Hybrid desalination technologies for sustainable water-energy nexus: Innovation in integrated membrane module development

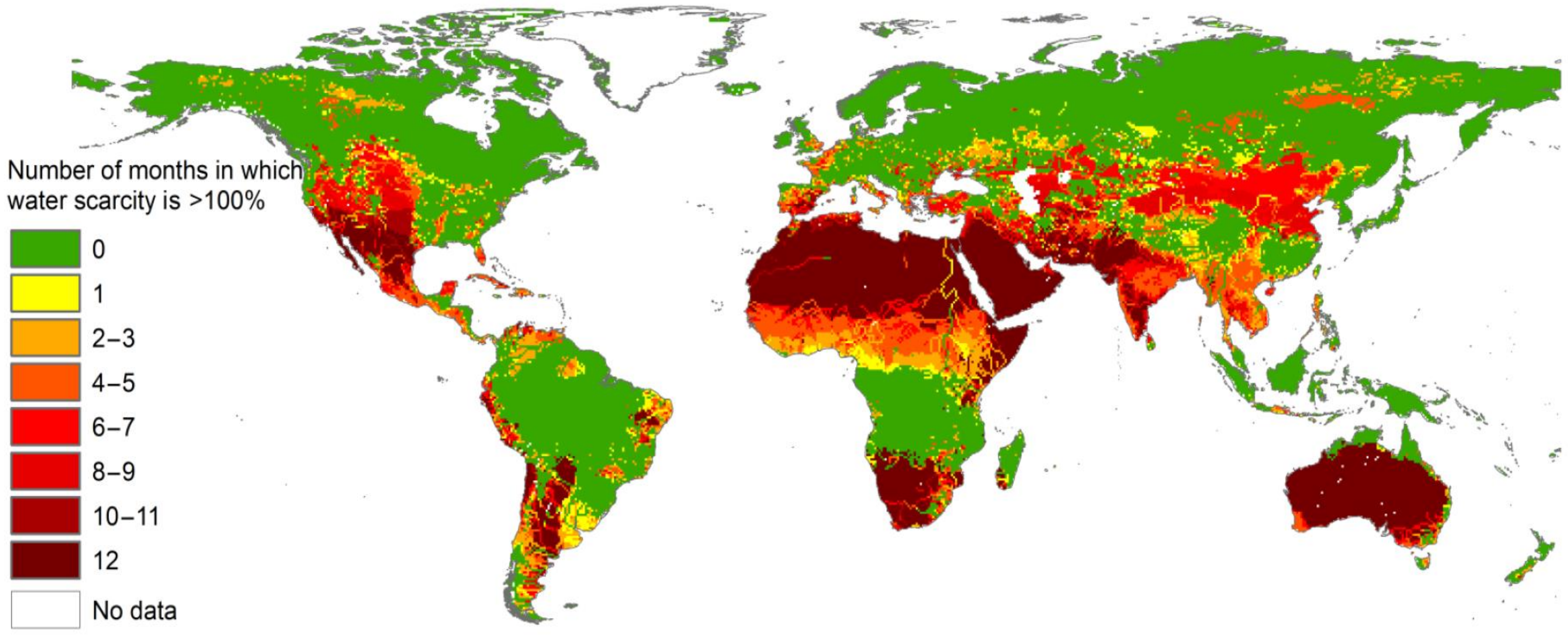
Hyuk Soo Son
Assistant Professor, Prince Sultan University, KSA
hson@psu.edu.sa

Overview

- Introduction
- Hybrid Desalination
- Case study: FO-MD Hybrid system
  - Methodology & Results
- Conclusion and Recommendations
- Credits and Acknowledgements

Introduction

Global water scarcity



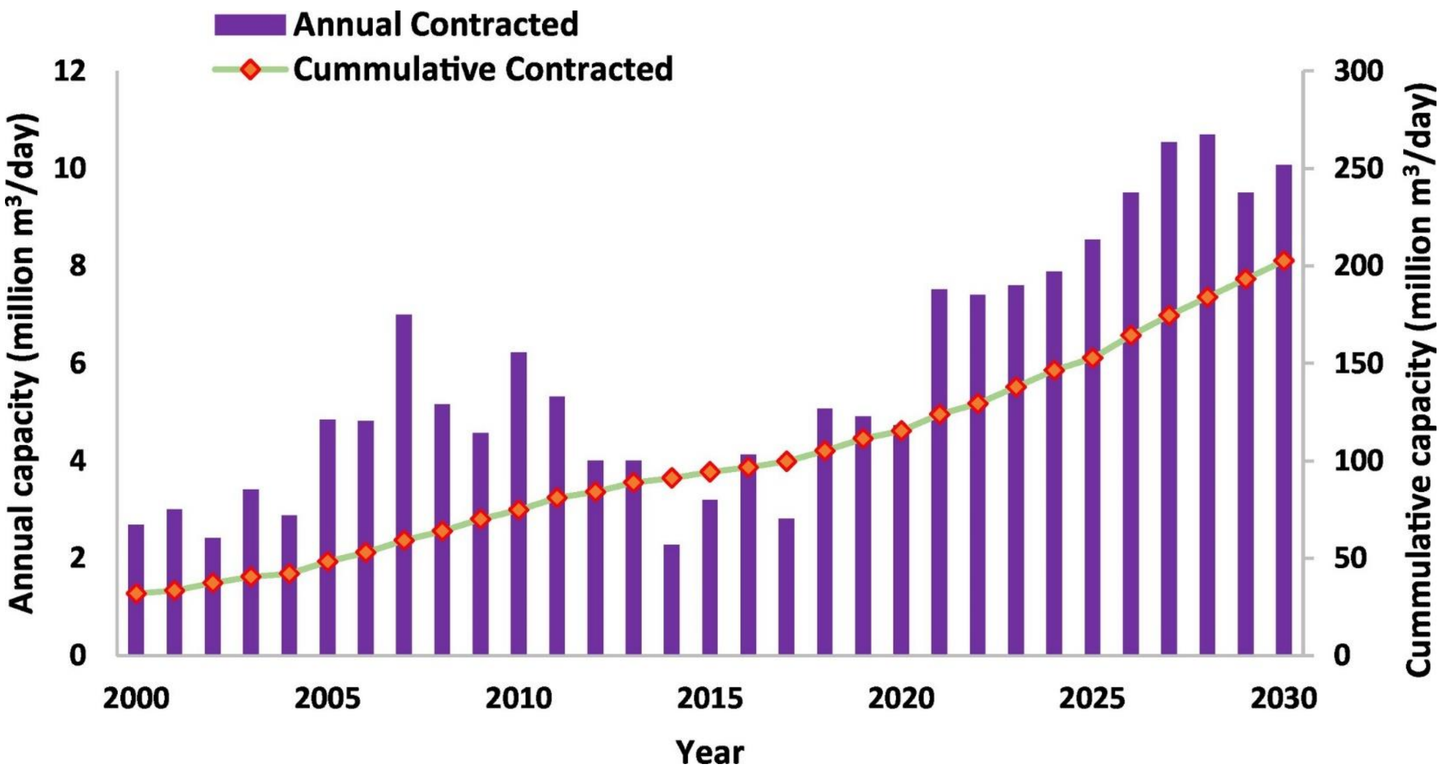
- ✓ Climate change
- ✓ Environmental pollution
- ✓ Population growth

Higher demand on sustainable water resource management

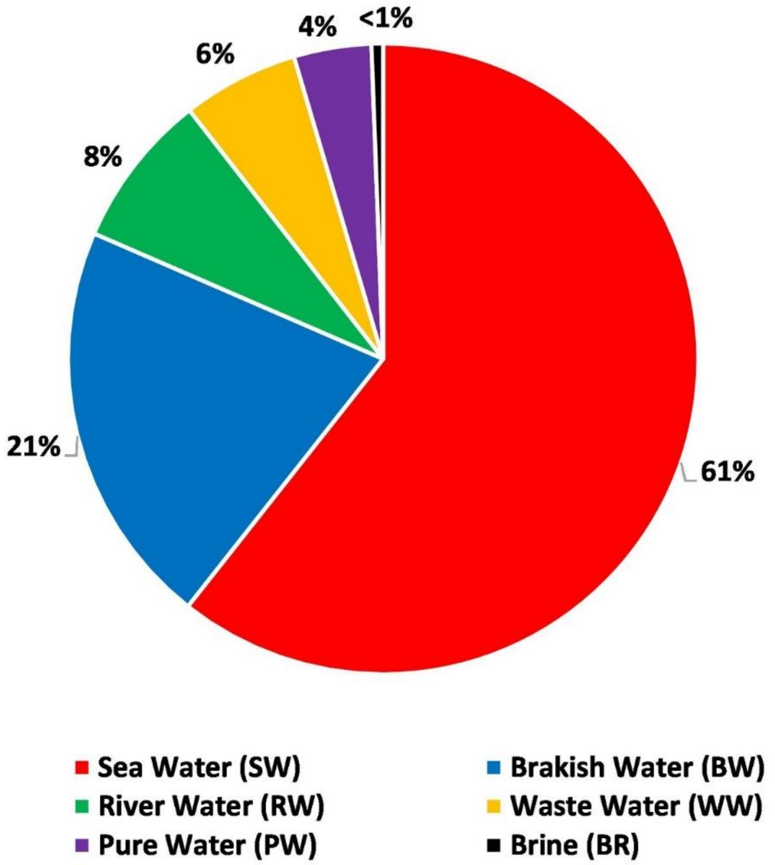
(Homaeigohar 2020)

Introduction

Desalination



Desalination capacity forecast plot over 30 years

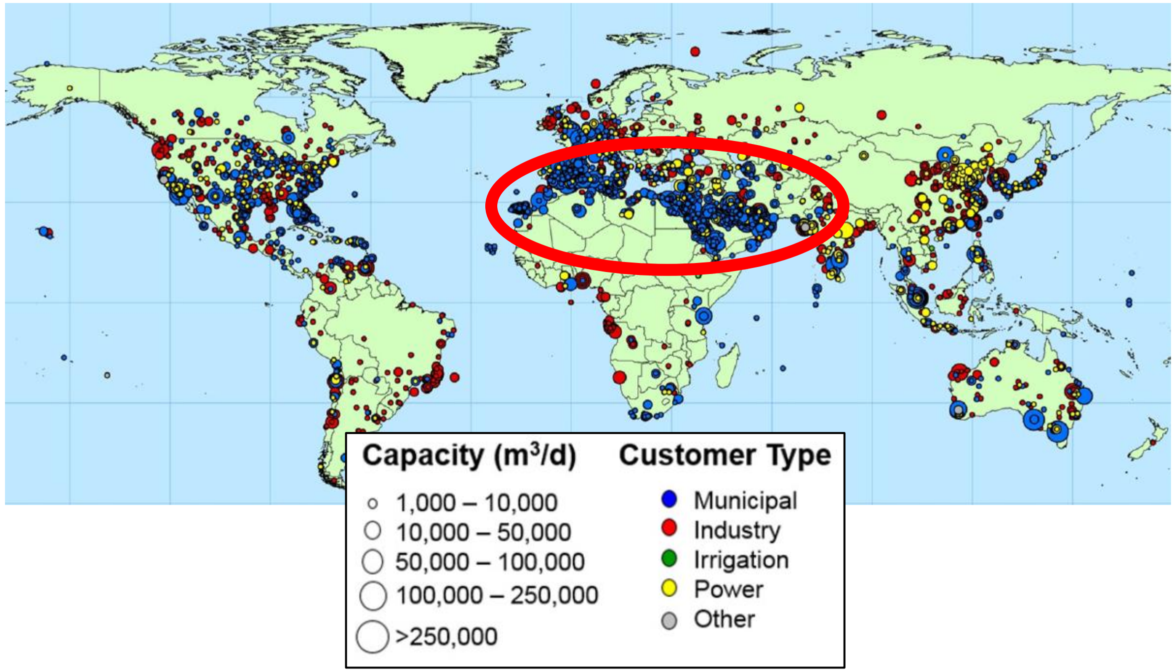


(Ihsanullah et al. 2021)

Introduction

Desalination

	Number of desalination plants	Desalination capacity	
	(-)	(million m^3/day)	(%)
Global Total	**15,906**	**95.37**	**100**
Middle East and North Africa	**4,826**	**45.32**	**47.5**
East Asia and Pacific	3,505	17.52	18.4
North America	2,341	11.34	11.9
Western Europe	2,337	8.75	9.2
Latin America and Caribbean	1,373	5.46	5.7
Southern Asia	655	2.94	3.1
Eastern Europe and Central Asia	566	2.26	2.4
Sub-Saharan Africa	303	1.78	1.9



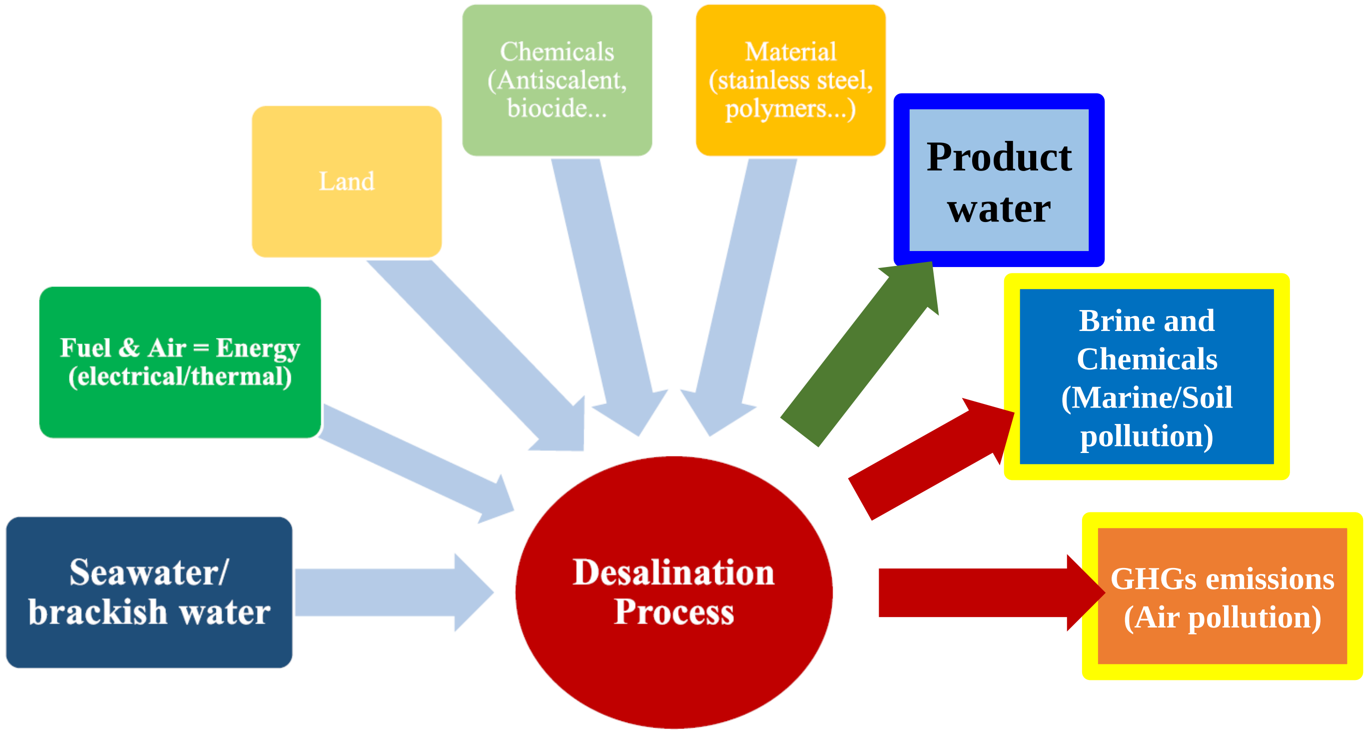
Global distribution of operational desalination facilities and capacities (>1000 m3/day) by sector user of produced water

(Jones et al. 2019)

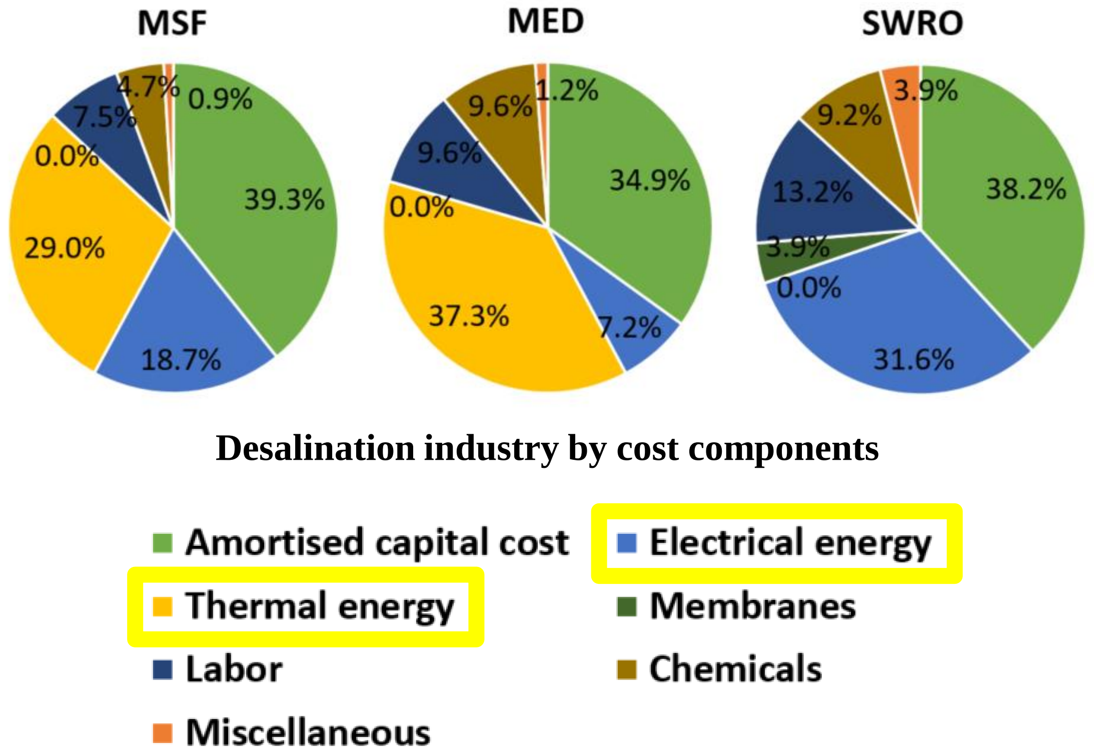
Introduction

Sustainability of desalination: water-energy nexus

✓ Environmental sustainability



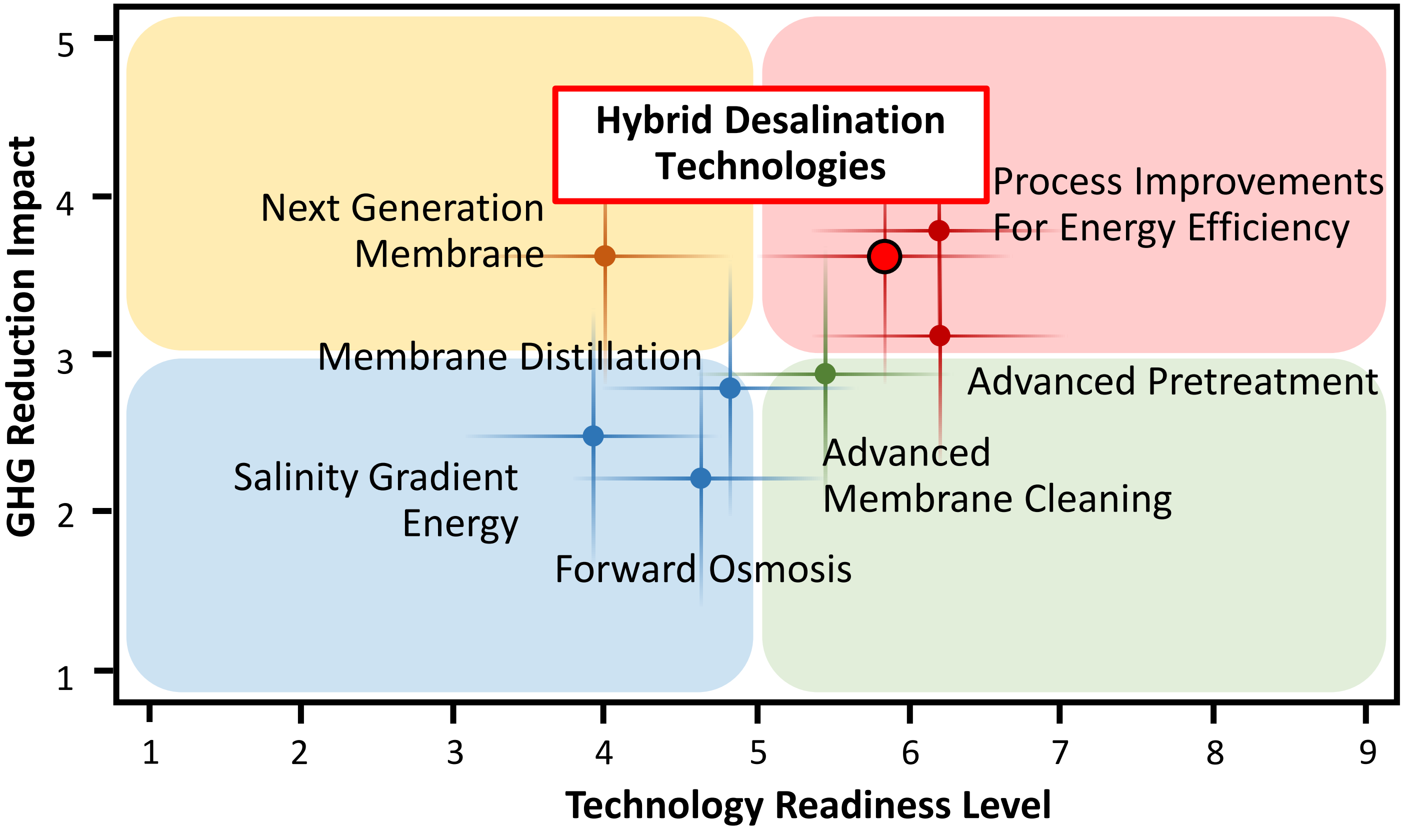
✓ Economic sustainability



Desalination industry by cost components

(Elsaid et al. 2020, Gude 2016)

Hybrid Desalination

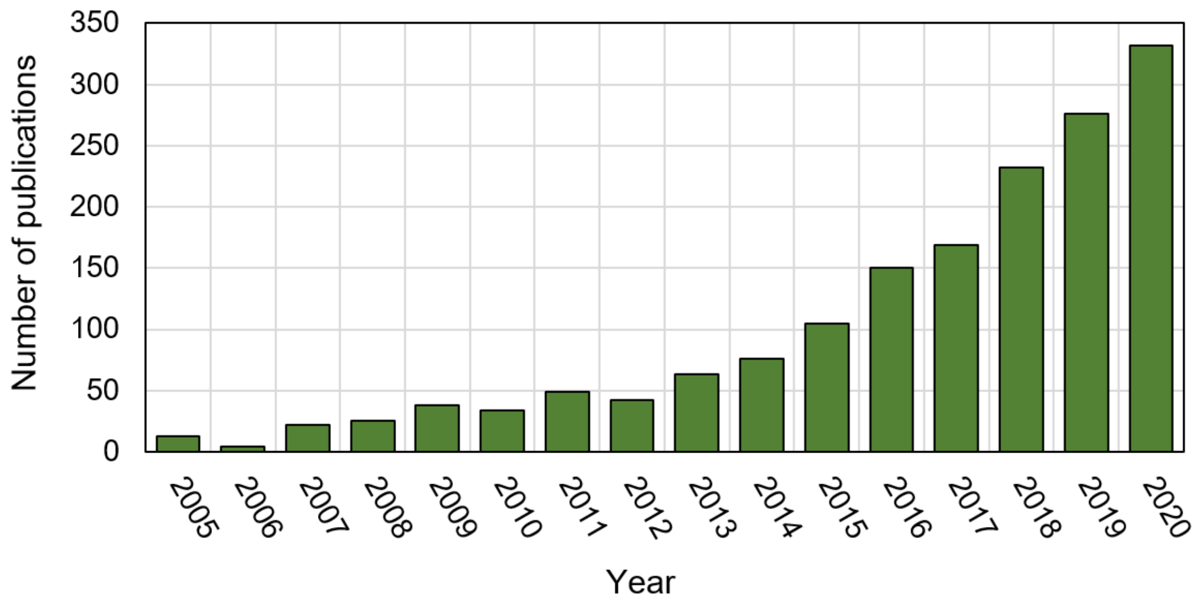


✓ **Maximizing advantages** ✓ **Minimizing drawbacks & footprint**

(Lienhard et al. 2016)

Hybrid Desalination

✓ **Research**



Number of publications on hybrid desalination

✓ **Implementation**

MSF-RO

Capacity
: 1,036,000 m^3/day

(MSF) 727,000 m^3/day
(RO) 309,000 m^3/day

FO-RO *pilot plant

Capacity: 21.8 m^3/day

(FO) 1.21 m^3/day

(Lienhard et al. 2016, Al-Zuhairi et al. 2015)

FO-MD Hybrid Desalination

Collaboration project – Saudi Aramco & KAUST

Objectives

To investigate the feasibility and performance of a **novel integrated membrane system** for the **simultaneous treatment of produced water** in different impaired water quality

Produced water

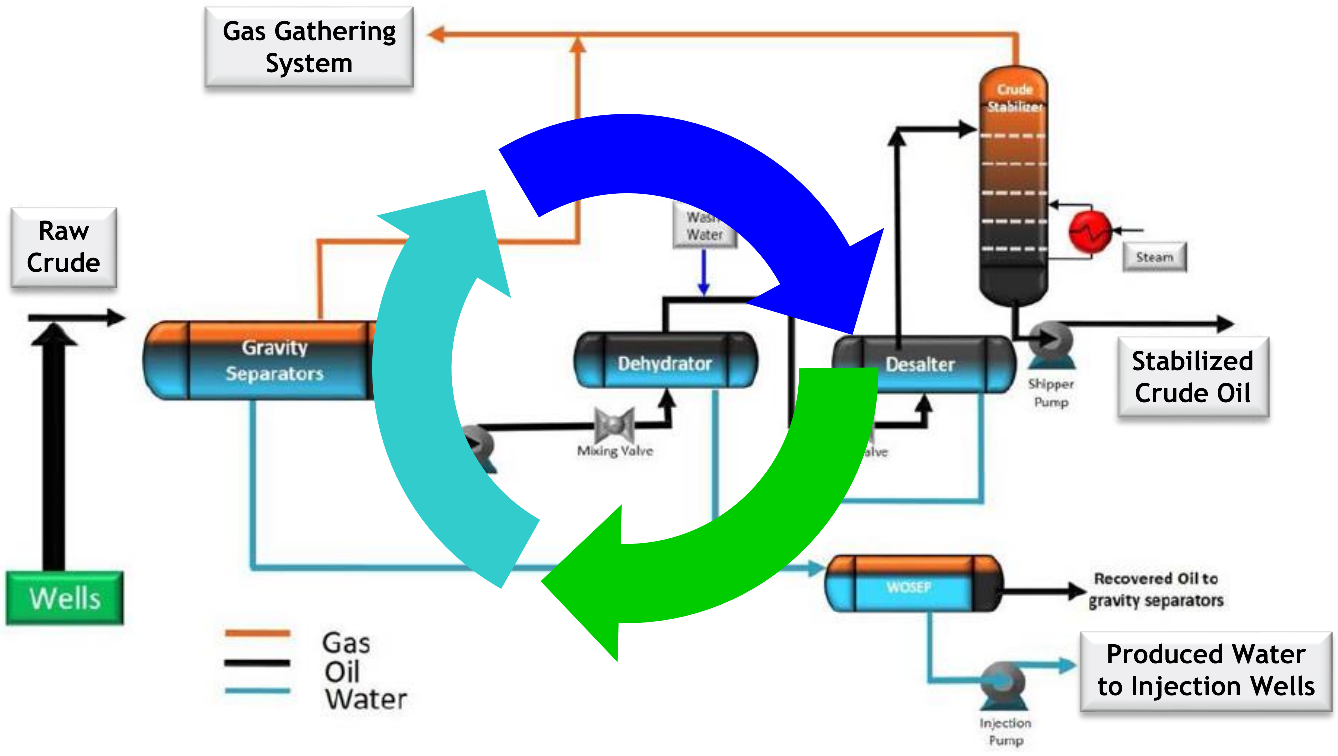
- ✓ Formation and injected water containing production chemicals
- ✓ **Largest volume waste stream** in oil and gas production
- ✓ **Complex mixture** of dissolved and particulate organic and inorganic chemicals in water
- ✓ **Wide ranges** from essentially freshwater to concentrated saline brine

	Range of Conc. (mg/L)
Total Dissolved solids	100 - 400,000
Total Suspended Solids	1.2 - 1,000
Total Organic carbon	0.1 - 11,000
Total Oil and Grease	2 - 560

(Lee & Neff 2011, Al-Ghouti et al. 2019)

FO-MD Hybrid Desalination

Produced water



Typical Saudi Aramco GOSP

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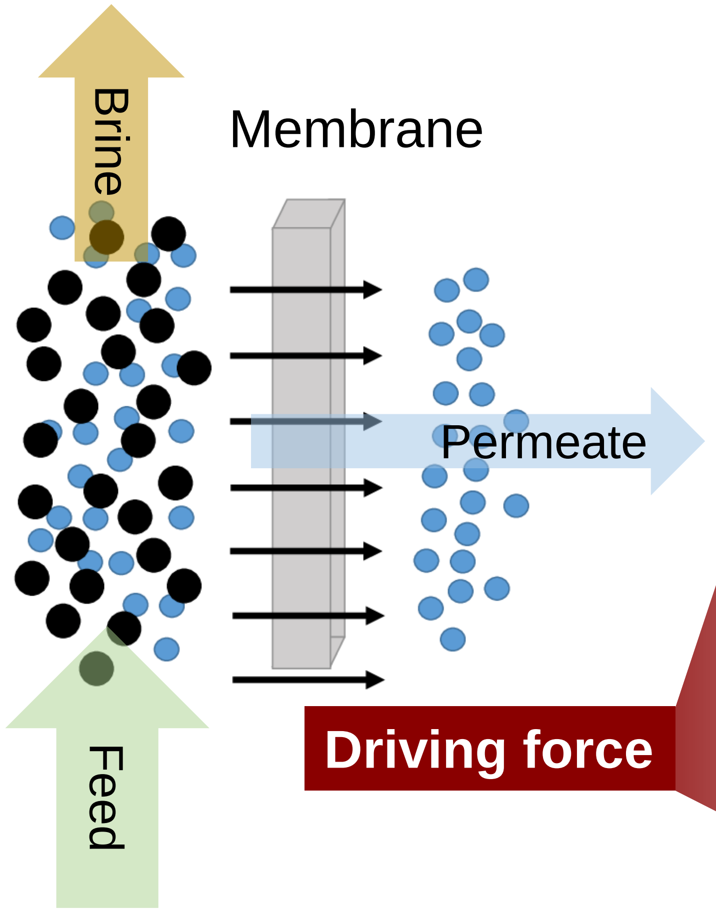
Sustainable water cycle in Oil Processing facility

- ✓ Minimizing water loss
- ✓ Maximizing water quality

(Ahmed et al. 2020, Lee & Neff 2011, Al-Ghouti et al. 2019)

FO-MD Hybrid Desalination

Membrane processes



Process	Driving force
Dialysis	Concentration (ΔC)
	Activity (Δa)
Electrodialysis	Electrical potential ($\Delta \varphi$)
Forward osmosis	**Osmotic Pressure ($\Delta \pi$)**
Gas separation	Hydrostatic pressure (Δp)
	Fugacity (Δf_i)
Membrane distillation	**Vapor pressure (Δp)**
Microfiltration	Hydrostatic pressure (Δp)
Pervaporation	Partial pressure (Δp_i)
	Fugacity (Δf_i)
Reverse osmosis	Hydrostatic pressure (Δp)
	Chemical potential ($\Delta \mu_i$)
Ultrafiltration	Hydrostatic pressure (Δp)

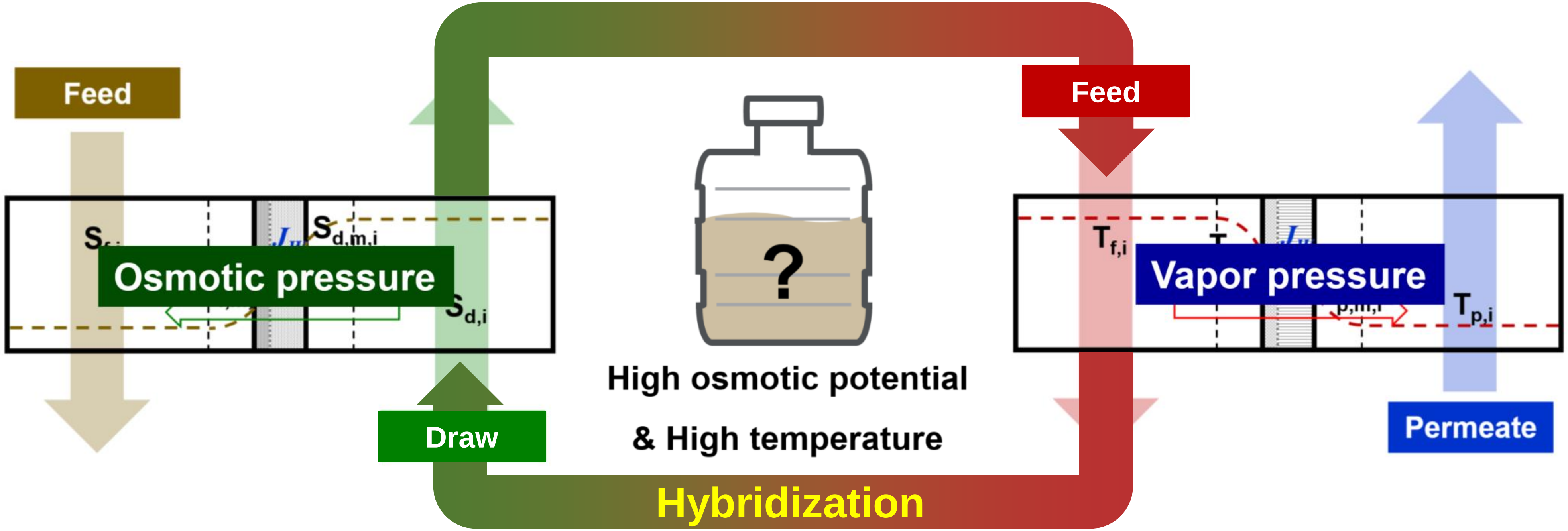
(Wang 2016, Li et al. 2015)

FO-MD Hybrid Desalination

Forward osmosis & membrane distillation

✓ **Forward osmosis (FO)**

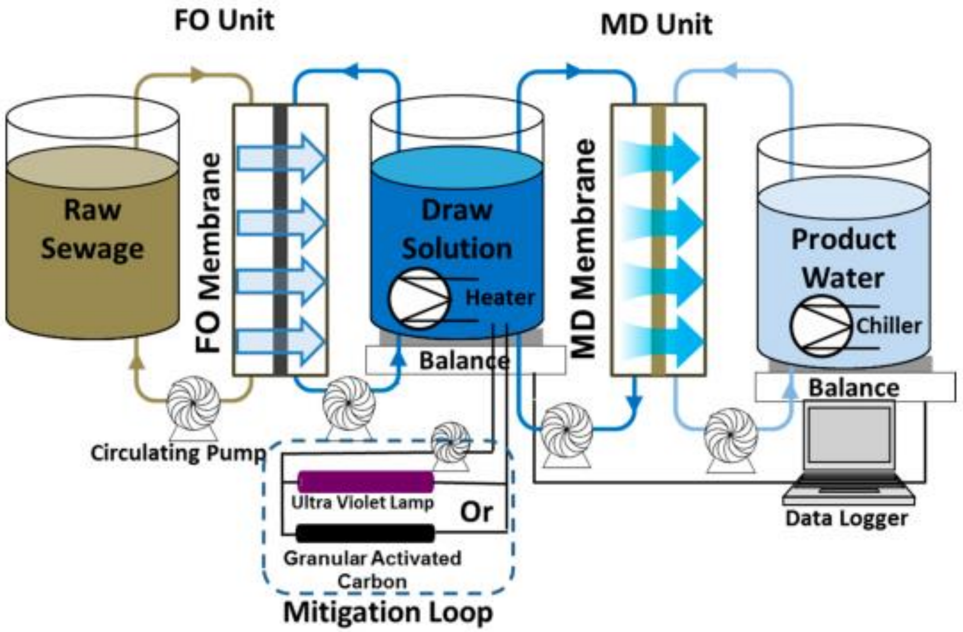
✓ **Membrane distillation (MD)**

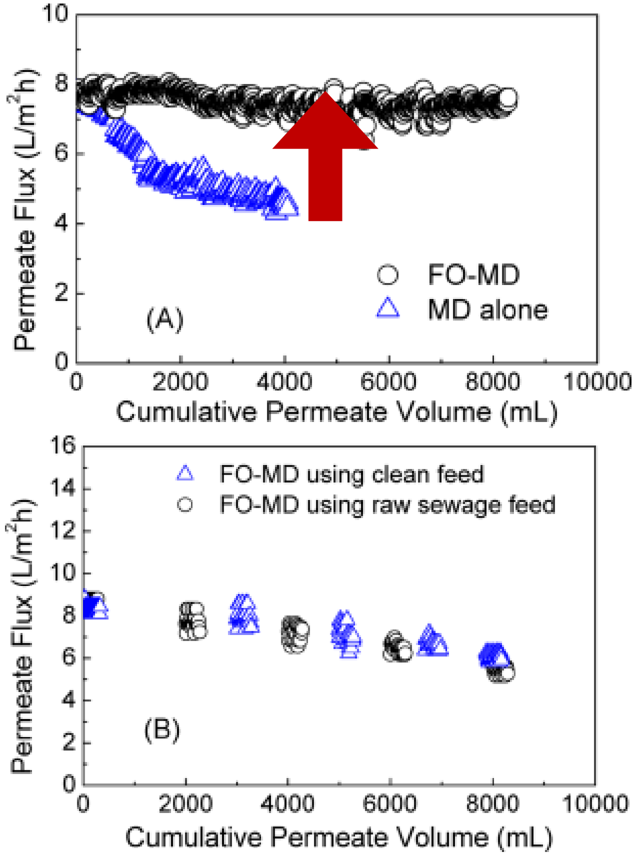


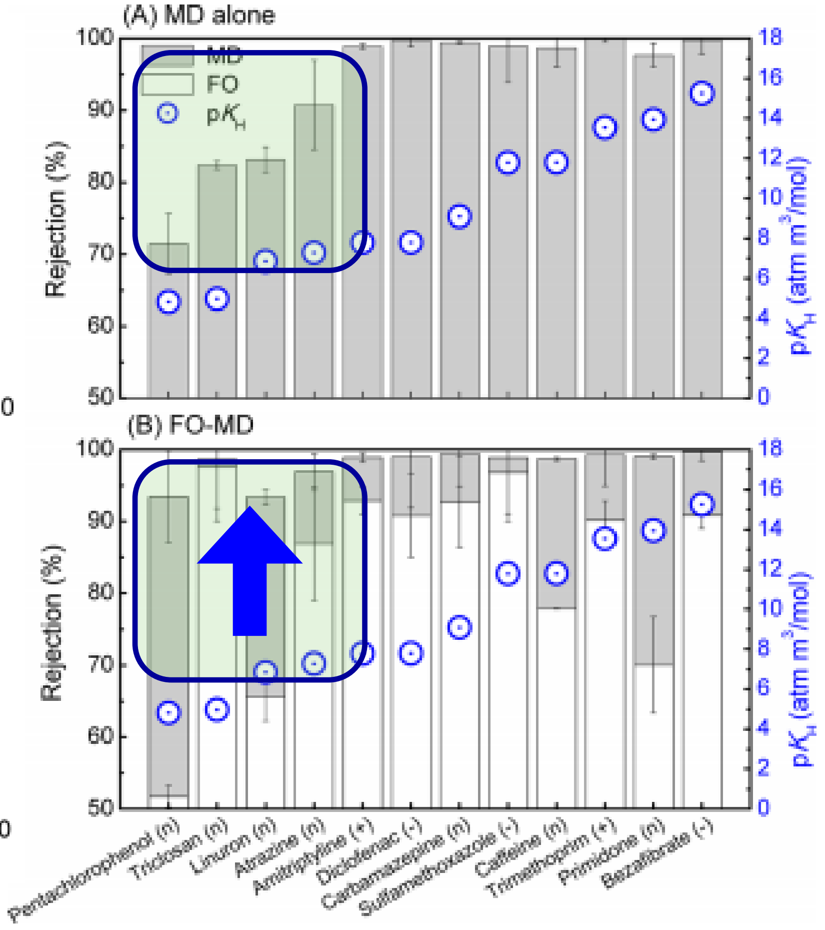
Maximizing energy potential

FO-MD Hybrid Desalination

Forward osmosis & membrane distillation







Stable operation

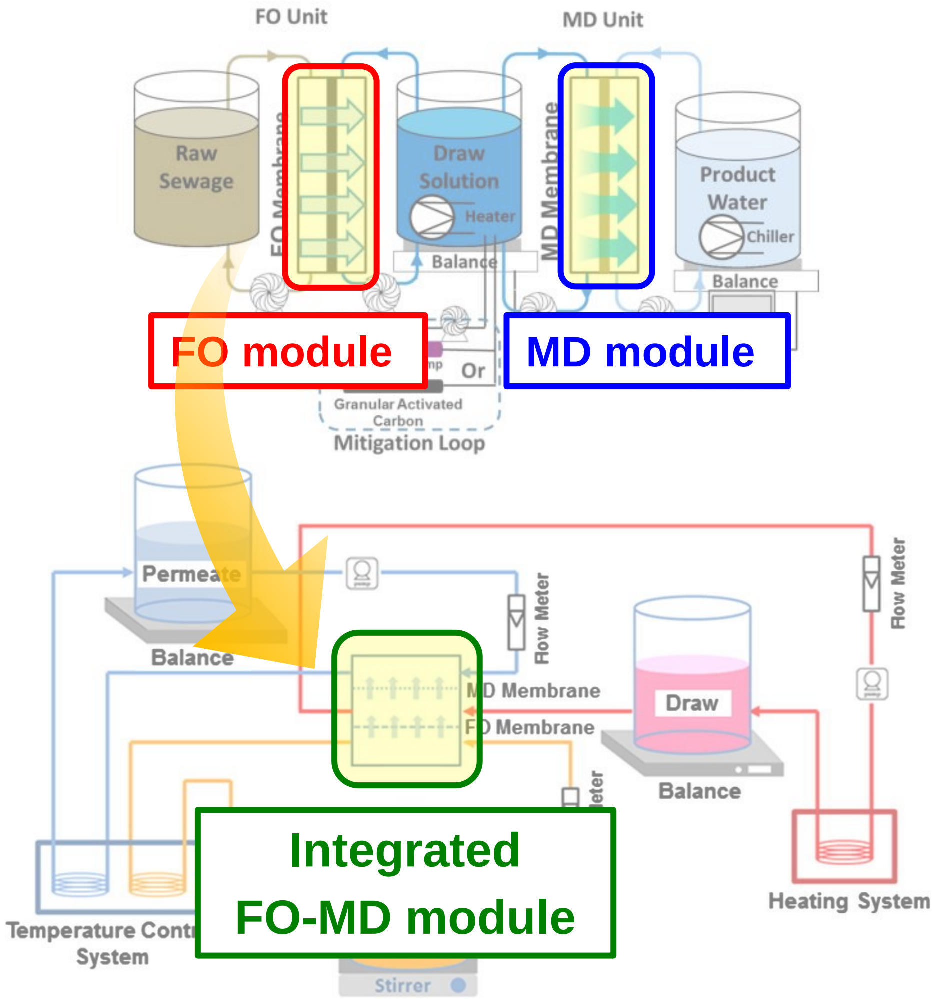
with higher permeate quality

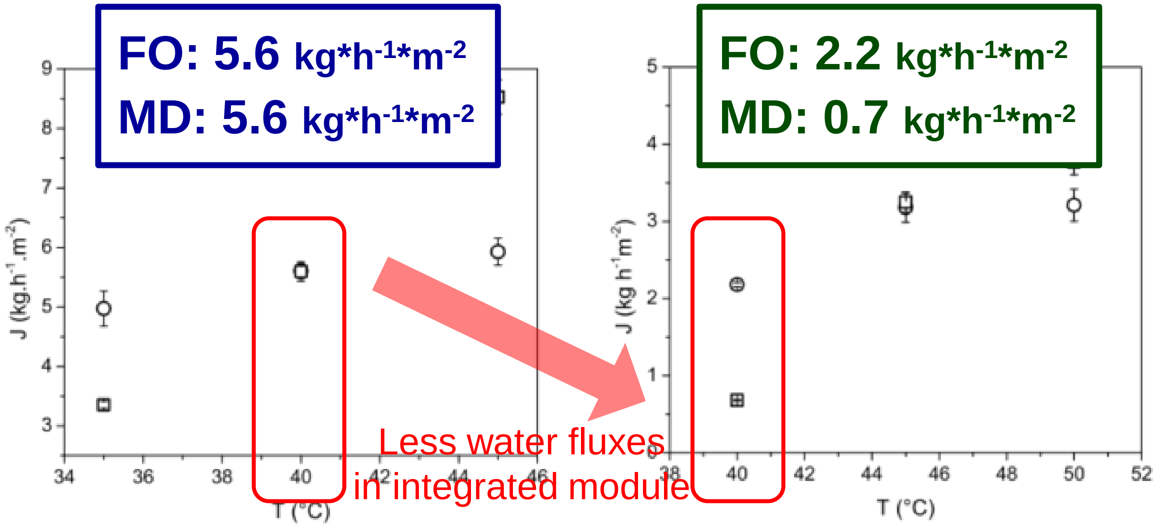
in FO-MD hybrid system

(Xie et al. 2013)

FO-MD Hybrid Desalination

Forward osmosis & membrane distillation





Separate FO & MD hybrid operation

Integrated FO-MD hybrid operation

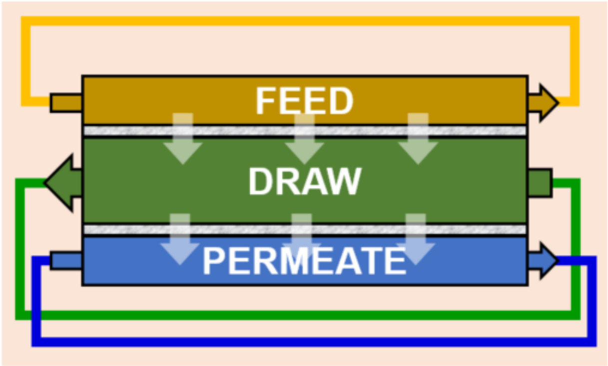
Importance of module design in hybrid system

(Xie et al. 2013, Husnain et al. 2015, Ricci et al. 2019)

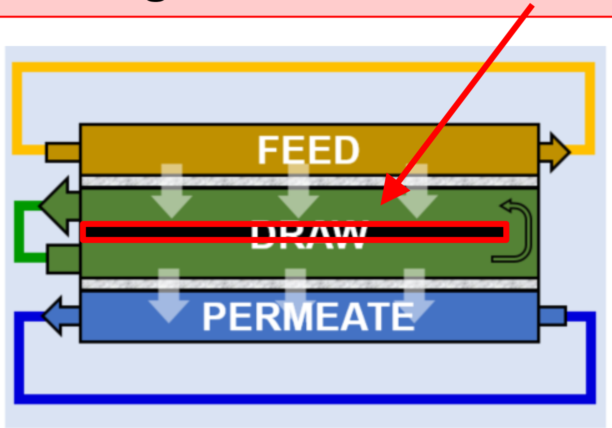
FO-MD Hybrid Desalination

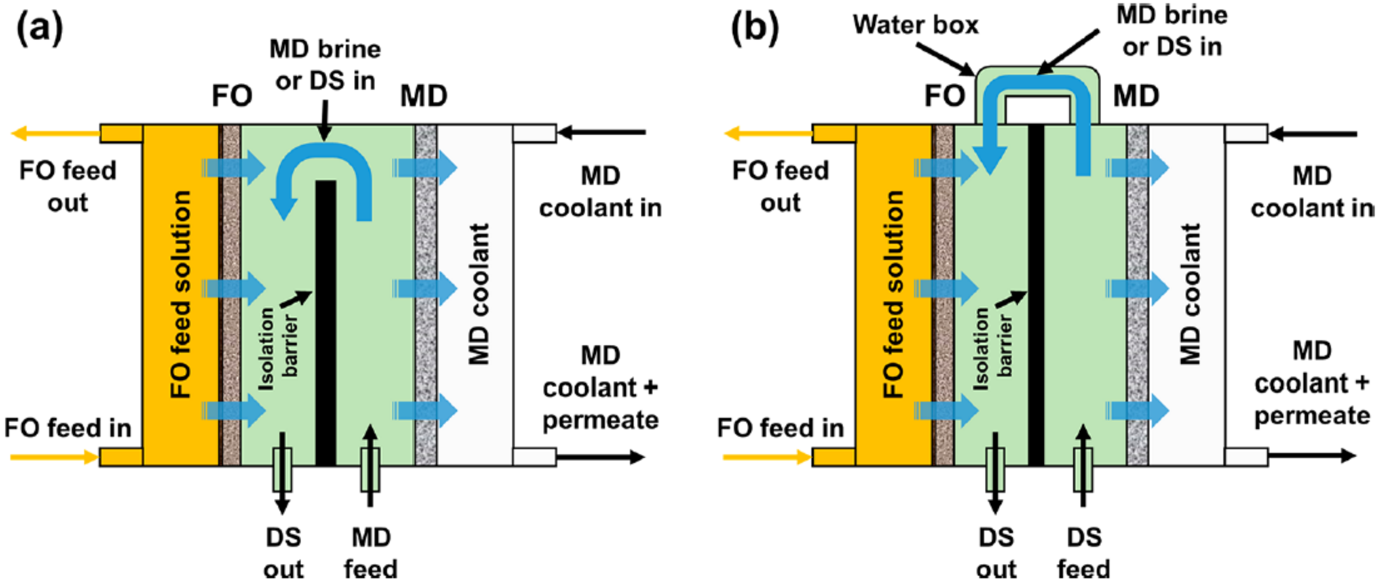
Osmotically and thermally isolated FO–MD integrated module

Conventional FO-MD module design



Novel design with isolation barrier





(a) internal and (b) external using a water-box

- <u>Innovation</u> in hybrid membrane module design

  a) maximizing energy potential   b) improving system sustainability

(Kim et al. 2019)

FO-MD Hybrid Desalination

Collaboration project – Saudi Aramco & KAUST

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Objectives

To investigate the feasibility and performance of a **novel integrated membrane system** for the **simultaneous treatment of produced water** in different impaired water quality

Project phases

1st
- Feed water selection
- Characterization and lab-scale experiments using Synthetic feeds

2nd
- Lab-scale experiments using synthetic/real feeds

3rd
- Feasibility and performance evaluation of a large-scale, hybrid FO-MD Module.

4th
- Pretreatment requirement
- Estimation of energy consumption analysis

FO-MD Hybrid Desalination

1st

- Feed water selection
- Characterization and lab-scale experiments using synthetic feeds

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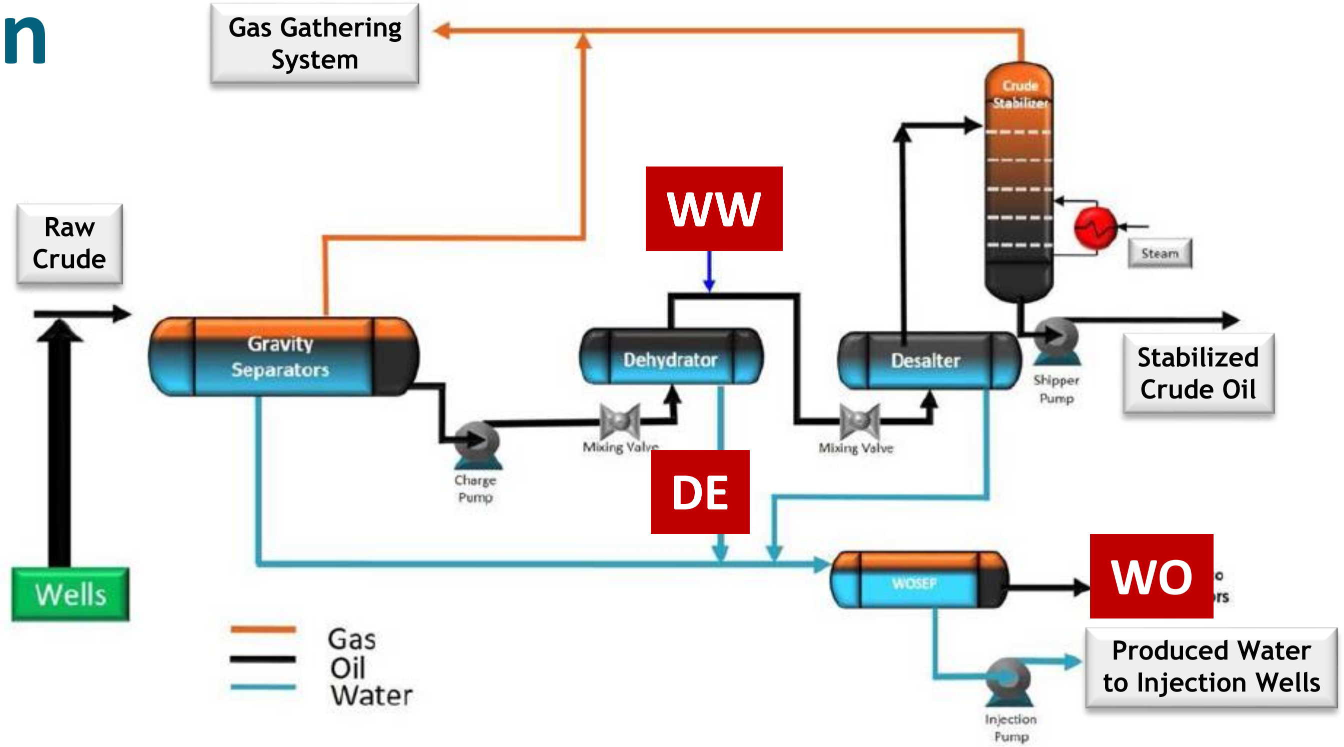


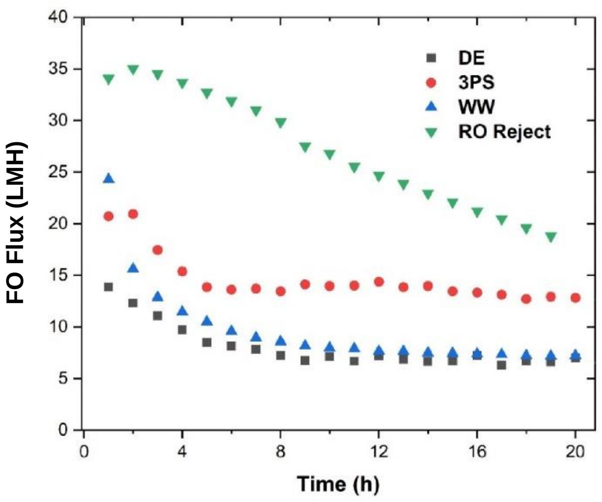
Stream Name	Stream abbreviation	TDS (mg/L)
Desalter Effluent	DE	6,943
Water oil separator (WOSEP) Outlet	WO	96,856
Wash Water	WW	6,083
Three Phase Separator	3PS	4,853
Reverse Osmosis (RO) Reject	RO Reject	6,020

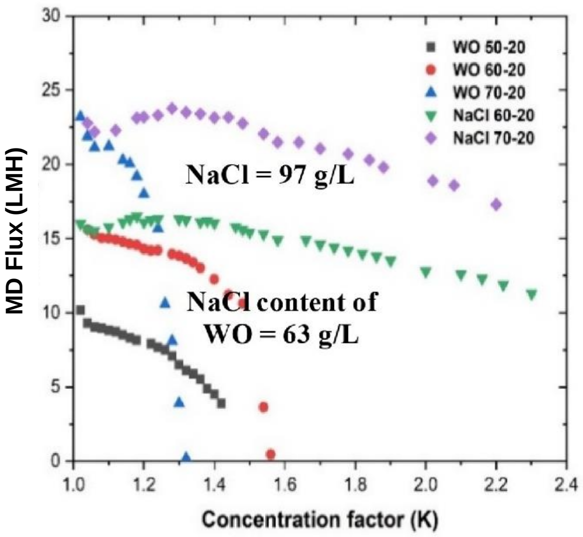
(Nawaz et al. 2021)

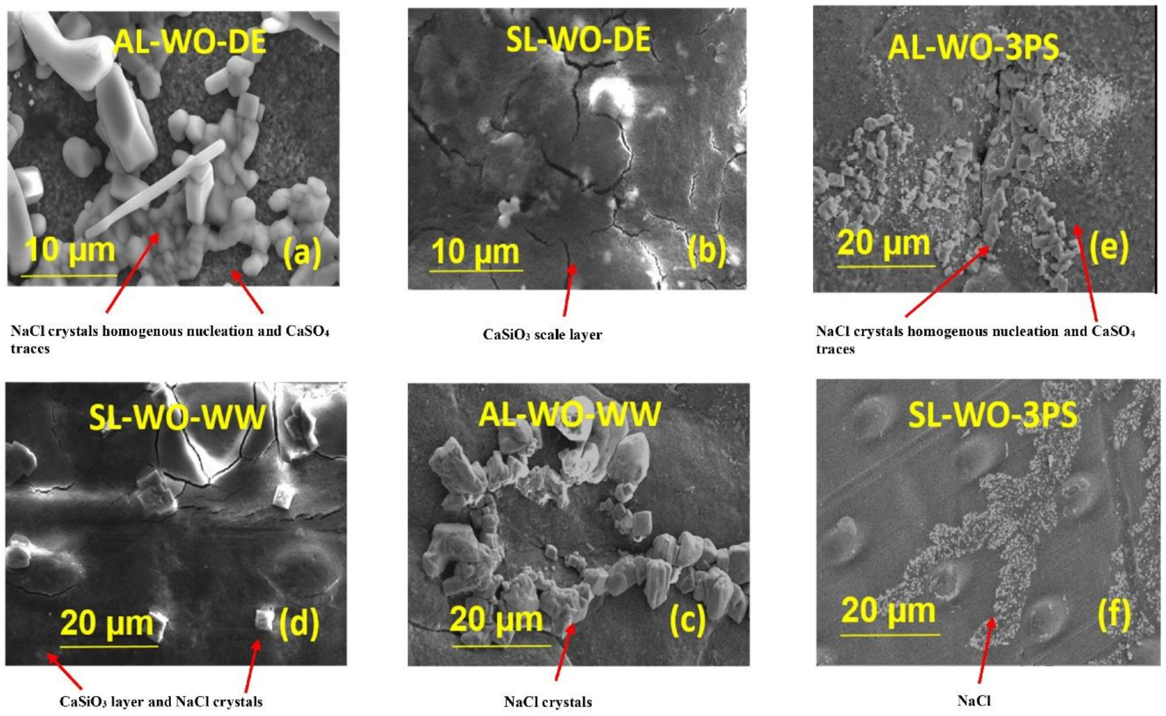
FO-MD Hybrid Desalination

1st

- Feed water selection
- Characterization and lab-scale experiments using synthetic feeds







FO membrane fouling characterization

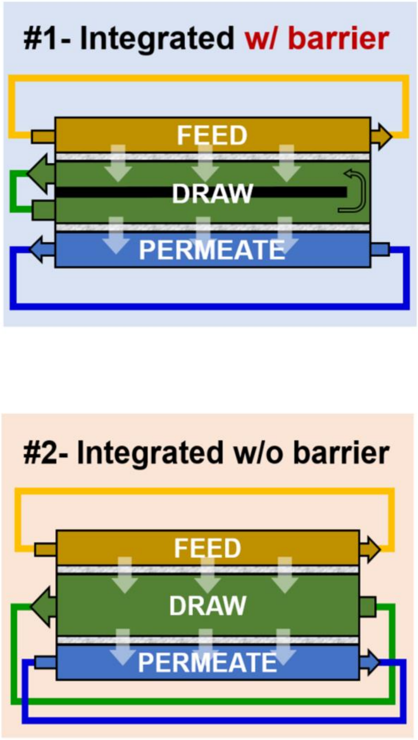
➢ **Selection of feed / draw water sources and operating conditions**

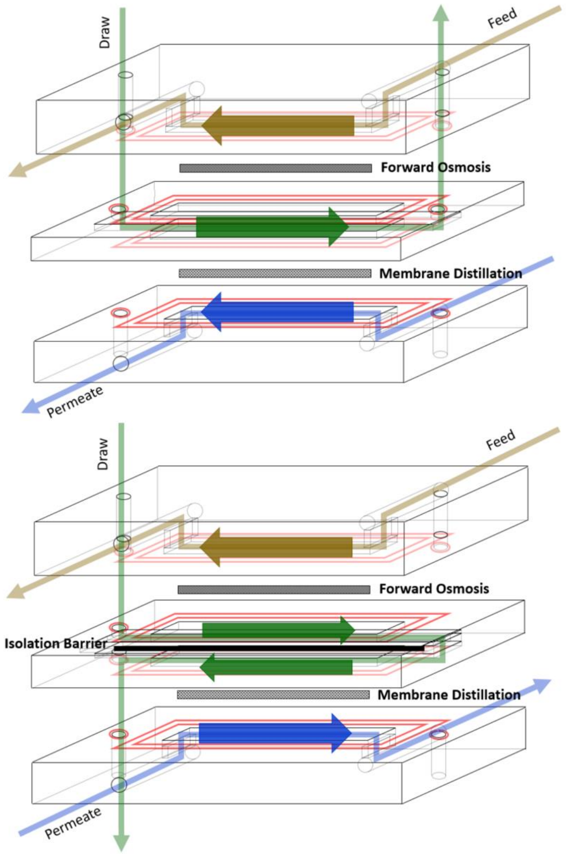
(Nawaz *et al.* 2021)

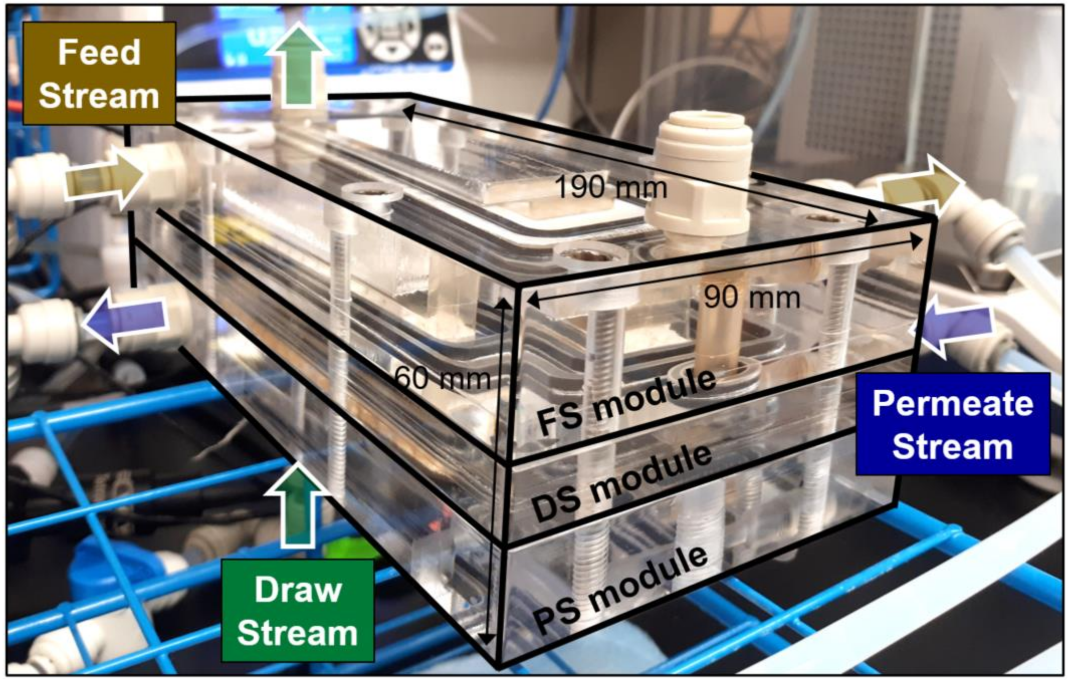
FO-MD Hybrid Desalination

2nd

- Lab-scale experiments using synthetic/real feeds







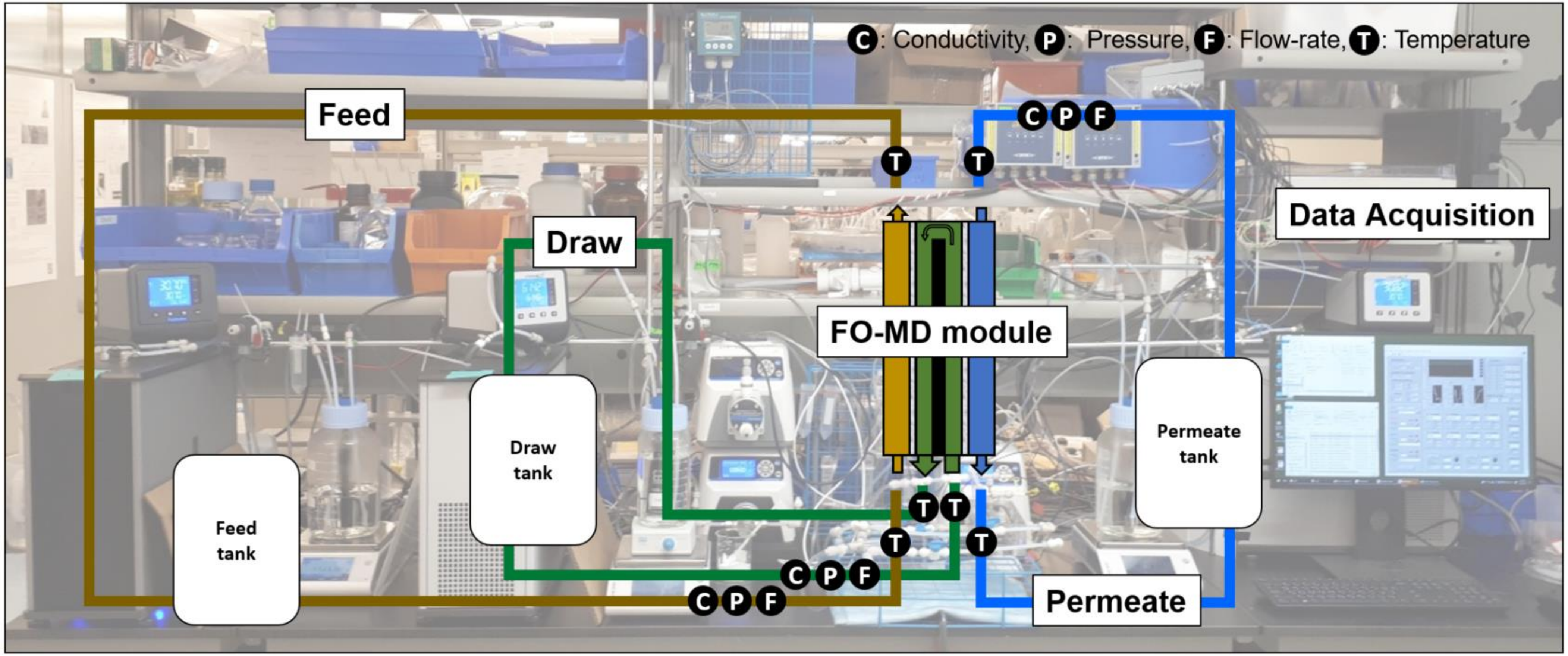
➢ **Innovation in hybrid membrane module design**

(Son *et al.* 2021)

FO-MD Hybrid Desalination

2nd

- Lab-scale experiments using synthetic/real feeds



(Son *et al.* 2021)

FO-MD Hybrid Desalination

2nd

- Lab-scale experiments using synthetic/real feeds

Comparative analysis between conventional and novel design in

1) different hydrodynamic conditions

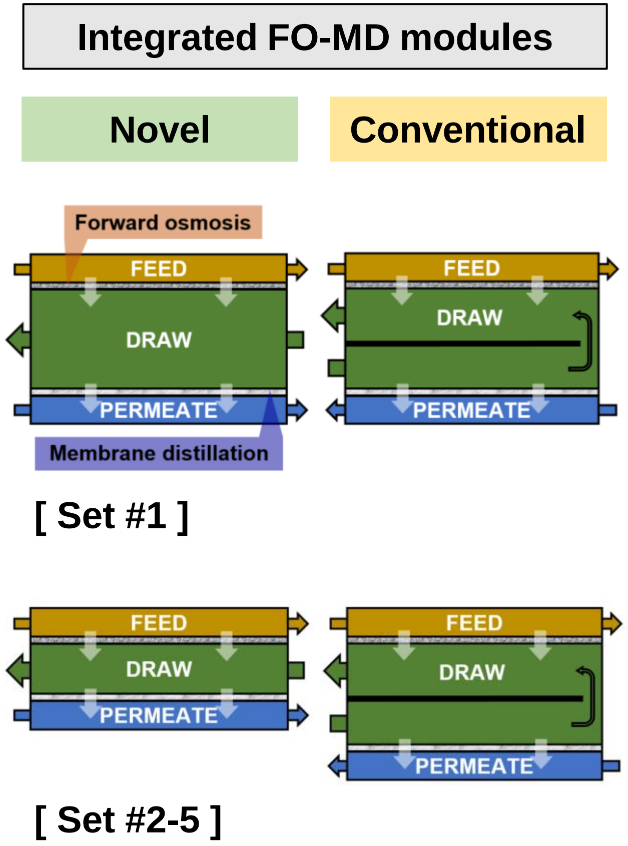
- in the same module thickness (Set #1)

- In the same flow-channel thickness (Set #2)

2) different feed solution concentrations (Set #3)

3) different draw solution temperatures (Set #4)

4) different draw solution concentrations (Set #5)



(Son et al. 2021)

FO-MD Hybrid Desalination

2nd

- Lab-scale experiments using synthetic/real feeds

Concentration and temperature polarization of FO-MD hybrid system

Polarization Coefficient WITH Barrier

	CPC_{FO}	TPC_{MD}	CPC_{MD}
Avg.	0.215 ± 0.03	0.657 ± 0.02	1.146 ± 0.00

Polarization Coefficient WITHOUT Barrier

	CPC_{FO}	TPC_{MD}	CPC_{MD}
Avg.	0.209 ± 0.02	0.567 ± 0.01	1.117 ± 0.00

% Increase of Polarization Coefficients with Barrier

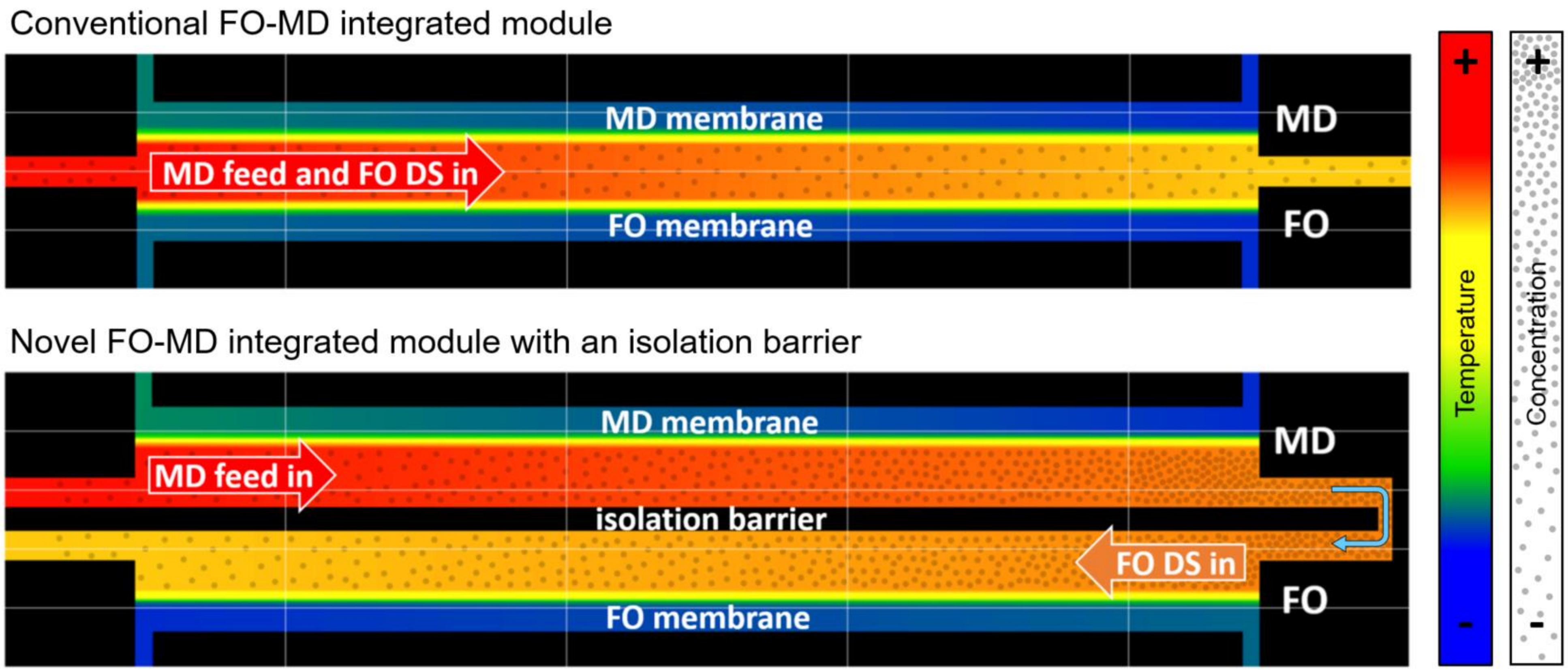
CPC_{FO}	TPC_{MD}	CPC_{MD}
1.9%	17.4%	2.6%

(Son et al. 2021)

FO-MD Hybrid Desalination

2nd

- Lab-scale experiments using synthetic/real feeds



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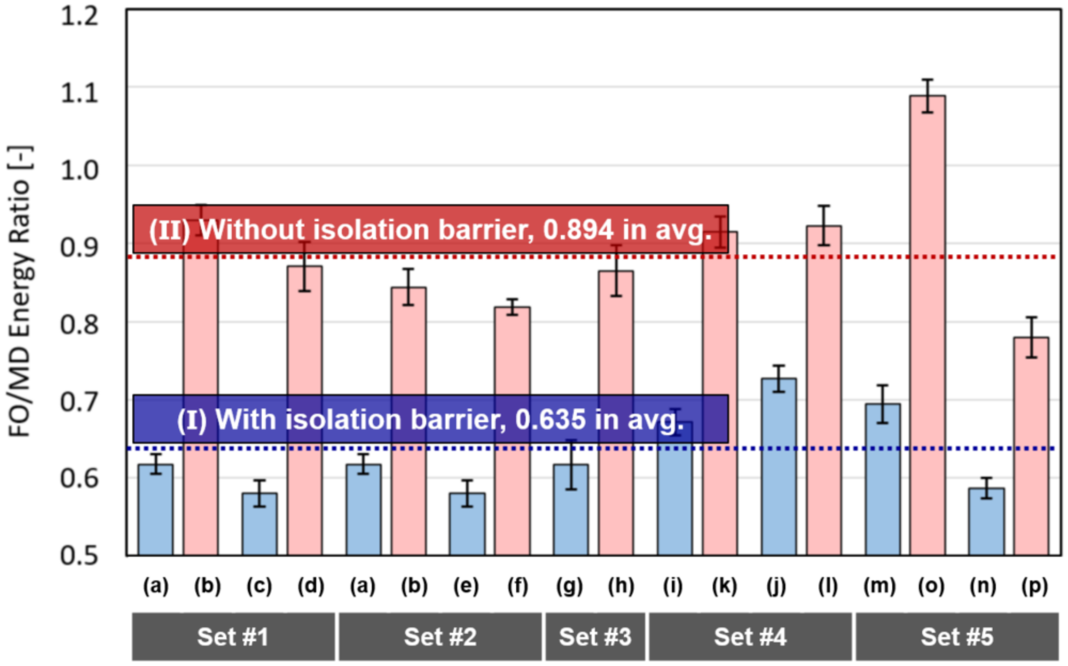
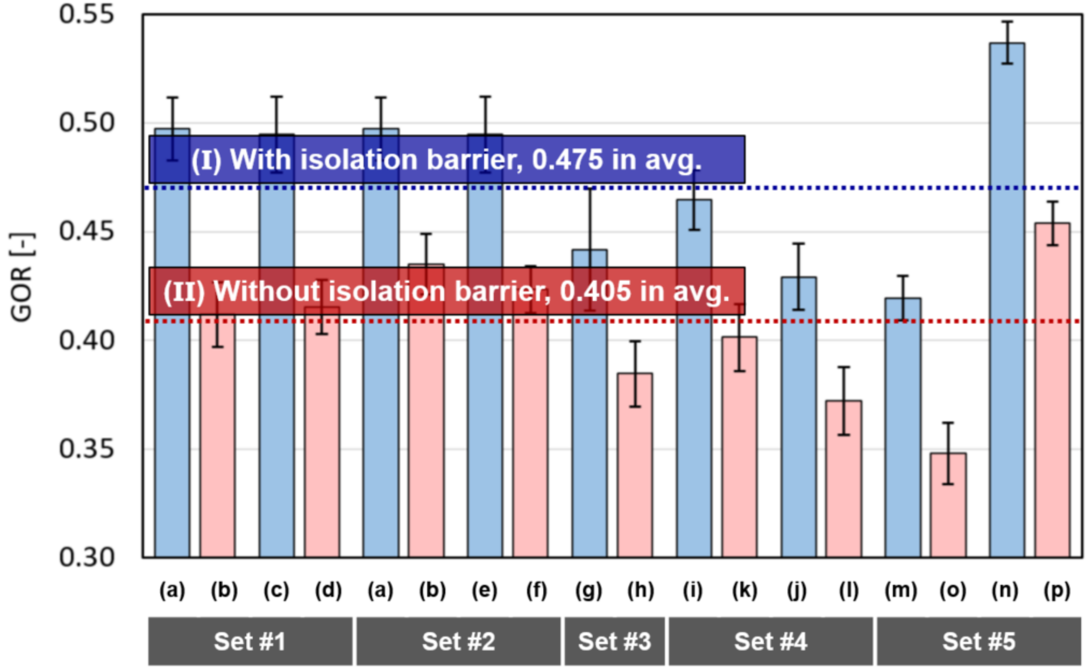




✓ Lower FO/MD energy ratio indicates targeted energy usages in MD >> Thermal isolation

✓ Enhanced GOR considering total energy used

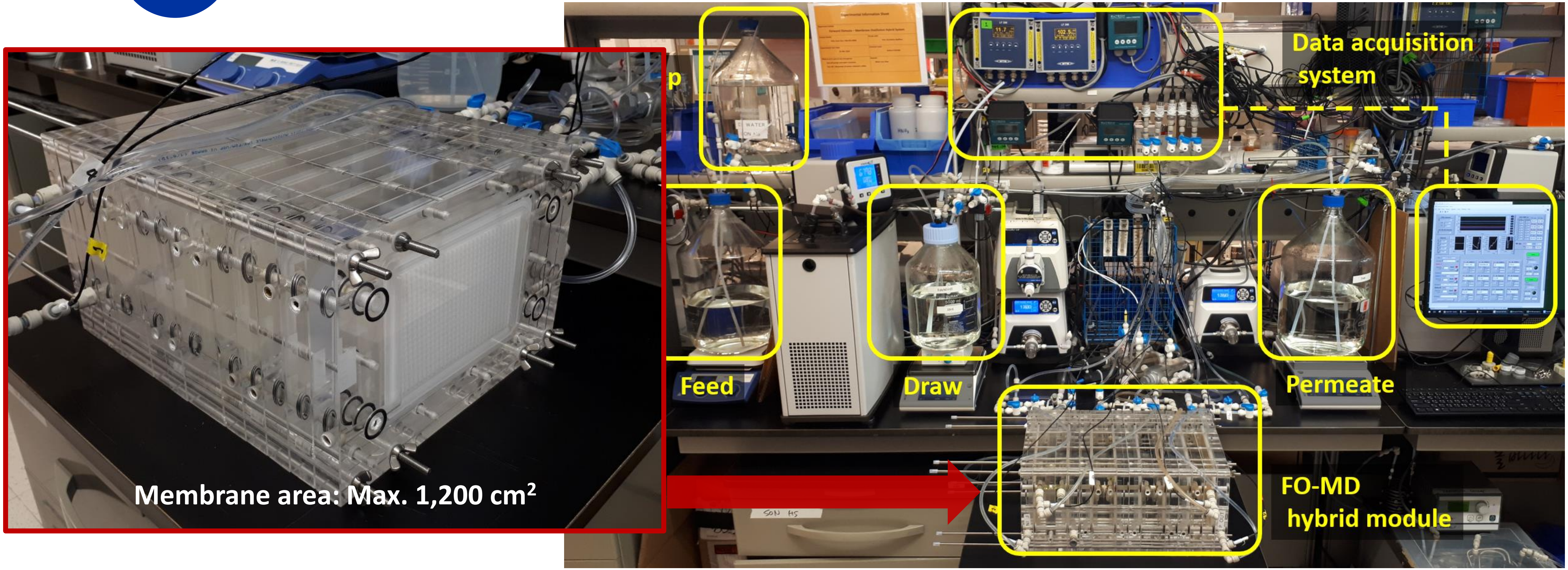
>> In average, from 0.475 to 0.405 & maximum, from 0.497 to 0.412

(Son *et al.* 2021)

FO-MD Hybrid Desalination

3rd

- Feasibility and performance evaluation of a large-scale, hybrid FO-MD Module



FO-MD Hybrid Desalination

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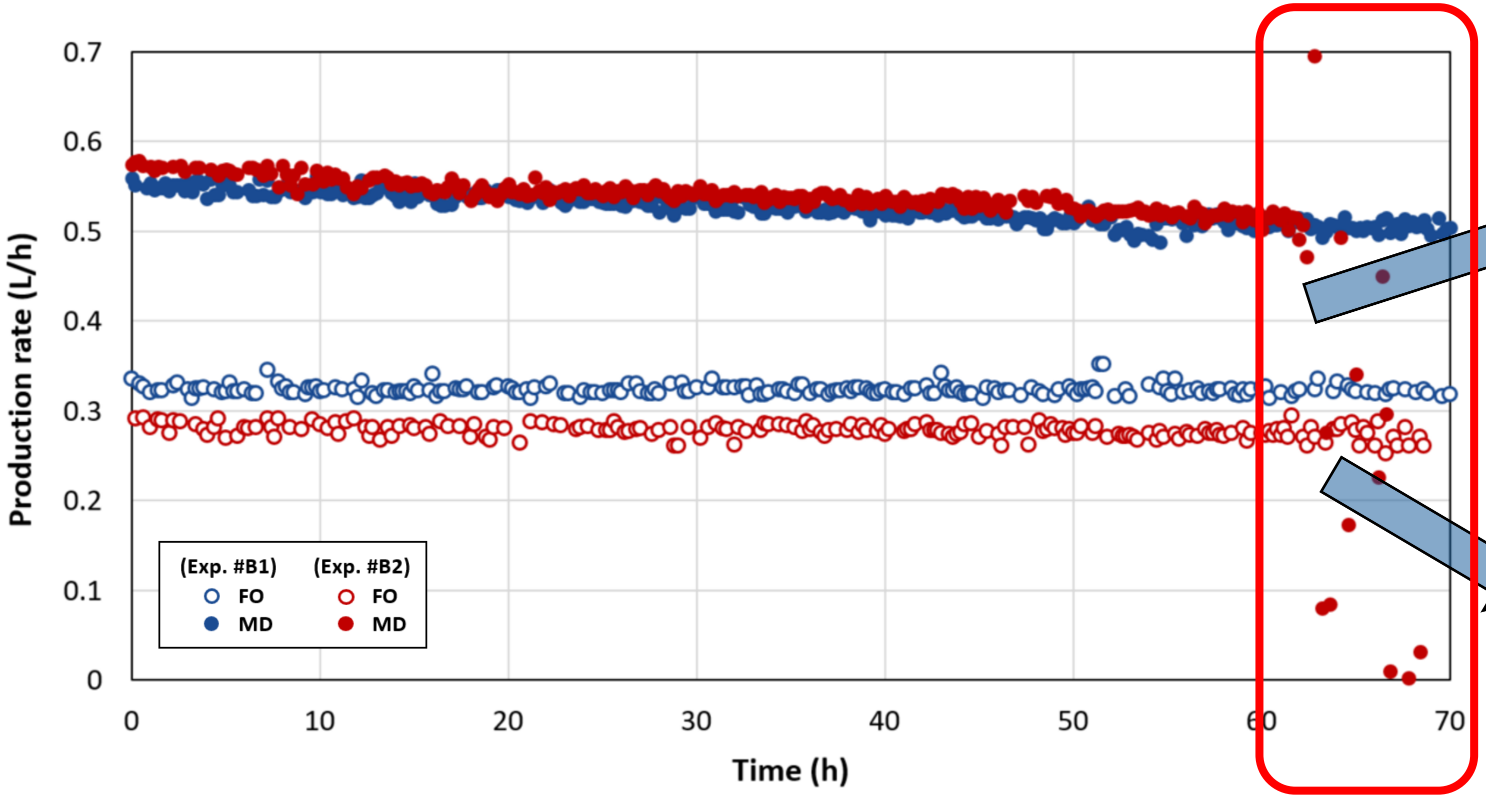

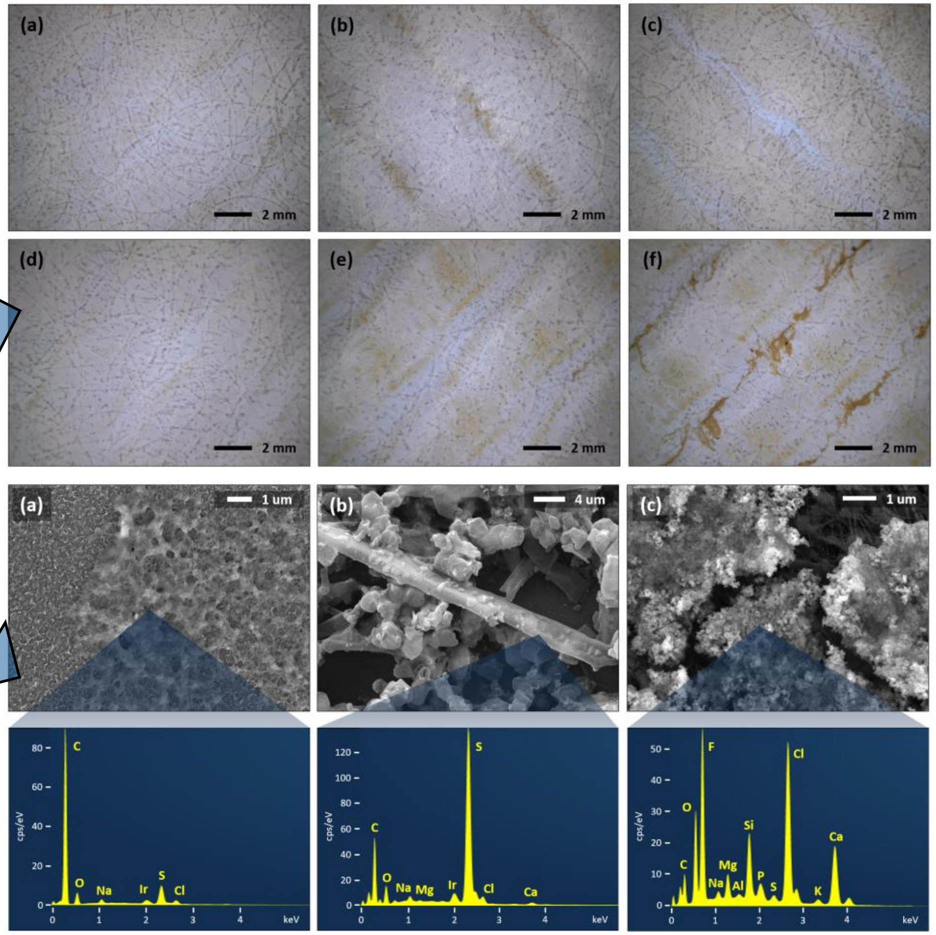

FO-MD Hybrid Desalination

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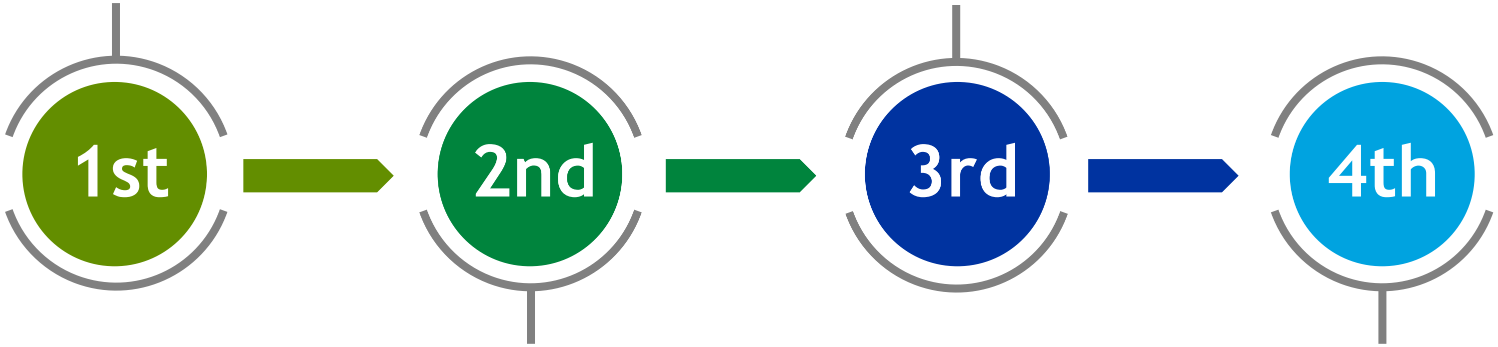

- Lab-scale experiments using synthetic/real feeds

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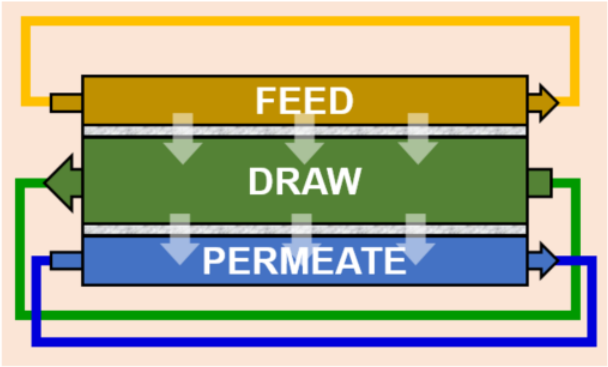
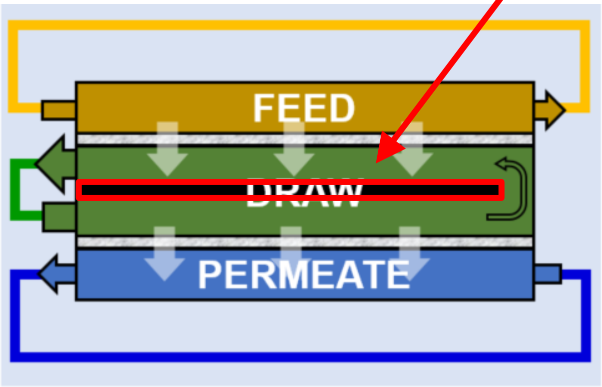
FO-MD Hybrid Desalination

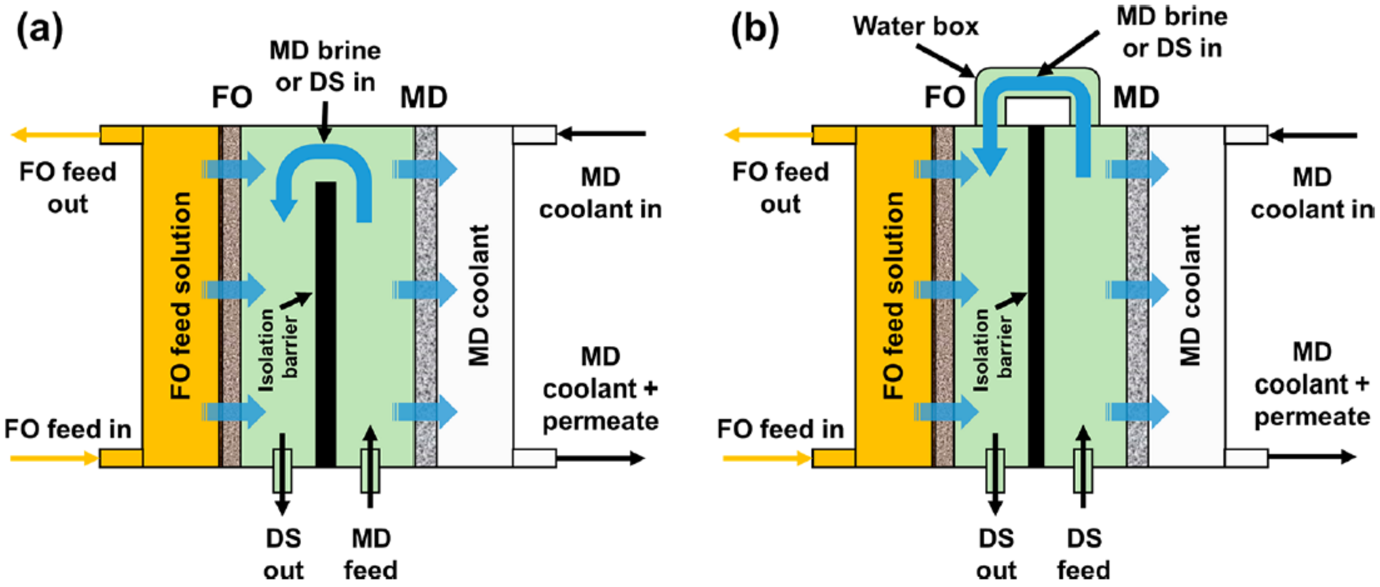
Osmotically and thermally isolated FO–MD integrated module

Conventional FO-MD module design



Novel design with isolation barrier





(a) internal and (b) external using a water-box

- **<u>Innovation</u> in hybrid membrane module design**

  a) maximizing energy potential   b) improving system sustainability

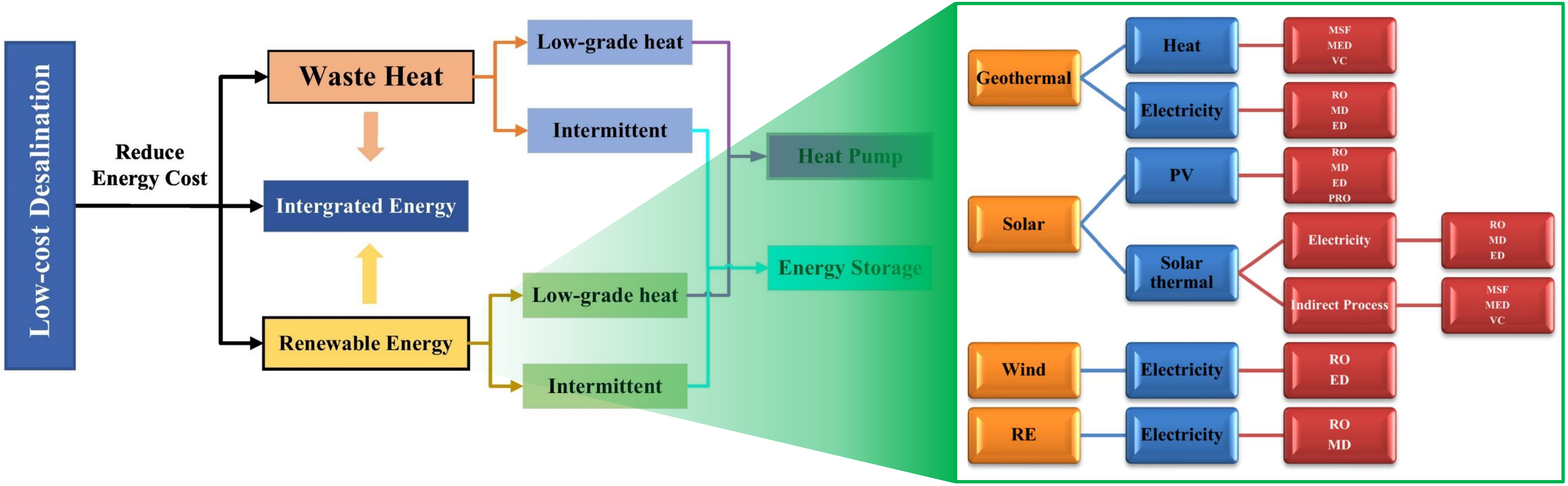
(Kim et al. 2019)

Conclusion and Recommendations

- **Hybrid desalination** is one of the most practical and efficient technologies that can afford **environmental and economic sustainability**
- **Membrane hybrid desalination** system requires a niche **membrane module design** depending on its technology and target water resources
- The innovation of **FO-MD integrated membrane module** improves **thermal and osmotic energy efficiency** of the hybrid system by an isolation barrier design

Conclusion and Recommendations

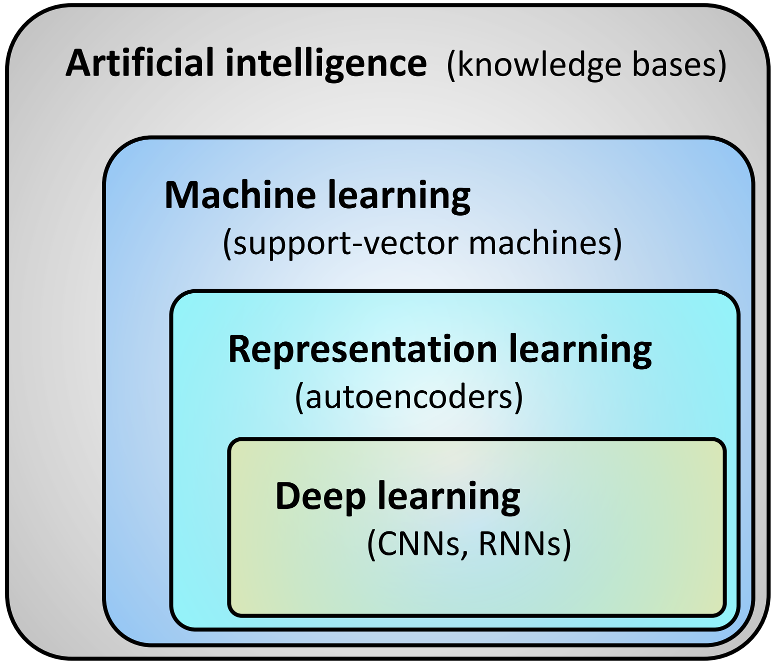
- **Hybrid desalination technology with renewable energy**

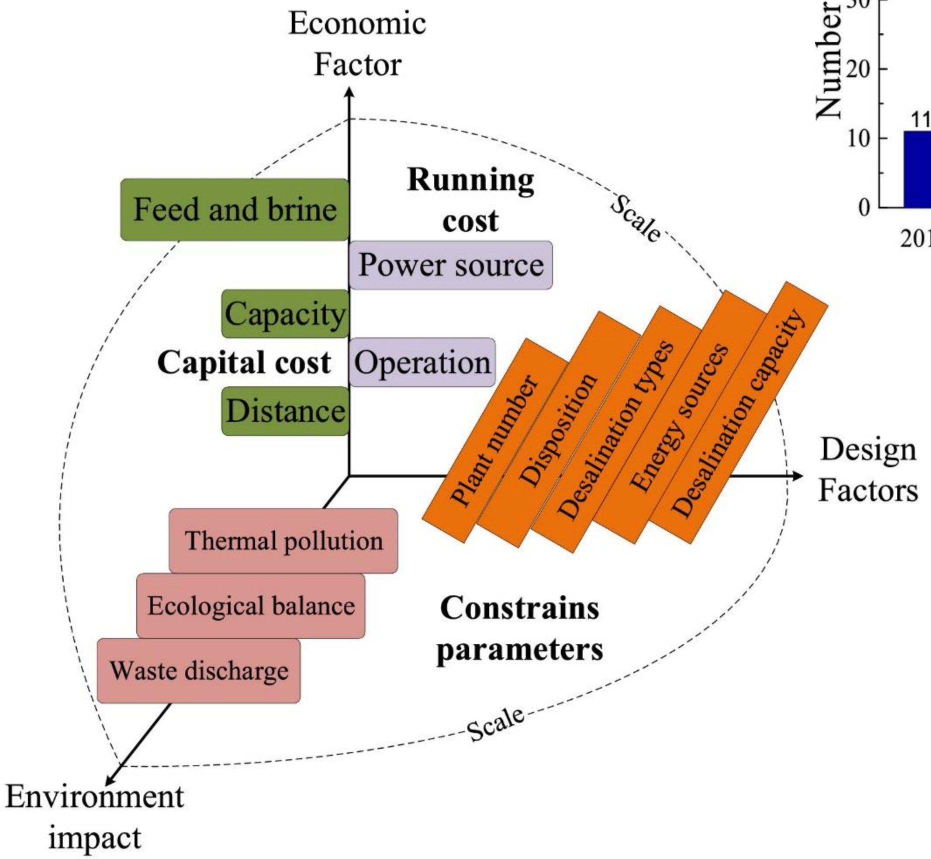


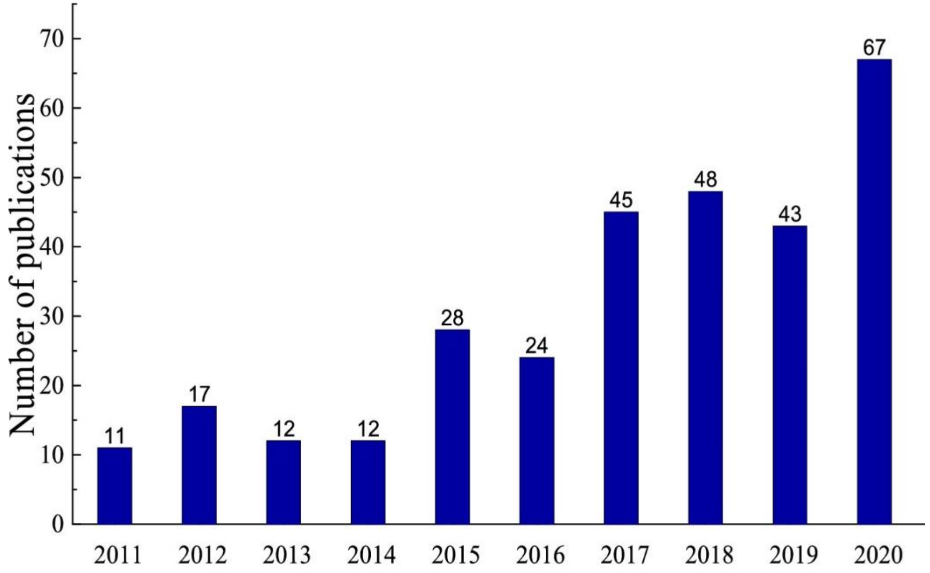
(Li et al. 2021, *Sarathe et al. 2022*)

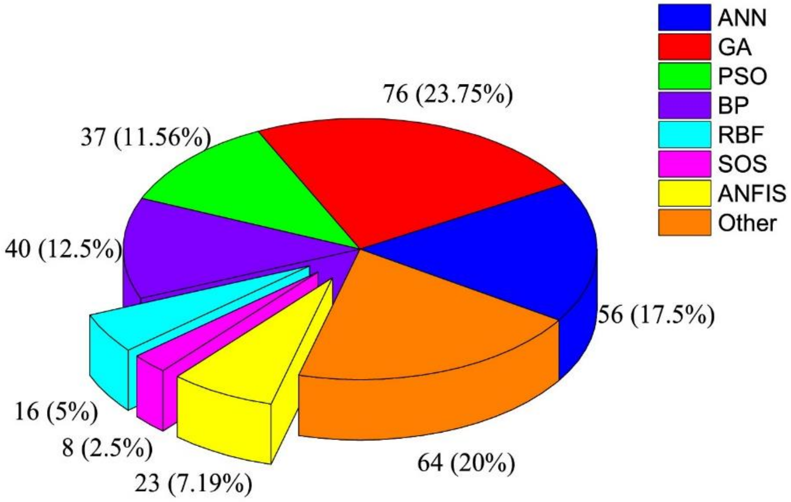
Conclusion and Recommendations

- **Artificial intelligence; machine learning; deep learning**









(Akinosho et al. 2020, He et al. 2022)

Credits and Acknowledgements

King Abdullah University of Science and Technology (KAUST)

- Prof. NorEddine Ghaffour
- Dr. Muhammad Saqib Nawaz
- Dr. Sofiane Soukane
- Water Desalination & Reuse Center (WDRC)

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King Abdullah University of Science and Technology

Saudi Aramco

- Process & Control Systems Department (P&CSD)

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Prince Sultan University

- Department of Engineering Management

جامعة الأمير سلطان
PRINCE SULTAN UNIVERSITY
PSU.1998

Thank you for your kind attention.

Hyuk Soo SON / hson@psu.edu.sa , hyuksoo.son@kaust.edu.sa