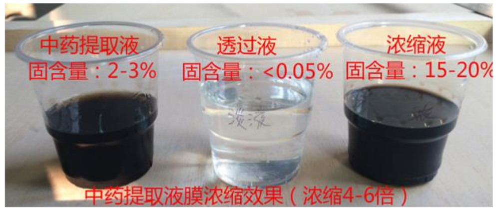
Forward Osmosis (FO) Technology for Cold Concentration

Notable Use Case: Coffee Concentration

Aromatec

Using our pilot FO system

Other Proof-of-Concept



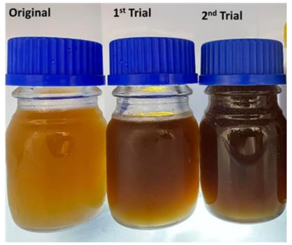
Chinese Herb

Concentrated concoction by 6x

Soy Sauce

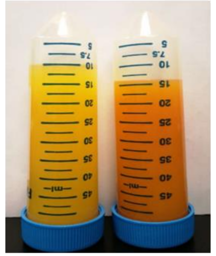
Concentrated sauce by 2x

Maltose



Concentrated maltose by 3.7x

Fruit Juice



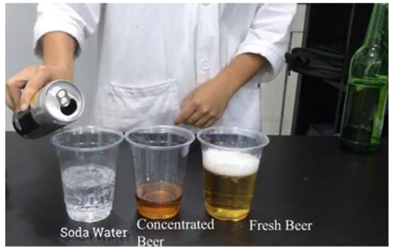
Concentrated juice by 6x

Tea

Concentrated tea by 20x

Milk

Concentrated milk by 10x



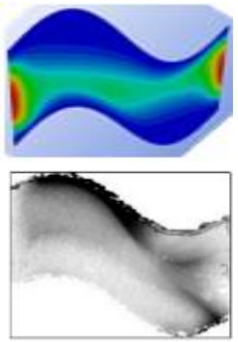
Beer

Concentrated beer by 5x

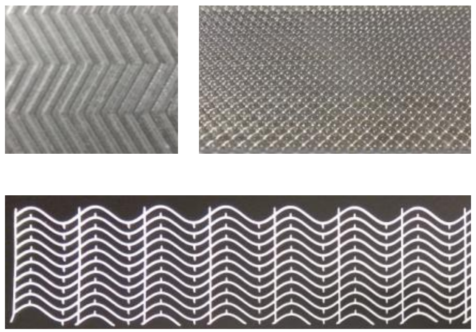
Prof. Wang Rong, NTU

Module Design & Process Intensification

- Improved separation performance, increased recovery, energy reduction, fouling reduction etc.



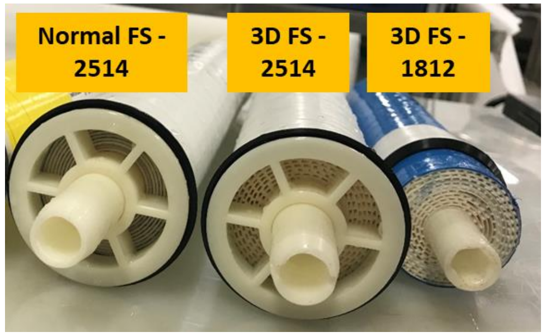
Modelling & Simulation



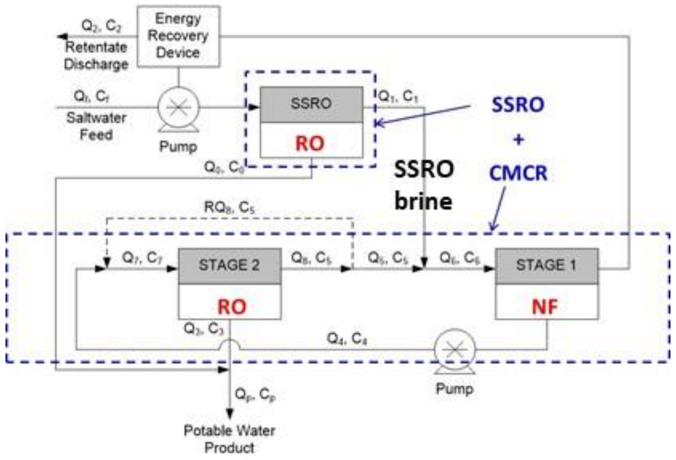
Novel Spacers by 3D Printing

CAD model

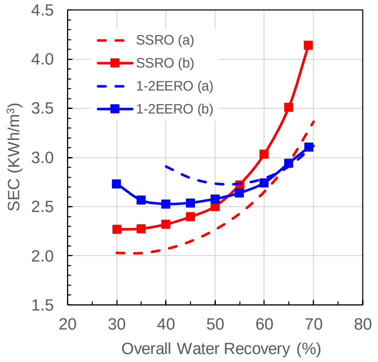
3D-Printed Spacer



3D-Printed Spacers for Spiral Wound Module (SWM)



Schematic diagram of a 1-2 EERO (i.e., add more NF stages to increase the overall water recovery)



(i) Calculations of the SEC are based on operation at (a) thermodynamic limit, (b) including the effects of CP and ΔP_{ch}
(ii) Pump and ERD efficiencies of 85 and 90%, respectively
(iii) Intersection between SSRO and 1-2 EERO i.e., blue and red lines represents the 'critical' recovery i.e. 65% for (a) 55% for (b)

Specific energy consumption (SEC, kWh/m³) of SSRO and 1-2 EERO processes

Pilot testing of EERO process

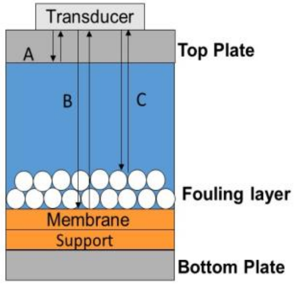
Energy-efficient reverse osmosis (EERO) for high water recovery and resource recovery

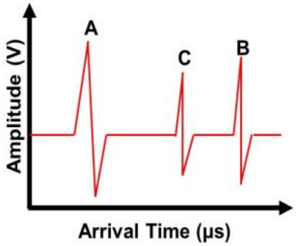
A/P Chong Tzyy Haur

Sensors & Instruments

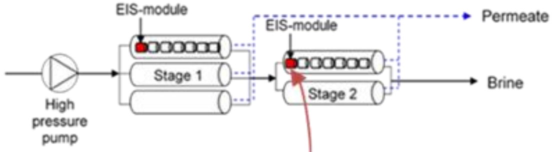
- Smart sensors for rapid detection and high accuracy

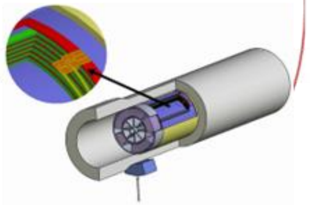
Evapo-porometer (EP) for accurate pore size measurement



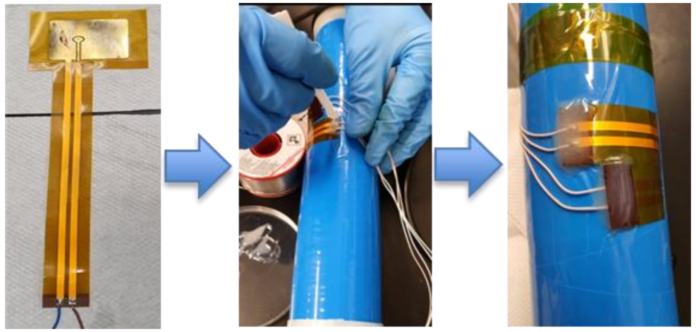


Ultrasonic sensor (UTDR) for fouling detection

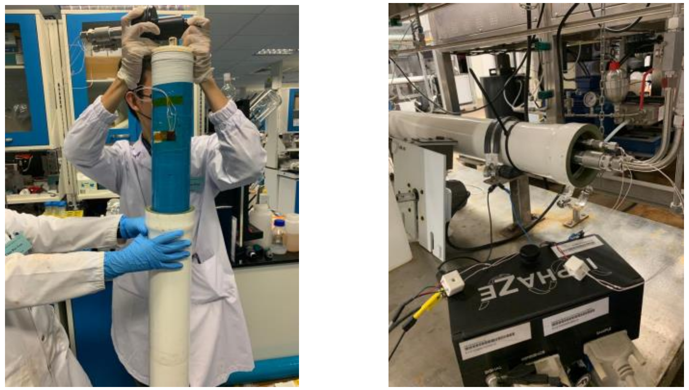




EIS-module
EIS electrode is embedded in SWM RO



EIS electrode inserted to 4" SWM RO



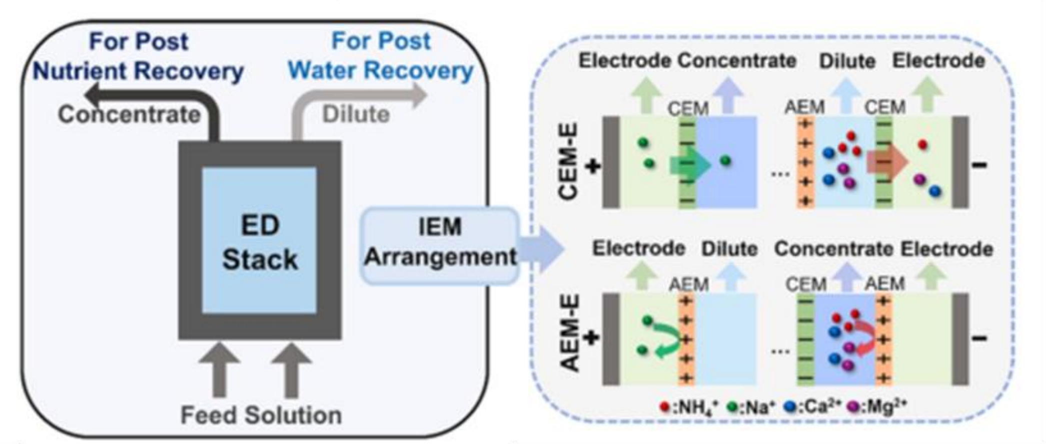
4" EIS-module connected to EIS spectrometer

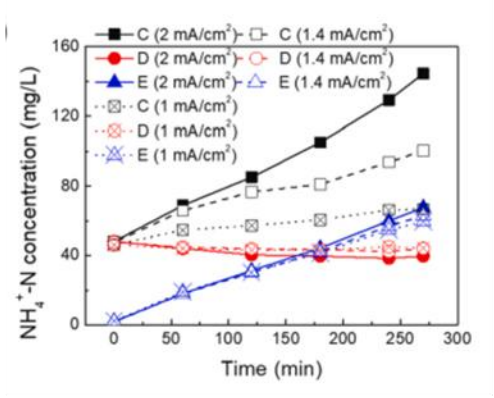
Electrical impedance spectroscopy (EIS) for early fouling detection

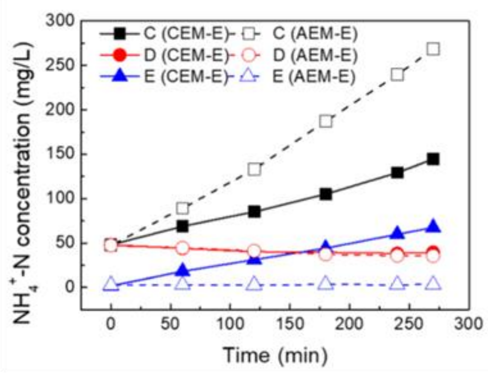
A/P Chong Tzyy Haur

Electrochemical Membrane Technology

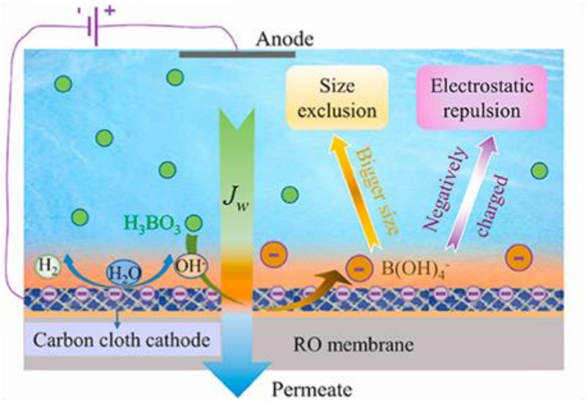
Electrodialysis: desalination & nutrient (N, P) recovery

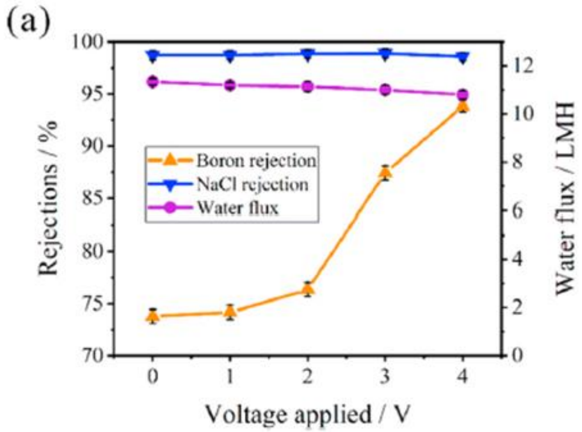




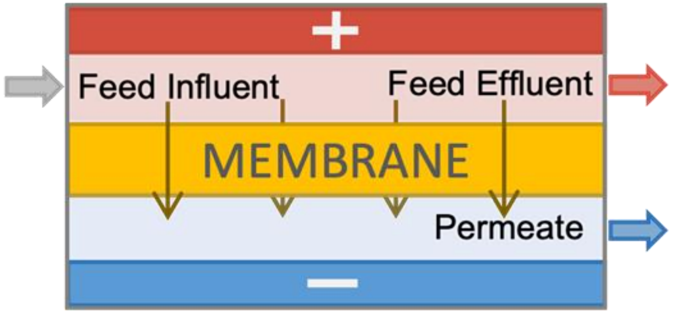


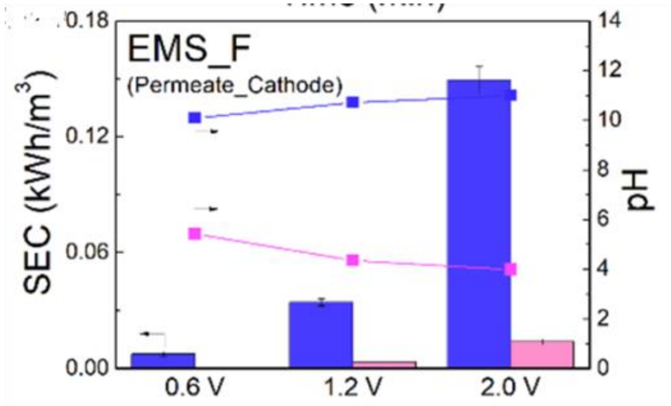
Electrochemically assisted reverse osmosis (EARO)





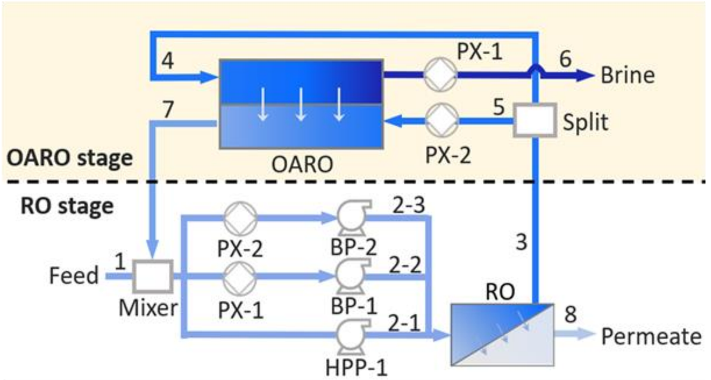
Electrochemically membrane system (EMS) for chemical free pH regulation

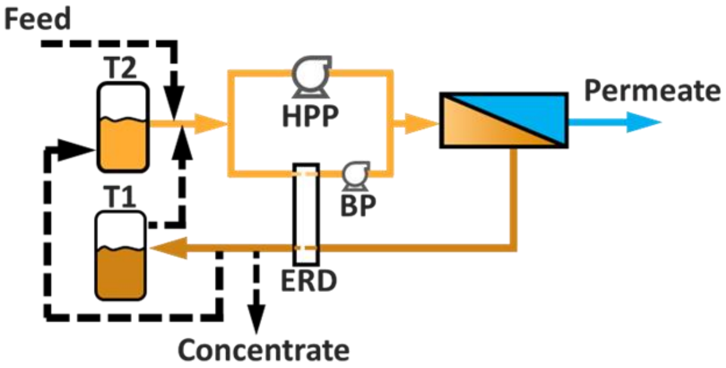


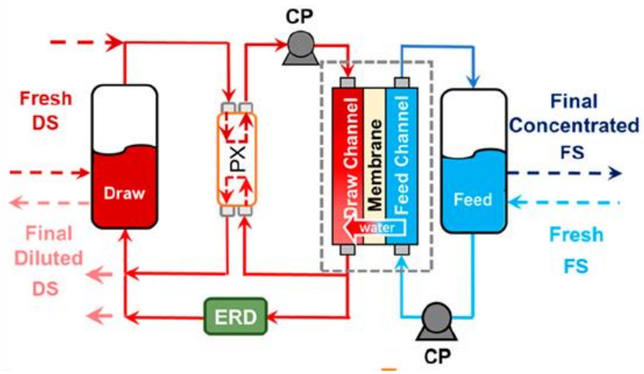


Asst/P She Qianhong

Membrane process and system for desalination and osmotic energy harvesting

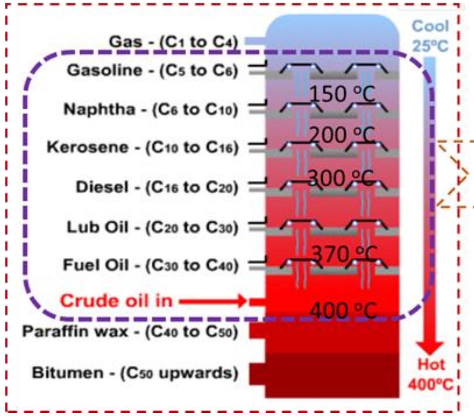


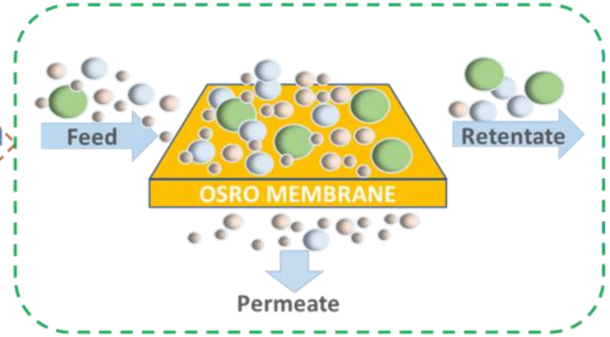




Osmotically-assisted reverse osmosis (OARO)

Batch/Semi-batch RO and PRO for desalination and osmotic energy harvesting





Organic solvent reverse osmosis membranes for separating complex hydrocarbon mixtures

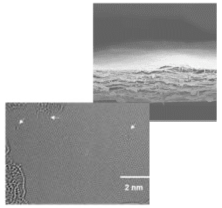
Asst/P She Qianhong

Sui Zhang's Advanced Membrane Lab at National University of Singapore (NUS)

Fundamentals

New materials with controlled transport

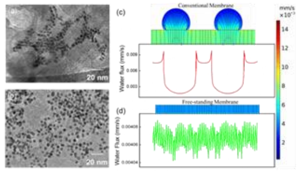
- Microporous polymers
- 2D materials
- Machine learning



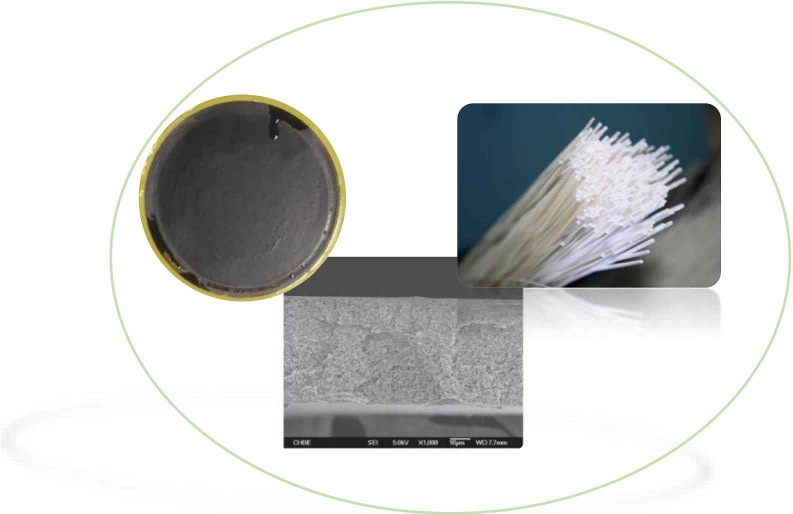
L. Shen et al., Science Advances, 2021.
Y. Lu et al., PNAS, 2021.
S. Zhang et al., Adv. Mater. 2022
Q. Ding et al., Angew Chem 2022
C。Zhao et al., Nat. Comm. 2023

Surface structure: Impact on transport

- Surface structure design
- Surface property vs transport



Shang et al., Environ. Sci. & Technol., 2020, 54, 5288-5296
Shang et al., Environmental Science & Technology, 2020.
Shang et al., AIChE J. 2023



Team: > 20 members

https://blog.nus.edu.sg/suizhang/

Applications

Desalination

- High permeability and fouling resistant hollow fibers
- **From lab scale to 4-inch modules**
- **Commercialization by company (ongoing)**
- Collaboration with Pfizer

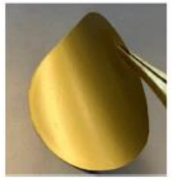
WO/2020/076240 AU2019358704 SG11202102024W
F. Li et al., J. Membr. Sci. 2021. CN112867555 US20210339206

Organic solvent nanofiltration

- Separation under challenging conditions

Gas separation

- Material design (machine learning)
- Hollow fiber membranes
- Joint research with industry



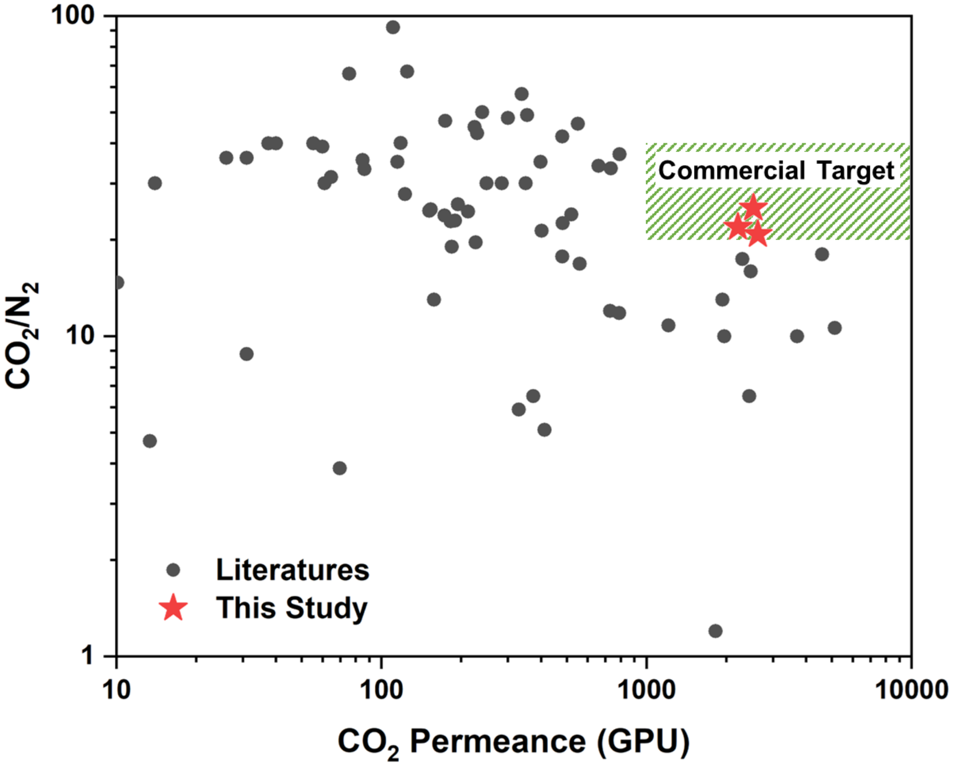
W. Liu et al., Nature Communications, 2020
J. Guan et al., Macromol. Rapid Comm. 2022

Sui Zhang's Advanced Membrane Lab at National University of Singapore (NUS)

6-month pilot study at Wastewater plant

Municipal wastewater desalination: ~ 40% energy saving

Membranes for carbon capture



Collaboration with industries;
1-inch module demonstrated in lab

Appreciate your time & attention

- We welcome opportunities for collaboration
- Please do not hesitate to contact us for more information & further enquires

NTU – SMTC

https://www.ntu.edu.sg/newri/research-focus/membrane-technology

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SGMEM & START

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https://www.ntuitive.sg/start

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Thank You!