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XIX WORLD WATER CONGRESS
International Water Resources Association (IWRA)
Marrakech, Morocco | 1-5 December 2025

Kingdom of Morocco



Ministry of
Equipment and Water

Membrane cascades: A tool to enhance RO performances and overcome membrane ageing in desalination ?

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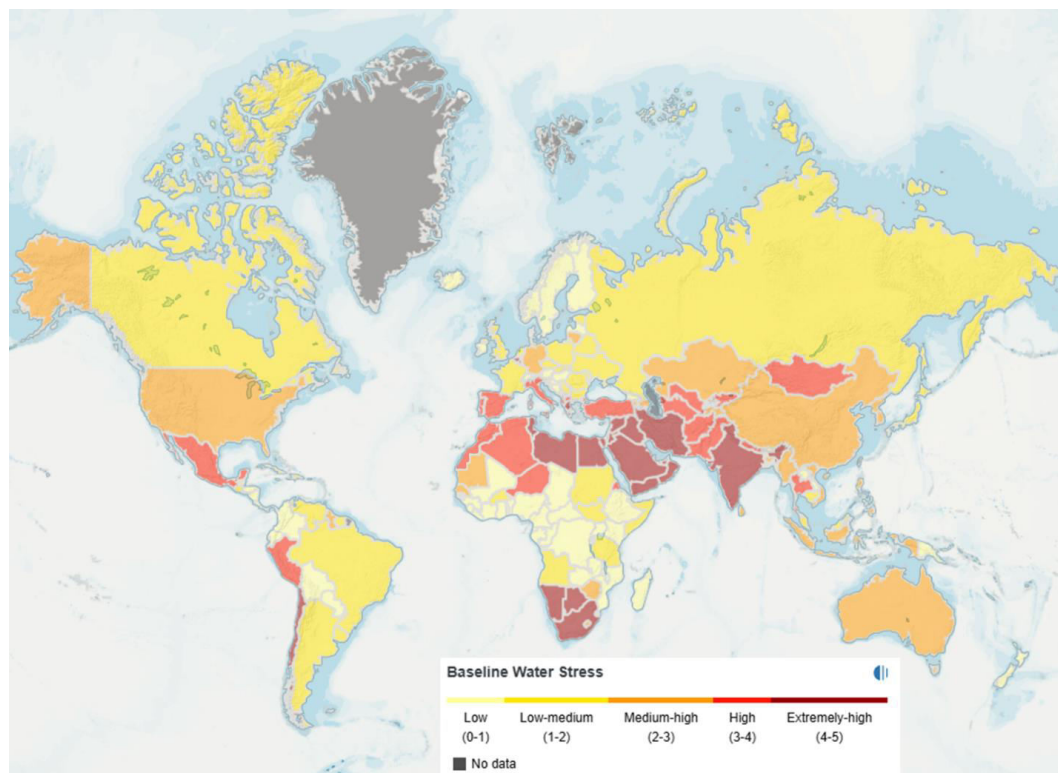
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December 3rd, 2025

General motivation



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World map illustrating water stress intensity according to the Water Stress Index. This index measures the ratio between total water demand and available renewable water resources.

Source : World Resources Institute (2023).

- In 2023, ~30% of counties are experiencing high and extremely high levels of water stress with Morocco ranks 27th.
- The renewable freshwater availability per capita is estimated between 560 and 600 m³ per year, which is below the international threshold of 1,000 m³/year defining water scarcity.
- In line with the “National Water Plan 2020–2050”, Morocco is progressively shifting from the exploitation of conventional water resources to the development of non-conventional resources, notably through treated wastewater reuse and seawater desalination.



General motivation

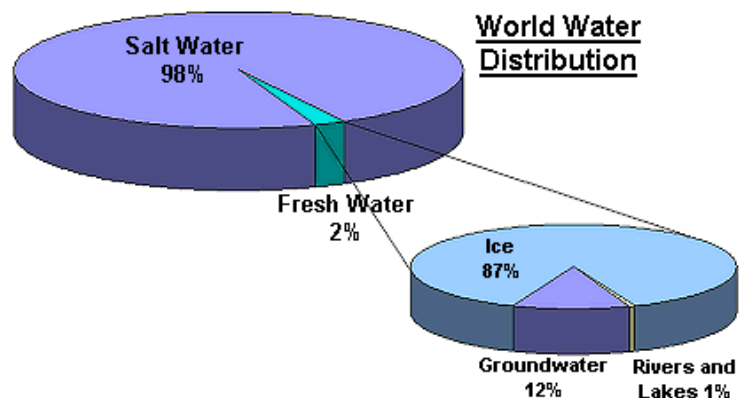


Desalination is the process of removing dissolved salts from saline water (seawater or brackish water) to produce freshwater.



Why desalination?

Global water distribution: 98% is saline.



→ A sustainable approach to achieve independence from conventional water resources.



General motivation

Brackish water : salt content between 10 and 25 g L⁻¹.

Seawater : salt content varies based on the source.

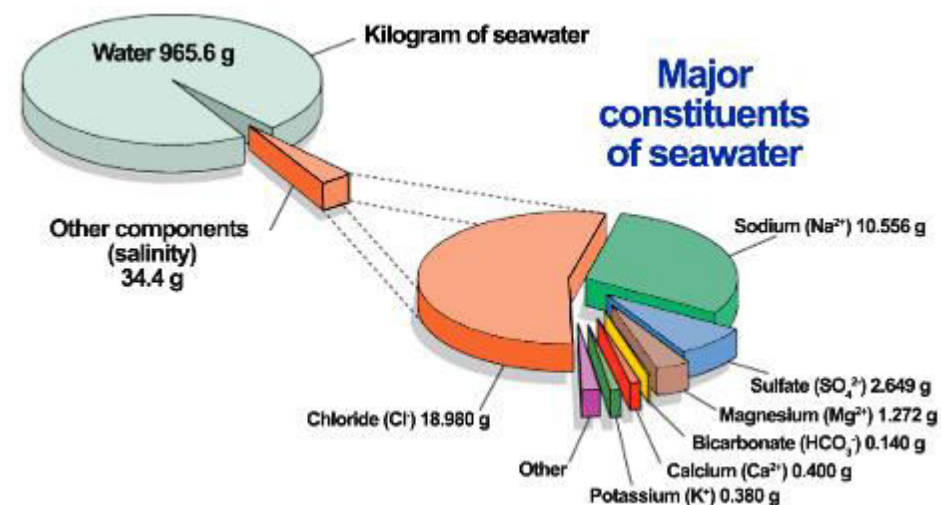
Atlantic Ocean: ~35 g L⁻¹

Mediterranean Sea: ~38 g L⁻¹

Red Sea: ~40 g L⁻¹



Atlantic ocean composition



Are brackish and seawater only salt and water?

- Due to human activities, organic and inorganic (micro)-pollutants can also be present



General motivation



However, even with efficient pretreatment, organic micropollutants ($MW < 1000 \text{ g.mol}^{-1}$) will still reach the RO stage.

Some micropollutants pose health risks at concentrations as low as 1 ng.L^{-1} .

→ RO must be efficient at fully removing these compounds to guarantee the high quality of produced water.

RO membranes undergo ageing during operation, leading to a decline in performance.

Degradation has a direct impact on both CAPEX and OPEX considering nearly 25% of RO membranes are replaced every year in desalination plants.

→ Identify strategies capable of extending membrane lifespan while maintaining high water quality and energy efficiency



Three main objectives



- 1st: Evaluate single stage RO performance of salt/micropollutants
 - ❖ Experimentally evaluate the effect of micropollutant presence on salt removal and assess RO effectiveness in removing them
 - ❖ Use the Spiegler–Kedem model combined with Film theory to project salt and micropollutant rejections at 55 bar
 - ❖ Simulate water recovery and specific energy consumption and compare single stage performance at 40 vs 55 bar

- 2nd: Explore membrane cascade with internal recycling as a tool to improve RO desalination
 - ❖ Design overview with recycling in continuous mode
 - ❖ Performance comparison by design vs NaCl concentration

- 3rd: Assess the interest of membrane cascade to overcome performance degradation due to membrane ageing
 - ❖ Simulate RO performance at different membrane ageing levels
 - ❖ Compare the results with RO performance of new membrane at single stage



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Materials and Methods



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RO Membrane:
Filmtec SW30-2540 (2 inches, 2.5 m²)



RO/NF pilot

RO membrane: (provider data)

Membrane	Membrane material	Permeance L.h ⁻¹ .m ² .bar ⁻¹	NaCl rejection		pH range stability	Maximum pressure (bar)
			Pressure (bar)	Rejection		
SW30	Aromatic Polyamide /Polysulfone	2.15 (2.05 ± 0.1exp)	55	99.4 (32 g L ⁻¹)	2-11	69

Feed solution:

- ❖ **Model solutions:**
 - 29 g L⁻¹ NaCl
 - 29-31 g L⁻¹ NaCl + 0.45-0.48 mmol L⁻¹ contaminant

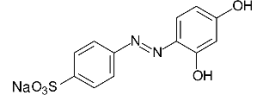
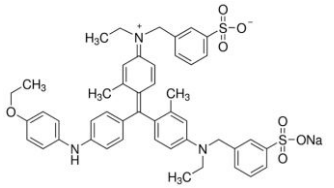
RO operating conditions:

- ❖ Flow rate = 1000 ± 10 L h⁻¹
- ❖ Applied pressure: 10-40 bar



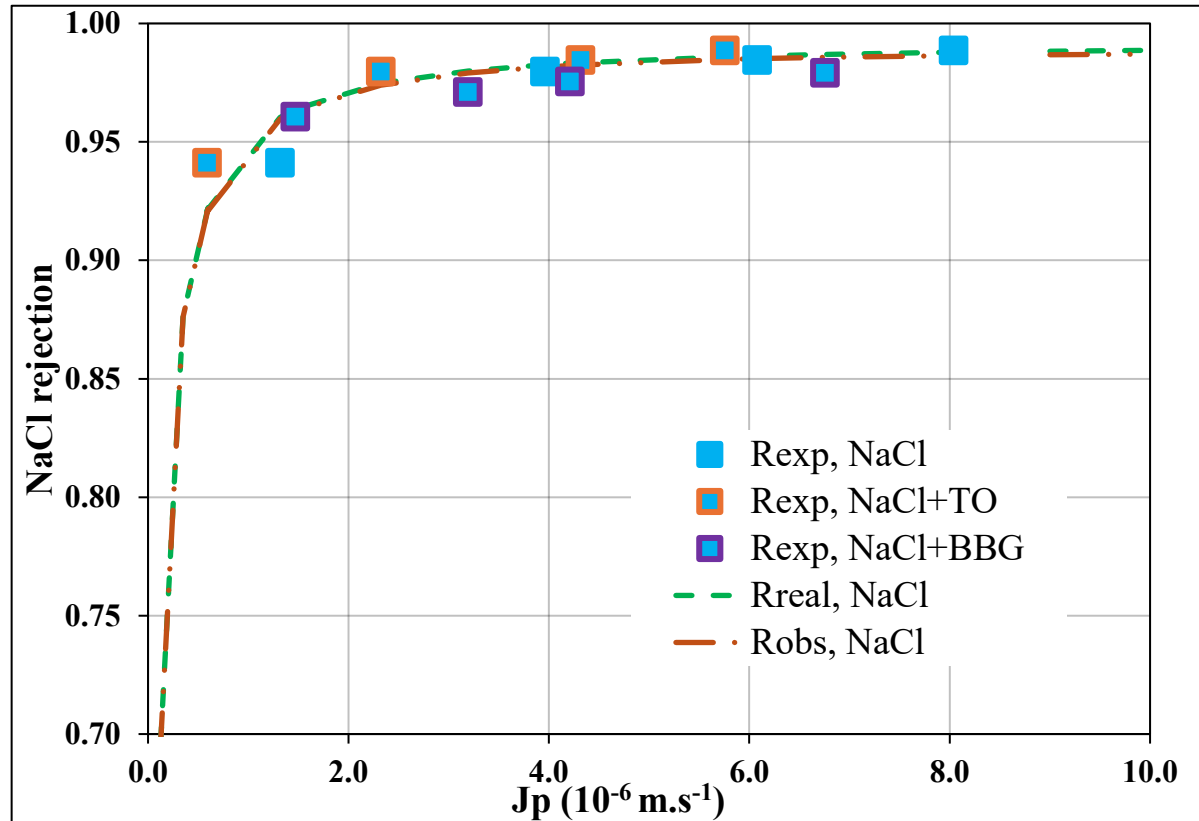
Selected model contaminant textile dyes



Solute	Molecular weight in dissociated form (g.mol ⁻¹)	Charge at natural pH	logK _{ow} [*]	Structure in sodium salt form	V _m ^{**} excluded volume Connolly (Å ³)	r _s ^{***} (nm)
Tropaeolin O CAS 547-57-9	293	pH=5.3 -1	1.53 (hydrophilic)		170	0.34
Brilliant Blue G CAS 6104-58-1	831	pH=7.6 -1	-2.55 (highly hydrophilic)		745	0.56



Single stage RO performance of salt/micropollutants mixture



$$R_{\text{NaCl}} (40 \text{ bar}) = 98.6 \pm 0.03\%$$

No significant impact of
Tropaeolin O & Brilliant Blue G
on NaCl rejection

Spiegler Kedem + Film model

$$P_{SK} = 4.70E-08 \text{ m s}^{-1}$$

$$\sigma_{SK} = 0.994 \text{ (Max rejection)}$$

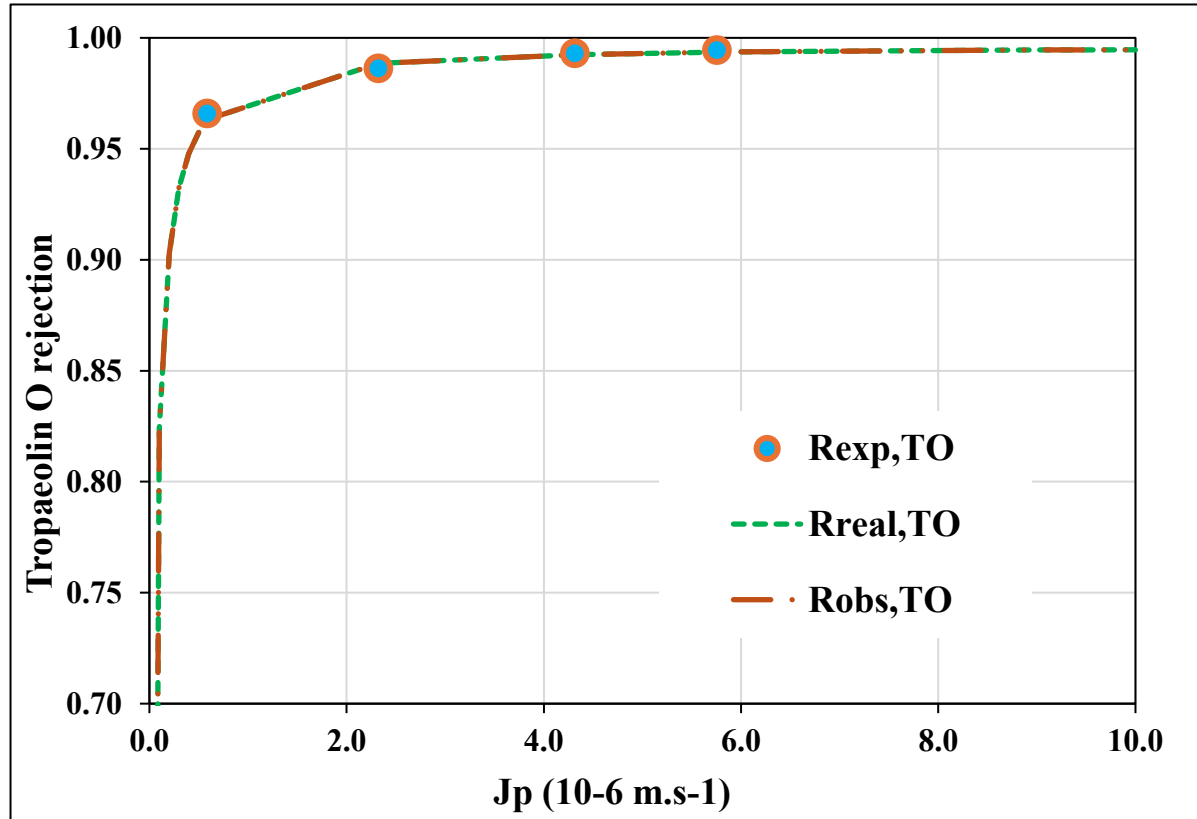
$$k_{SK} = 7.42E-05 \text{ m s}^{-1}$$

→ Extrapolation 55 bar
(industrial applied pressure)

Effect of micropollutant presence on salt removal at 40 bar and Spiegler
Kedem + Film modeling



Single stage RO performance of salt/micropollutants mixture



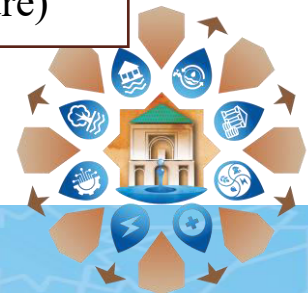
**Contrary to what could be thought
no full rejection**

$R_{TO} (40 \text{ bar}) = 99.4 \pm 0.2\%$
pH= 5.3
Few leakage in permeate

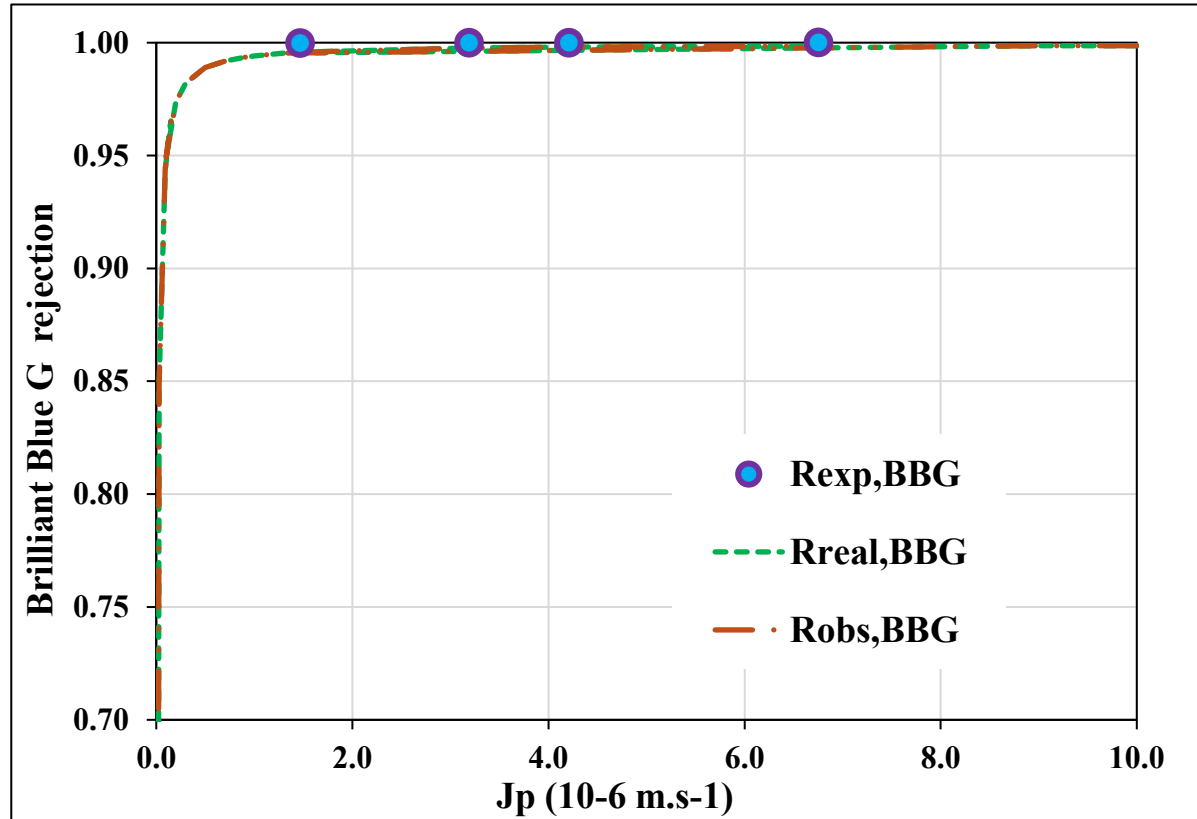
Spiegler Kedem + Film model:
 $P_{SK} = 2.10E-08 \text{ m s}^{-1}$
 $\sigma_{SK} = 0.996$ (Max rejection)
 $k_{SK} = 7.42E-05 \text{ m s}^{-1}$

→ Extrapolation 55 bar
(industrial applied pressure)

RO effectiveness in removing micropollutants at 40 bar and Spiegler Kedem + Film modeling: Tropaeolin O



Single stage RO performance of salt/micropollutants mixture



RO effectiveness in removing micropollutants at 40 bar and Spiegler Kedem + Film modeling : Brilliant Blue G

**Contrary to what could be thought
no full rejection**

$R_{BBG} (40 \text{ bar}) = 99.9 \pm 0.1\%$
pH= 7.6
Few leakage in permeate

Spiegler Kedem + Film model:

$$P_{SK} = 5.30E-08 \text{ m s}^{-1}$$

$$\sigma_{SK} = \mathbf{0.999} \text{ (Max rejection)}$$

$$k_{SK} = 7.42E-05 \text{ m s}^{-1}$$

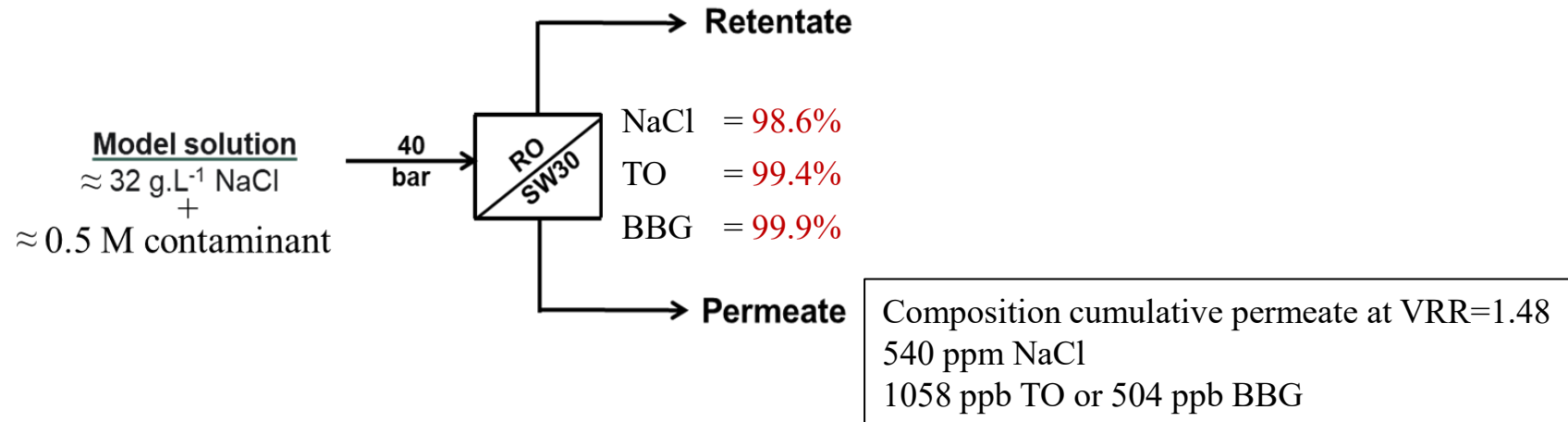
→ Extrapolation 55 bar
(industrial applied pressure)





Single stage RO performance of salt/micropollutants mixture

Performance evaluation of single stage at 40 bar



Few leakage of contaminants into the permeate
what about water recovery?

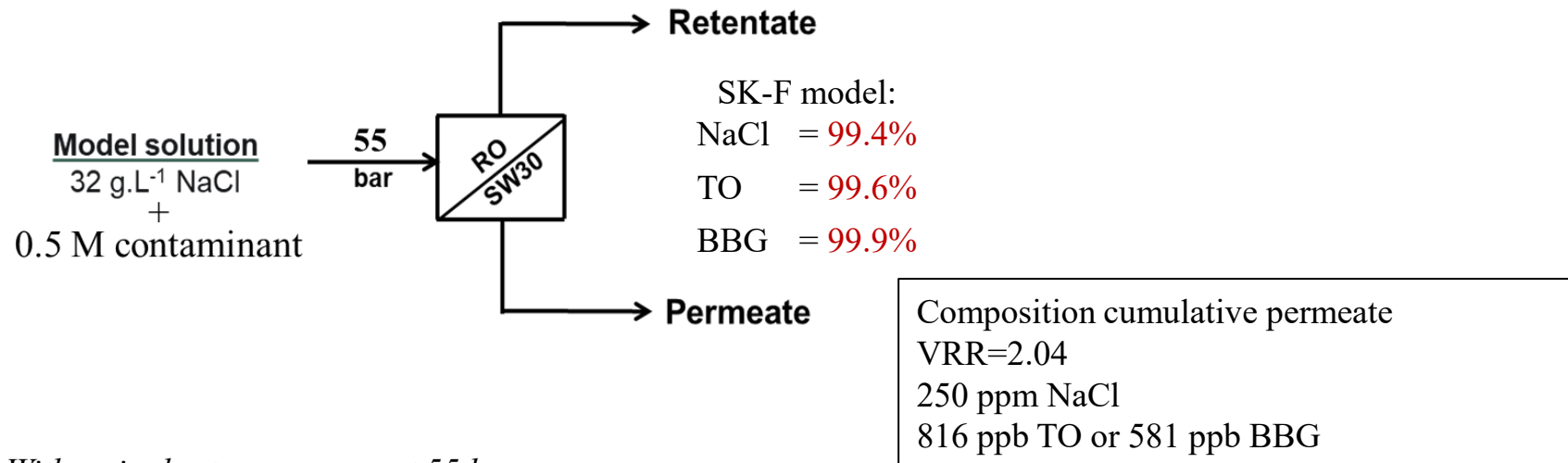
- With a single stage process, with a maximum pressure of 40 bar,
 - assuming a minimum effective pressure around 1 bar
- the highest possible water recovery is **32.5%** in continuous mode ($VRR=1.48$) and $SEC = \mathbf{4.95 kWh.m^{-3}}$
- How to enhance the RO performances ?
 - increase the applied pressure to 55 bar





Single stage RO performance of salt/micropollutants mixture

Performance evaluation of single stage at 55 bar



- With a single stage process at 55 bar;
 - Assuming a minimum effective pressure around 1 bar
- ➔ the highest possible water recovery is **51%** in continuous mode ($VRR=2.04$) and $SEC = 4.32 \text{ kWh.m}^{-3}$
 - ➔ in good agreement with industrial known results

Water quality, water recovery and SEC are enhanced by the increase of applied pressure

- How to further enhance the RO performances ➔ our proposal arrange membranes in cascade with internal recycling



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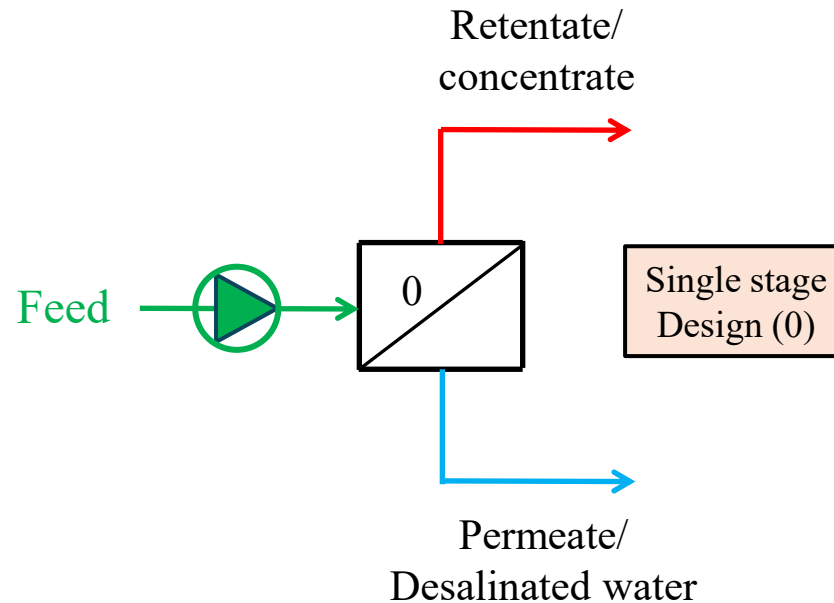


Membrane cascade with internal recycling to improve RO desalination



Membrane cascades refers to a series or sequence of membrane units used in a separation process.

Membrane cascades with internal recyclings and in continuous mode were tested with the aim of improving RO performance through simulation.

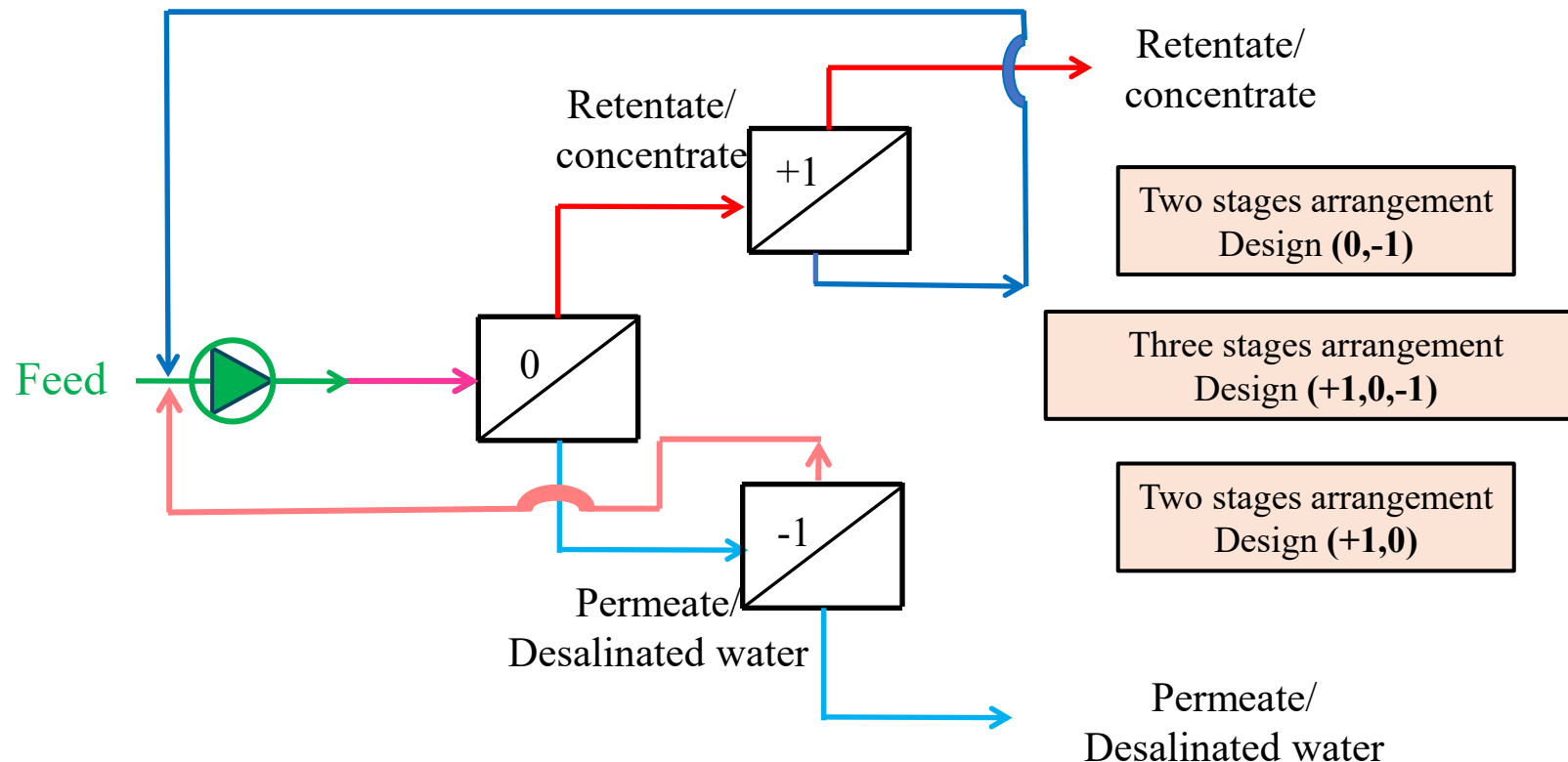


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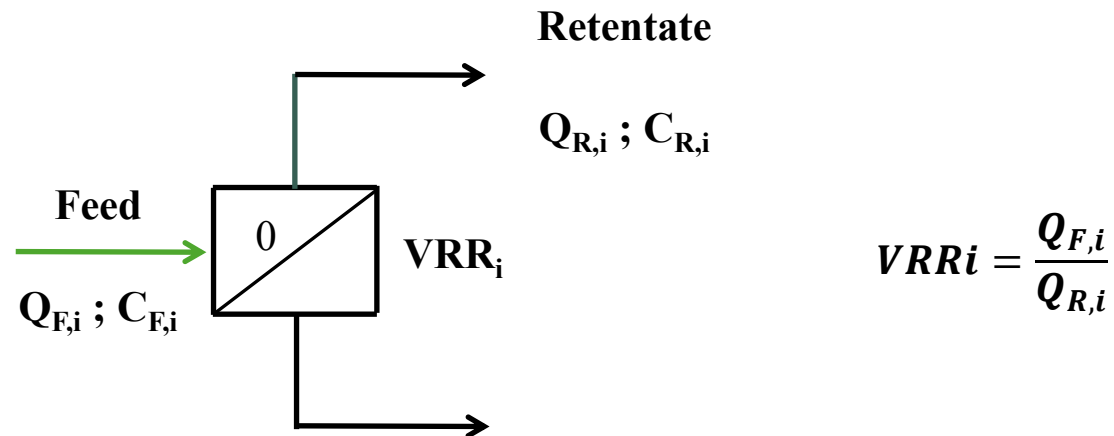
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Membrane cascade with internal recycling to improve RO desalination

Volume reduction ratio (VRR)

Defined as how much the volume of the feed solution is reduced to retentate after passing through a specific stage or the entire cascade.



Membrane cascade with internal recycling to improve RO desalination

Performance evaluation parameters



Water recovery

Fraction of feed water converted into permeate

$$\text{Water Recovery (\%)} = \frac{Q_{\text{Permeate}}}{Q_{\text{Feed}}}$$

Water quality

Concentration of NaCl and contaminants present in the permeate

Specific energy consumption (SEC)

Energy required to produce 1 m³ of permeate

$$\text{SEC (kWh.m}^{-3}_{\text{Permeate}}) = \frac{\text{Electrical power (kW)}}{Q_{\text{Permeate}}(\text{m}^3.\text{h}^{-1})}$$

with

$$\text{Electrical power (kW)} = \frac{101325 \times \Delta P(\text{bar}) \times Q_{\text{Feed}}}{1000 \times \eta}$$

η : the pump efficiency, assumed to be 0.7



Membrane cascade with internal recycling to improve RO desalination

Applied data for the cascade simulations

	NaCl	Tropaeolin O	Brilliant Blue G
Concentration (mol.L ⁻¹)	0.48 - 0.58 (25 - 34 g.L ⁻¹)	0.0005 (146 mg.L ⁻¹)	0.0005 (415 mg.L ⁻¹)
Rejection	0.994	0.996	0.999
Permeate flux (L.h ⁻¹ .m ⁻²)	-1.6784[NaCl]+111.1		
Applied pressure at each stage (bar)	55		
Feed flow (L.h ⁻¹)	1075		



Membrane cascade with internal recycling to improve RO desalination

Chosen volume reduction ratios

Variation of VRR_{stage} → high value as possible on each stage
With around 1 bar effective pressure on all stage

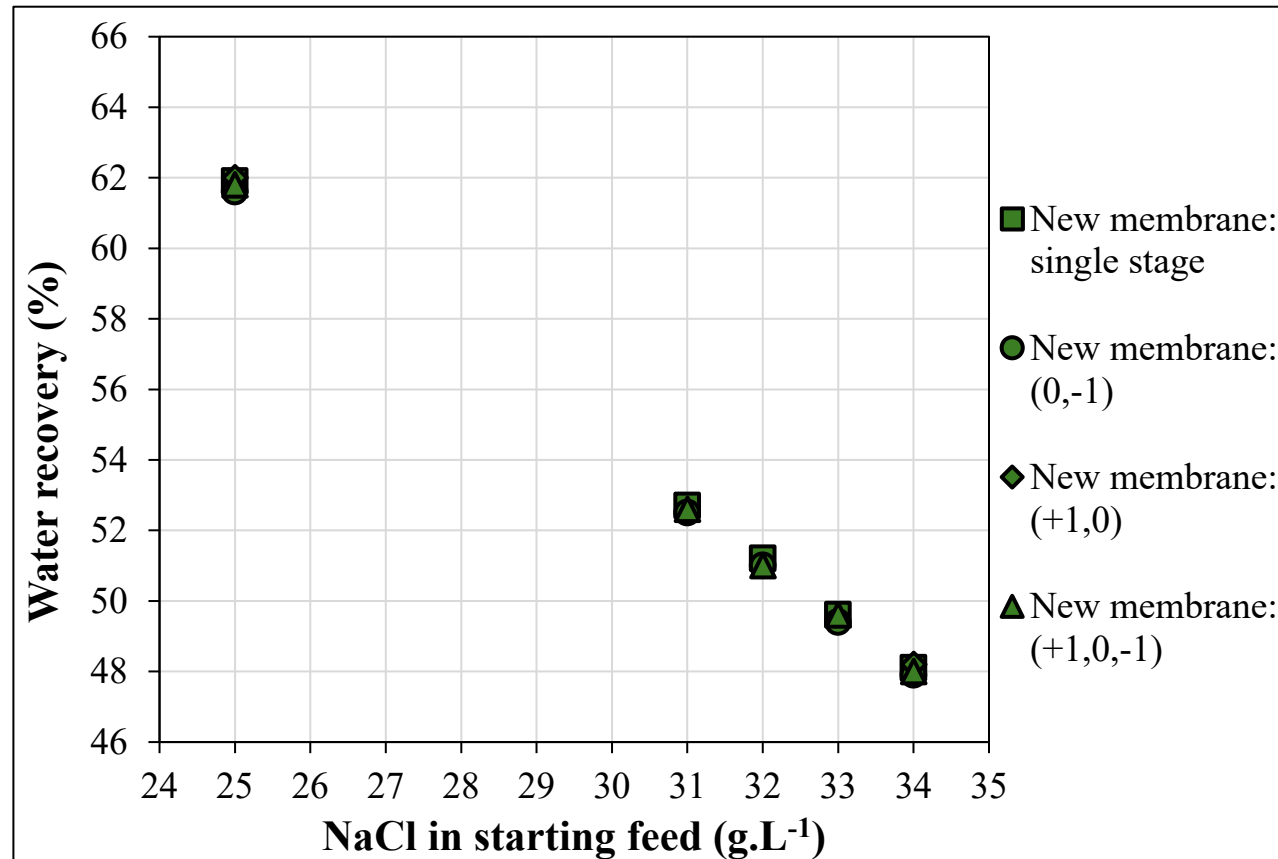
Cascade design	VRR ↓	[NaCl] (g.L ⁻¹)				
		25	31	32	33	34
(0)	$VRR_{stage\ 0}$	2.62	2.11	2.05	1.98	1.92
(0,-1)	$VRR_{stage\ 0}$	2.86	2.15	2.08	2.02	1.96
	$VRR_{stage-1}$	25	25	25	25	25
(+1,0)	$VRR_{stage\ 0}$	2.61	nd	nd	nd	1.93
	$VRR_{stage+1}$	1.01	nd	nd	nd	1.01
(+1,0,-1)	$VRR_{stage\ 0}$	2.68	2.15	2.08	2.02	1.96
	$VRR_{stage-1}$	25	25	25	25	25
	$VRR_{stage+1}$	1.01	1.01	1.01	1.01	1.01



Membrane cascade with internal recycling to improve RO desalination



Water recovery for different cascade configurations



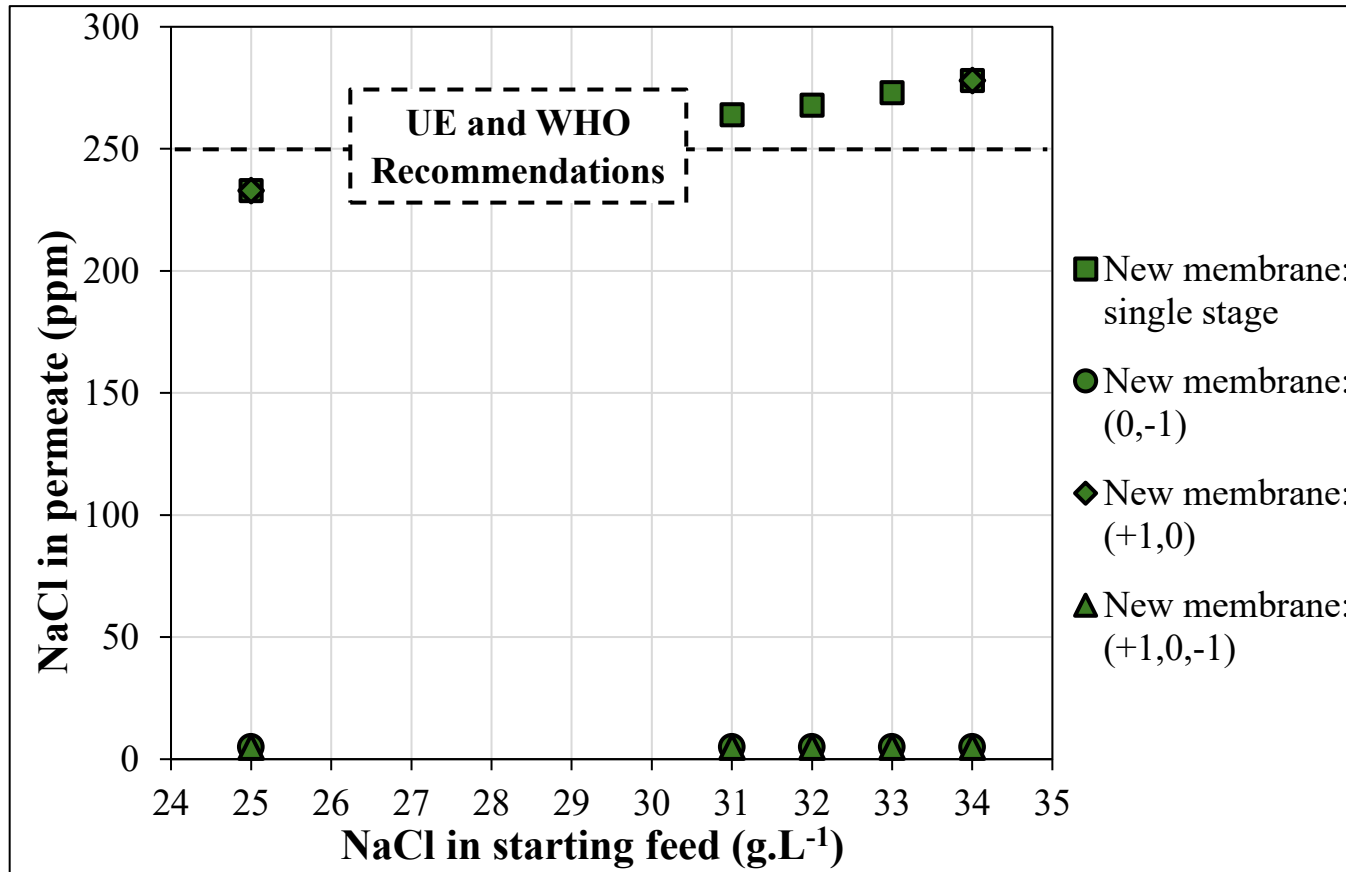
Whatever the configurations, at a given NaCl concentration
→ No significant effect on the water recovery



Membrane cascade with internal recycling to improve RO desalination



Permeate quality: NaCl concentration in the permeate



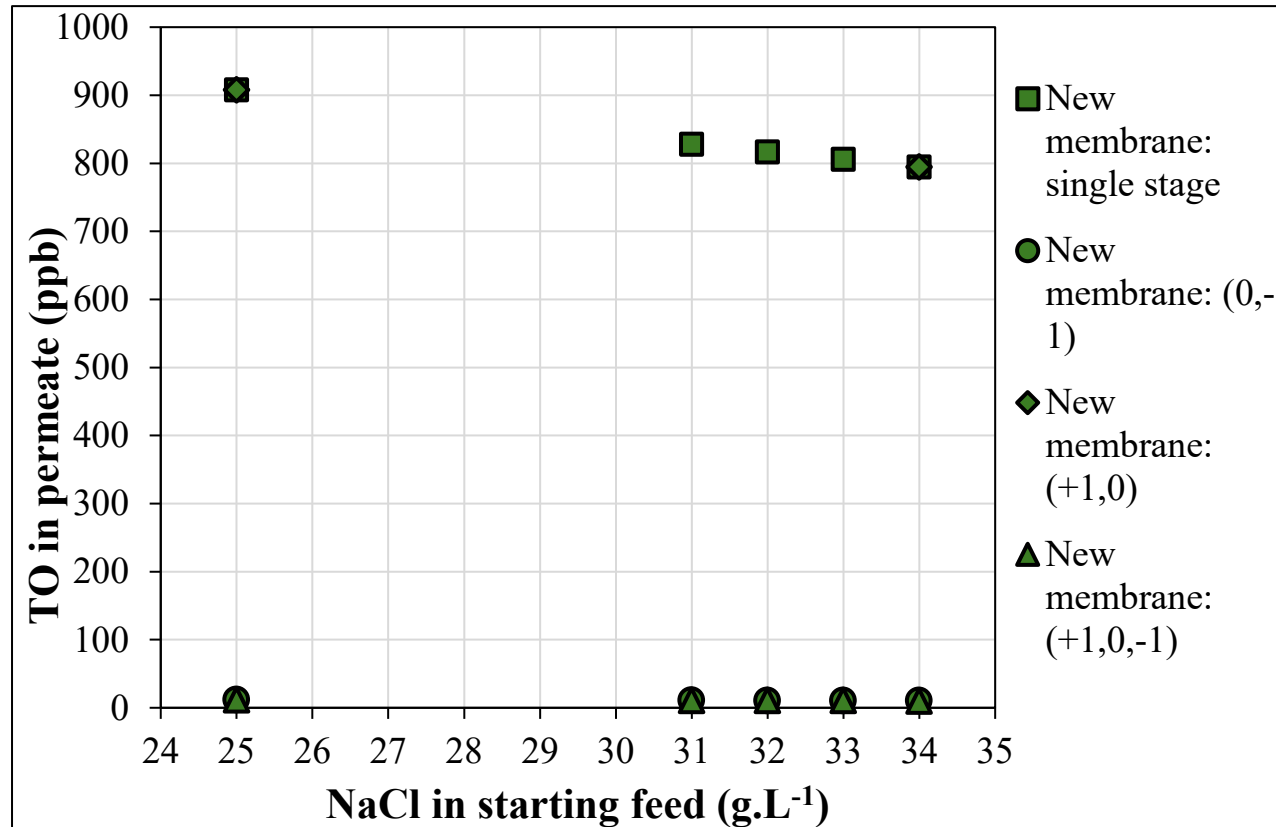
Whatever the NaCl concentration
→ The configuration with permeate retreatment (0,-1) and (+1,0,-1) are effective in decreasing NaCl in the permeate by 50-fold (from ≈250 to 5 ppm)



Membrane cascade with internal recycling to improve RO desalination



Permeate quality: TO concentration in the permeate



→ Cascades with permeate retreatment are effective to decrease TO in the permeate by 75-fold (from ≈820 to 11 ppb)

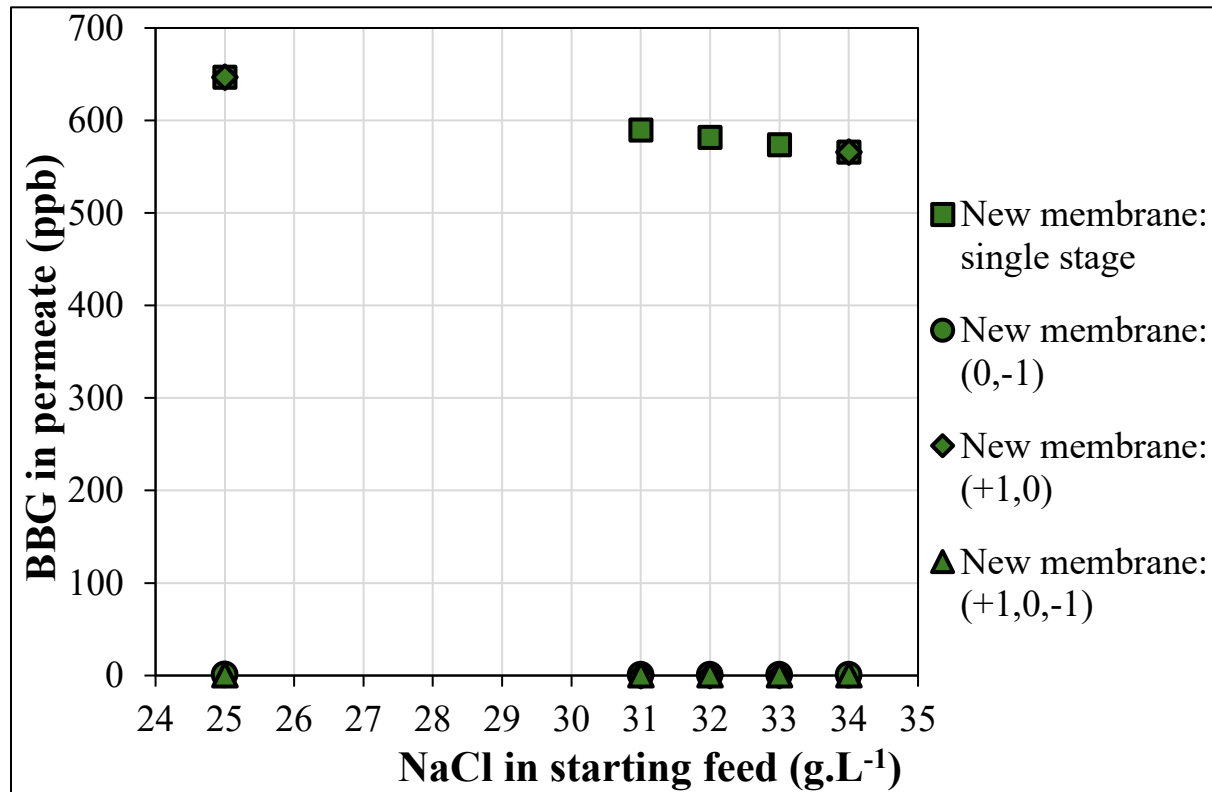


Membrane cascade with internal recycling to improve RO desalination

Permeate quality: BBG concentration in the permeate



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→ Brilliant Blue G concentration in the permeate is significantly lower by 582-fold when using (0,-1) and (+1,0,-1) configurations (from ≈ 582 to 1 ppb)

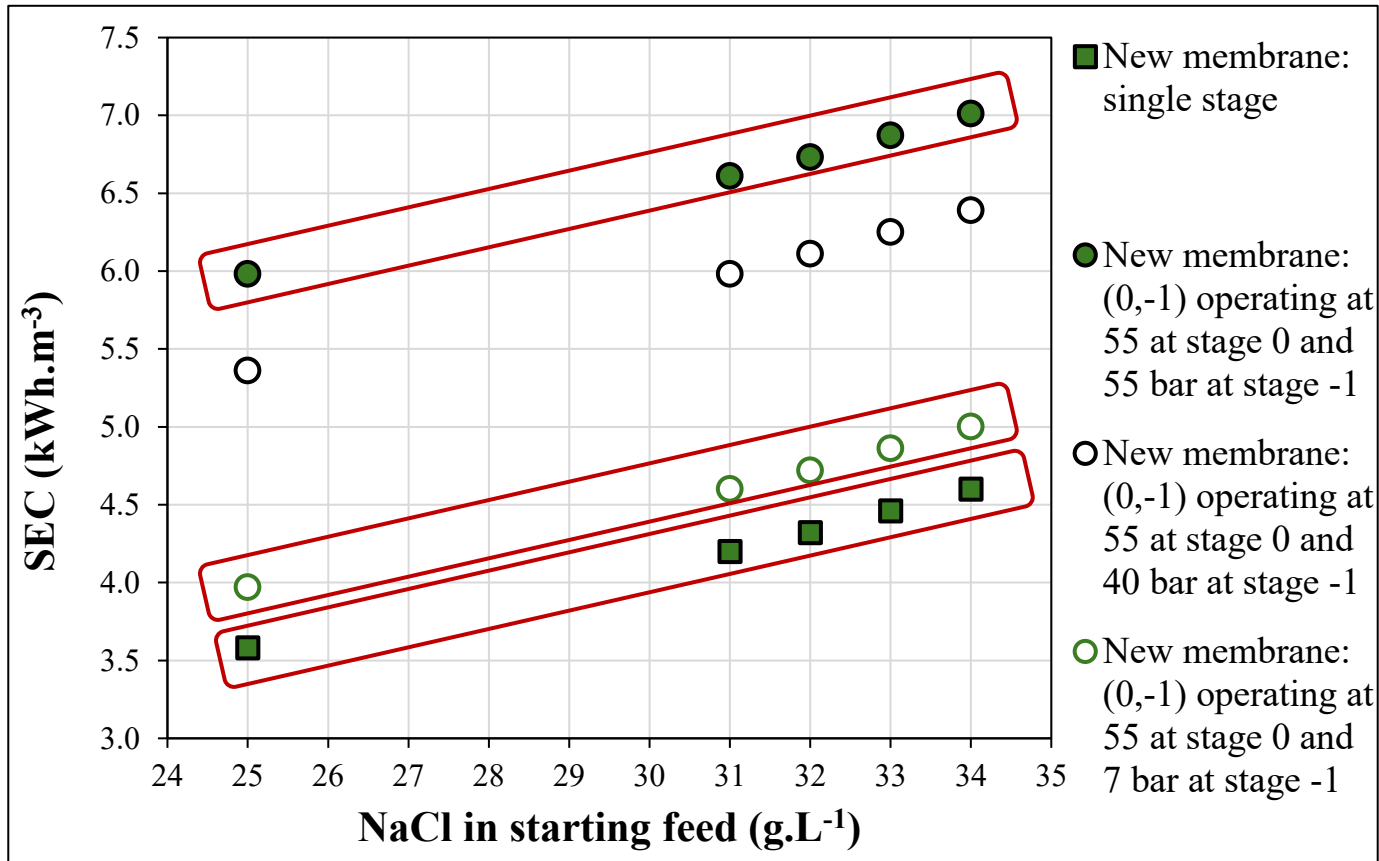
→ Compared to (0,-1), (+1,0) and (+1,0,-1) offer no performance benefit

→ Further investigation will be focusing mainly on (0,-1) design



Single stage RO performance of salt/micropollutants mixture

Specific energy consumption for different cascade configurations



→ As the second stage added, the required membrane area increases by ~54%

→ Due to the diluted feed and lower osmotic pressure, stage -1 can operate at ~7 bar, leading to only ~8% SEC increase.

→ No energy-recovery devices included in the calculations (potential reduction: 40–60%)



Single stage RO performance of salt/micropollutants mixture

Set of conclusions

- Cascade configuration improves permeate quality compared to single stage:
 - Decreased NaCl concentration by 50-fold and beyond WHO and EU guidelines
 - Decreased TO concentration by 75-fold
 - Decreased BBG concentration by 582-fold

- The configurations (+1,0) and (+1,0,-1) show no performance benefit compared with (0,-1)

- Compared to single stage, the (0,-1) configuration:
 - Increases required membrane area by ~40%.
 - Increases SEC by at least 8%, depending on the operating pressure at stage -1.

How would these results change in the case of aged membranes ?



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Interest of Cascade to overcome performance degradation due to membrane ageing



Parameters used in aged membrane cascade simulations under continuous mode at 55 bar

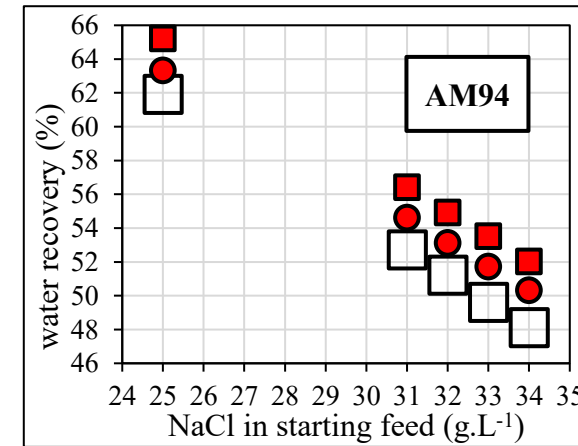
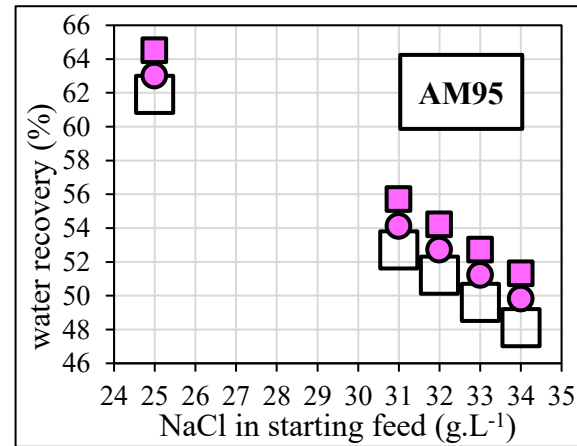
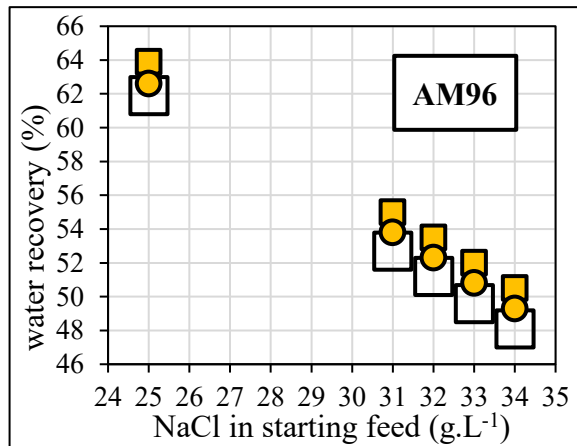
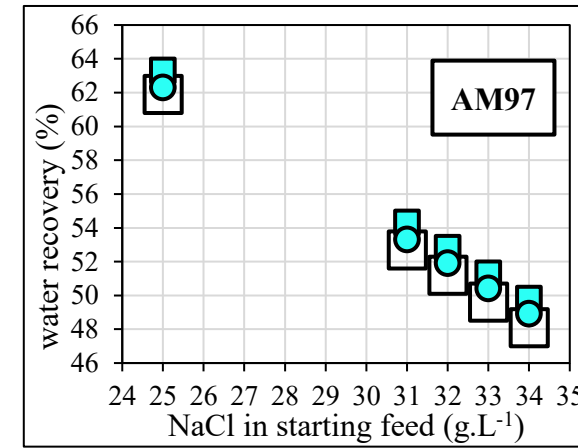
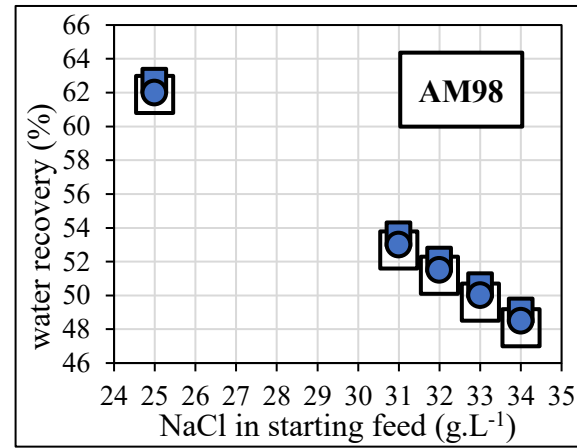
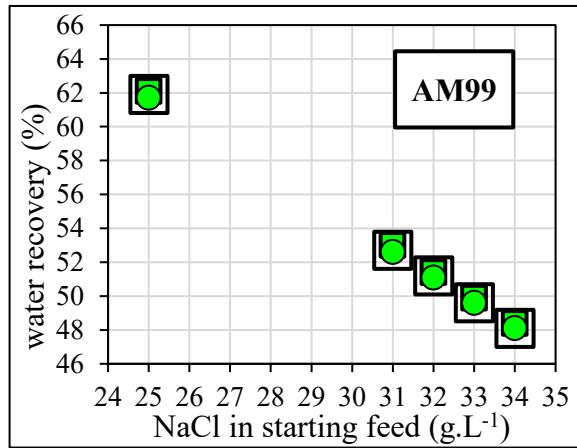
Membranes →	AM-99	AM-98	AM-97	AM-96	AM-95	AM-94
NaCl Rejection at 55 bar (%)	99.0	98.0	97.0	96.0	95.0	94.0
TO Rejection at 55 bar (%)	99.6	99.3	99.1	98.8	98.5	98.2
BBG rejection at 55 bar (%)	99.9	99.8	99.7	99.6	99.5	99.3
VRR	Highest possible value at each stage with about +1 net driving pressure					



Interest of Cascade to overcome performance degradation due to membrane ageing



Water recovery simulation at different aged membranes compared to single stage of new membrane



- NM, single stage
- AMxx, single stage
- AMxx, (0,-1)

→ At lower rejection rate, the cascades affects the water recovery

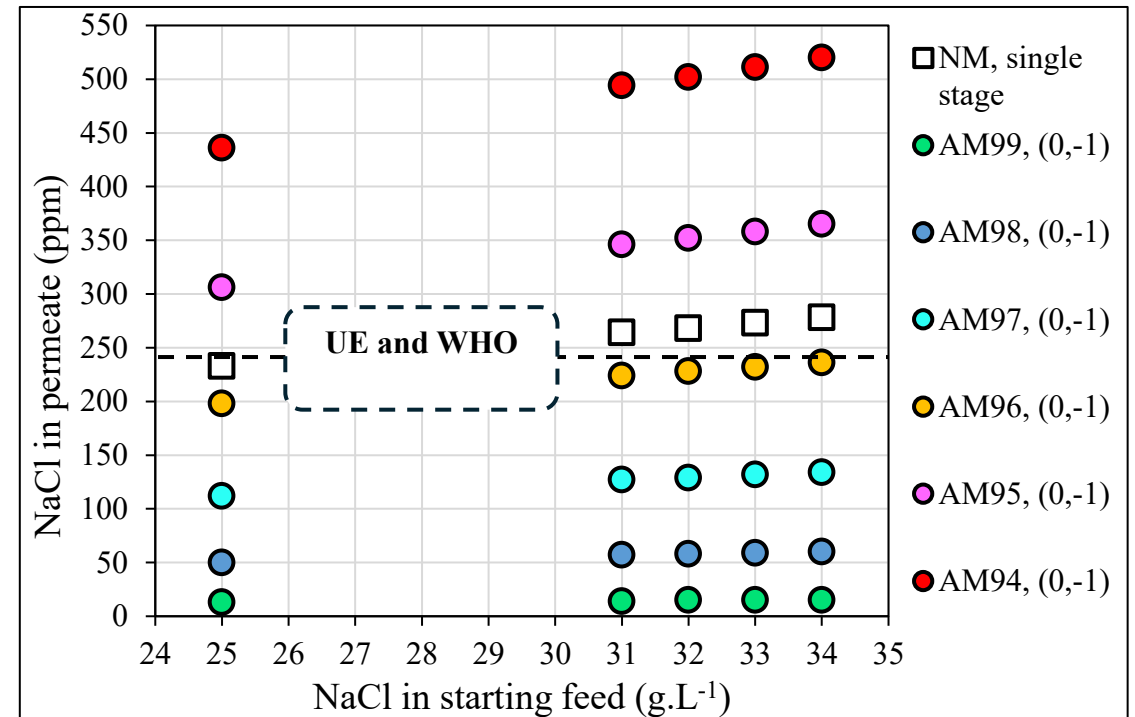
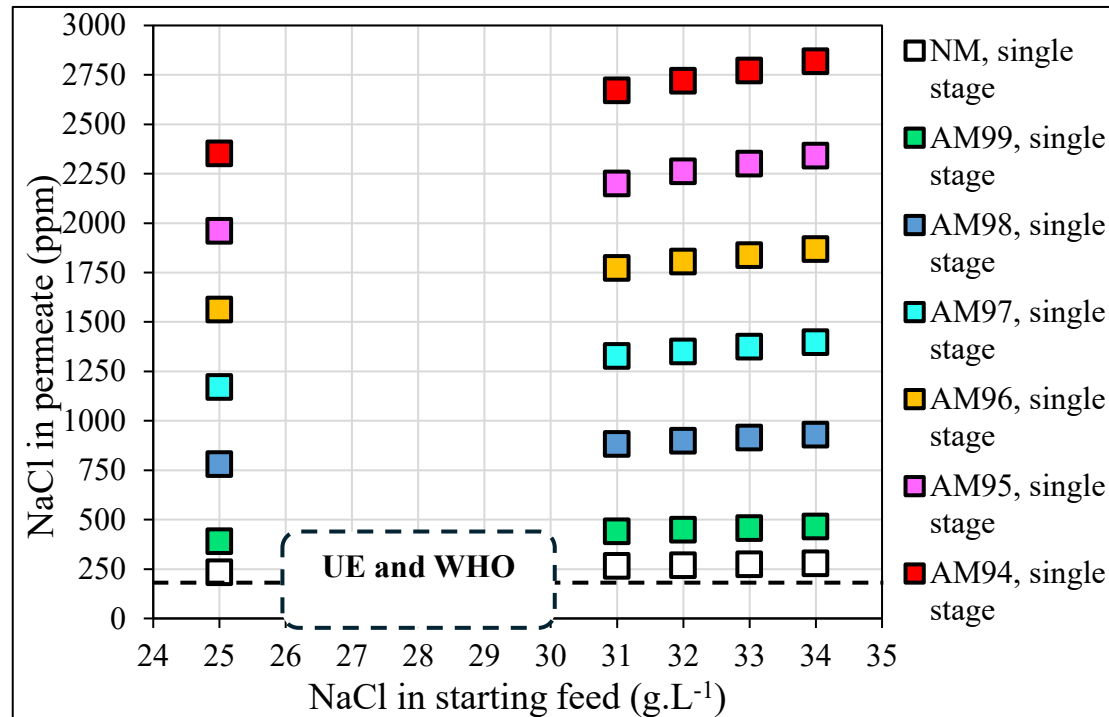
→ Whatever the design, the aged membrane shows increased water recovery compared to the new membrane at single stage



Interest of Cascade to overcome performance degradation due to membrane ageing



Permeate quality: NaCl concentration in the permeate



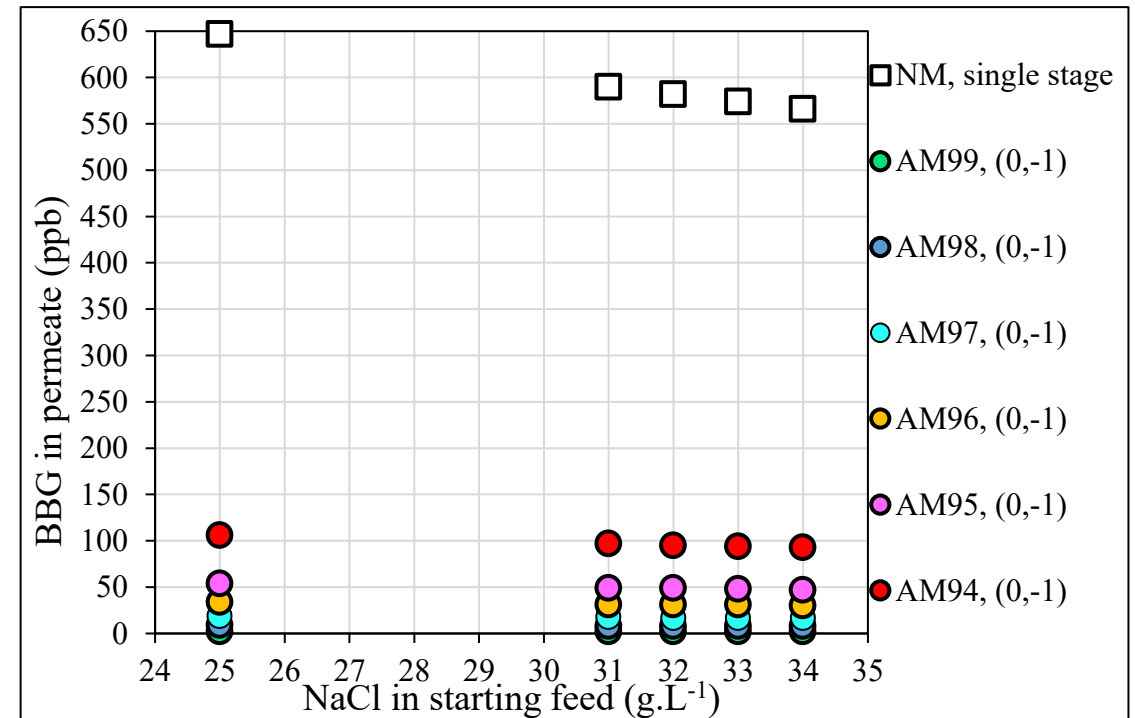
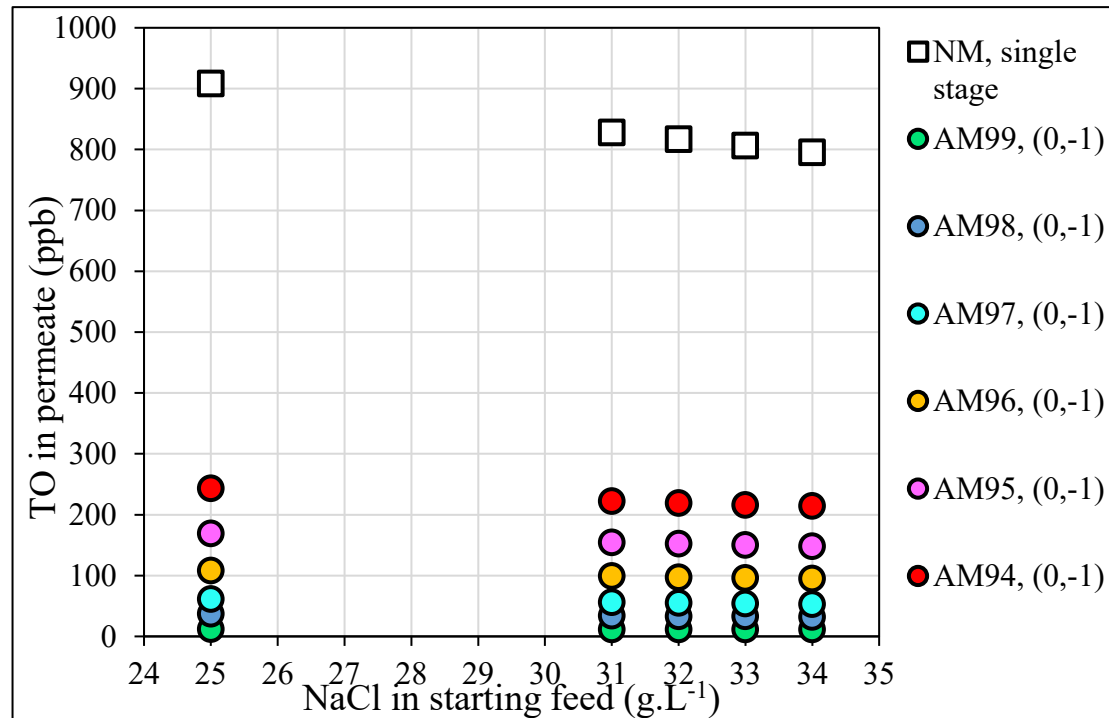
→ the single stage permeate quality was significantly compromised

→ (0,-1) configuration improved the permeate quality for aged membranes remaining better than the WHO and EU standards up to AM96

Interest of Cascade to overcome performance degradation due to membrane ageing



Parameters used in aged membrane cascade simulations under continuous mode at 55 bar



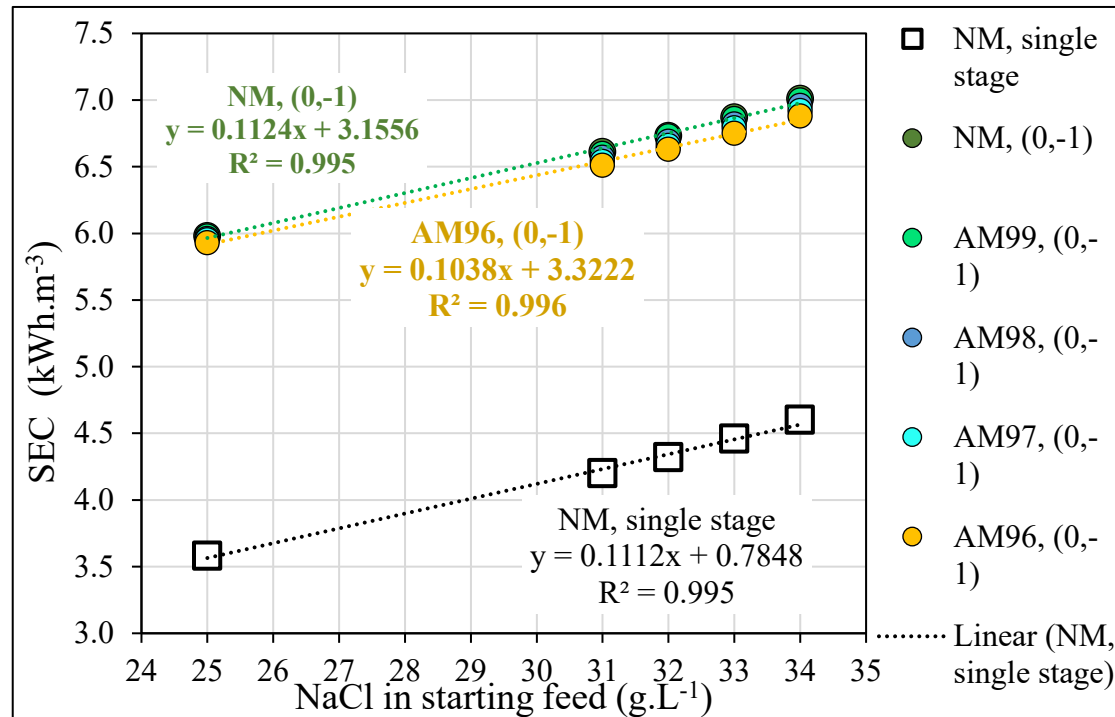
→ Even under extreme ageing, (0,-1) design kept both pollutants levels in the permeate lower than that of a new membrane at single-stage.



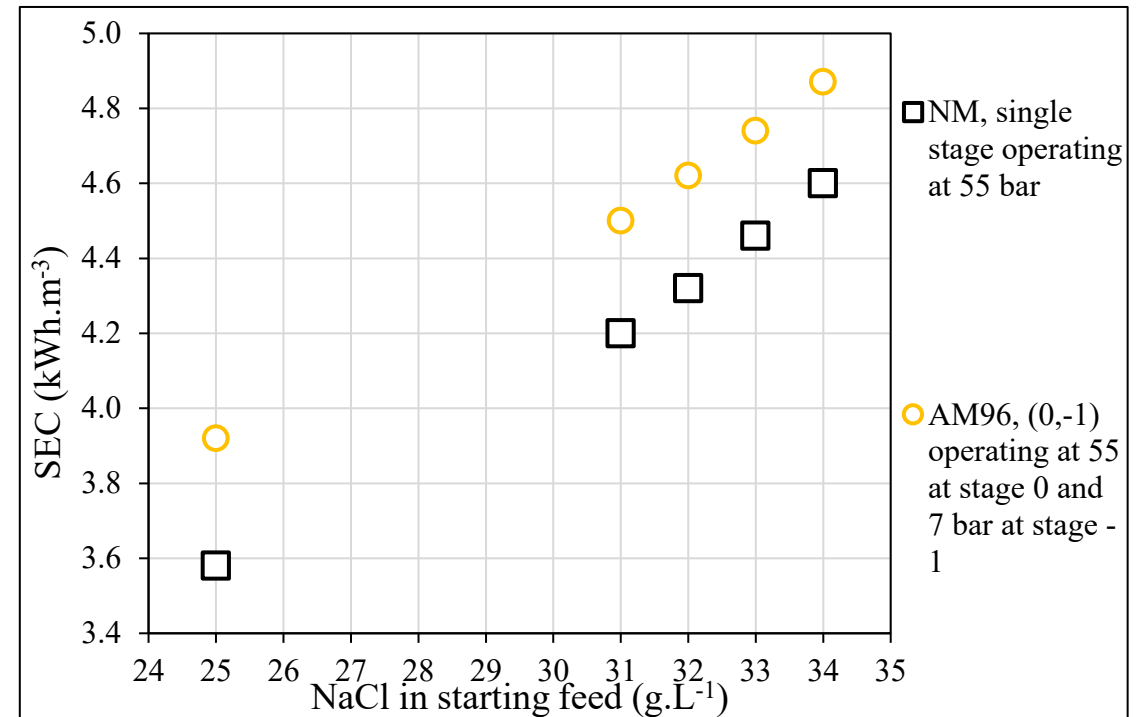
Interest of Cascade to overcome performance degradation due to membrane ageing



Specific energy consumption



→ As the membrane ageing degree increases, the SEC slightly decreases due to higher recovery of water

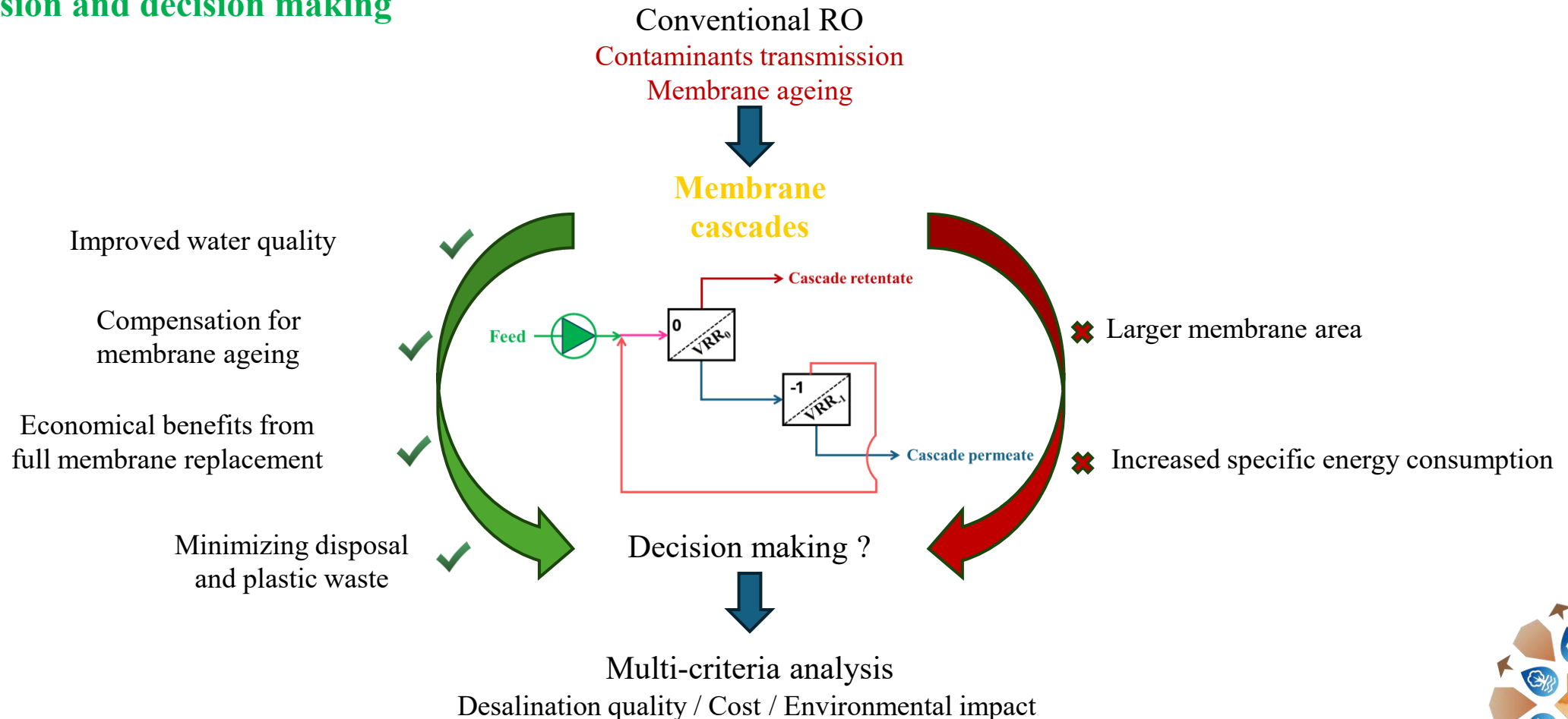


→ The SEC of AM96 at (0,-1) with applied pressure of 7 bar at the second stage is 5.8% higher than new membrane at single stage

Interest of Cascade to overcome performance degradation due to membrane ageing



Conclusion and decision making



Acknowledgements



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Thank you!

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