Optimizing treated wastewater for sustainable agricultural irrigation: A membrane-in-Series approach to minimize concentrate streams in reverse osmosis and nanofiltration processes

Fatima. Elazhar[a,b,c], Maryem. Elazhar[a], Haby D. Mamadou[a], Mohamed.Taky[a,c,] Nour-Eddine ELHaloui[c], Azzeddine. Elmidaoui[a,c]

[a] *Laboratory of Advanced Materials and Process Engineering, Faculty of Sciences, Ibn Tofail University, P.O. Box: .1246, Kenitra - Morocco*

.[b]*National School of Chemical Engineering, Ibn Tofail University, Kenitra - Morocco*

[c] *International Water Research Institute, Mohammed VI Polytechnic University, Ben Guerir - Morocco*

Corresponding author: fatima.elazhar@uit.ac.ma

Abstract

Utilizing wastewater as an irrigation water source has gained increasing attention for several countries such as Morocco. However, ensuring that the quality of treated wastewater aligns with irrigation standards has emerged as an essential practice. This necessitates enhancements in the treatment process to meet the required quality criteria for safe and effective irrigation use. Nanofiltration (NF) and reverse osmosis (RO) membrane processes are extensively used in water treatment, yielding water of superior quality. However, the discharge of untreated brine can pose environmental risks. Therefore, this study emphasizes the reduction of concentrate volume through the implementation of membrane-in-series configurations.

This research aims to achieve two main goals: first, to reduce the volume of concentrate streams produced by RO and NF processes, and second, to assess the potential reuse of the resulting permeate for agricultural irrigation. To meet these goals, a series of experiments were carried out using different membrane combinations (RO-RO, NF-RO, and RO-NF). The permeate performance was assessed based on Sodium Adsorption Ratio (SAR), Potassium Adsorption Ratio (PAR), salinity rejection, and energy consumption.The obtained results showed that the NF-RO hybrid systems was a very flexible design and the application of NF upstream of RO process is favorable where the satisfactory permeate quality required for irrigation.

Keywords: Configurations, Concentrate, Reverse osmosis, Nanofiltration, wastewater, treatment, batch mode.

I. Introduction

Water scarcity poses a significant threat to both social life and economic development in the Middle East and North Africa (MENA) region [1]. Globally, over 2.3 billion people lack access to safe drinking water [2], and Morocco is no exception, facing steadily dwindling water resources [3]. By 2030, the country's annual wastewater production is estimated to reach approximately 649 million m^3. In response, Morocco has initiated 41 wastewater reuse projects to recycle nearly 32 million m^3 of water annually [4], a promising step towards mitigating water stress that has attracted the attention of researchers [5]. Reusing treated wastewater for agricultural irrigation is a critical solution to global water scarcity, particularly in arid and semi-arid regions [6]. The membrane-in-series approach, which combines reverse osmosis (RO) and nanofiltration (NF), offers significant advantages by enhancing water recovery and minimizing concentrate streams. This method improves the efficiency of water reuse systems by sequentially processing wastewater through multiple membranes, thus reducing the volume of waste and supporting sustainable agricultural practices by providing high-quality irrigation water with a lower environmental footprint.

The objective of this research is to assess the potential of various combinations of membrane pairs operating in batch mode such as (NF-NF, RO-RO, NF-RO and RO-NF) to treat secondary effluent (SE) from the wastewater treatment plant (WWTP) of Kenitra,. The performances of permeate water were evaluated in terms of Sodium Adsorption Ratio (SAR), Potassium adsorption ratio (PAR), salinity rejection and energy consumption.

2. Experimental part

2.1. Characteristics of the SE

The operation of treatment is performed on SE (Feed Water) from the wastewater treatment plant (WWTP) of Kenitra. The characteristics of the collected treated sewage effluent are summarized in Table 1.

Table 1 : Characteristics of the SE (feed water).

Parameters	T (°C)	pH	E (µs/cm)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Cl^- (mg/l)	Na^+ ((mg/l	SO_4^{2-} (mg/l)
SE	**25**	7,4	2510	147,20	172.23	115.89	665,18	416,42	325,12

Experimental setup 2.2

NF and RO experiments are carried out on a semi-industrial pilot NF/RO (E3039) provided by the company TIA (Applied Industrial Technologies; France) (**Figure 1**). It is described in previous studies [7]. The pilot is equipped with two identical modules in series. The mainly characteristics of these membranes are shown in **Table 2**. NF /RO tests were performed with two combinations. Specifically, the concentrate stream from the first membrane was fed into the second membrane, utilizing a membrane in series configuration (**Figure2**).

Figure 1: Photo of NF/RO pilot system

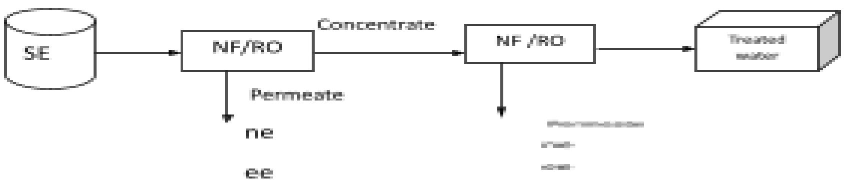

Figure 2: Different membrane combinations

.Table 2: Membranes characteristics

Membrane	Type	Area (m^2)	P max ((bar	pH	Max temp (C°)	Membrane configuration	Material
NF270-40*40	NF	7.6	41	10 - 3	45	Spiral wound	polyamide

BW30LE4040	RO	7.5	41	11 - 2	45	Spiral wound	polyamide

2.3. Performances of calculation

The performances of various tested process were quantified with:

- Salt rejection (R%), which is defined as:

$$R = \frac{C_0 - C_P}{C_0} \times 100$$

.Where $C_0$and Cp (mg/L) are ion concentrations respectively in the initial solution and in the permeate

- Recovery rate (Y) which is defined as:

$$Y = \frac{Q_P}{Q_0} \times 100$$

.(Where Q_p is the permeate flow (L/h) and Q_0 the feed flow (L/h

- Sodium Adsorption Ratio (SAR) which is a defined as

$$\mathrm{SAR} = \frac{[\mathrm{Na}^+]}{\sqrt{\frac{[\mathrm{Ca}^{2+}]+[\mathrm{Mg}^{2+}]}{2}}}$$

- Potassium Adsorption Ratio (SAR) is defined as :

$$\mathrm{PAR} = \frac{[\mathrm{K}^+]}{\sqrt{\frac{[\mathrm{Ca}^{2+}]+[\mathrm{Mg}^{2+}]}{2}}}$$

- Overall recovery rate (%) is defined as:

$$Y_T = \frac{Y_{NF/RO}}{1 - Y_{\frac{RO}{NF}}(1 - Y_{NF}/RO)}$$

Where YNF and YRO are the recovery rate (%) in each stage, respectively

- Specific energy consumption (SEC) for two stages [8]:

$$SEC = \frac{(P_{RO} + P_{NF}) \times 100}{36 \times Y \times \eta}$$

Where PRO, PNF, η and Y are the applied pressure in reverse osmosis and nanofiltration stage (bar), the global pumping system efficiency and the overall recovery rate (%), respectively.

3. Results and discussion

Table 3 indicates the system performance parameters for various two-membrane series configurations, highlighting differences in permeate flow, the overall quality parameters of the permeate produced and theirs salt rejection.

Table 3: Properties of the obtained permeates and their retention for various two membranes series configurations

Parameters	RO-RO		NF-RO		RO-NF		Limits of [irrigation[9
	[ ]	(%) R	[ ]	(%) R	[ ]	(%) R	----
pH	6,00	-	6,36	-	6,02		----

(E (µS/cm	270	89,24	118	95,70	374,25	85,09	1000
(Cl^- (ppm	27,6	92,84	19	97,14	68,47	89,71	102
(Ca^{2+} (ppm	8.21	95,24	1.2	99,30	9,5	94,48	40
(Mg^{2+} (ppm	10.96	90,54	7,84	93,23	13,08	88,71	24
(Na^+ (ppm	22,0	97,12	20,3	95,13	45,69	86,63	65
(SO_4^{2-} (ppm	12,68	96,10	6,75	97,92	22,03	93,22	20
(K^+ (ppm	9.2	90,53	5,63	94,40	10,05	90,63	10
(P(bar	12		8+10		10+8		----
(%) Recovery	37.4		20.12	15.74	----	17.64	-----
(%) Overall recovery	------		57.77		47,85		----
(Permeate flow (L/h	944		1554		1265		----
(SEC(KWh/m^3	0.45		0.31		0.40		----
SAR	2,5 Slight to moderatee		1,5 Slight to moderatee		4,51 Slight to moderatee		[10]
PAR	1,05 None		0,93 None		1,16 None		[10]

As shown in Table 7, the analysis of the results indicate that the:

- All the proposed treatment systems are capable of producing water in which all ion parameters comply with FAO regulations for irrigation, with an additional advantage for the NF-RO combination.
- The difference in separation performance between NF and RO membranes is due to structural differences, with NF having a larger pore size than RO.
- The hybrid system shows superior retention of chloride and sodium ions of all tested combinations.
- In terms of recovery rate, the order is as follows NF-RO > RO-NF > RO-RO, while the order of energy consumption and cost are decreased in the following order: RO-RO > RO-NF > NF-RO.
- All SAR values fall within the "slight to moderate" risk category, indicating a moderate potential for sodium accumulation in the soil.
- Sodium accumulation could affect soil structure over time, requiring some sodium management for irrigation.
- PAR values fall in the "None" risk category, meaning the water poses no significant risk to soil permeability.

4. Conclusion

The study demonstrates that membrane-in-series configurations, particularly NF-RO, effectively reduce concentrate volumes while producing permeate of high quality suitable for agricultural irrigation. All proposed treatment systems meet FAO regulations for irrigation water quality, with NF-RO showing superior chloride and sodium ion retention. Although NF membranes allow for slightly larger pores compared to RO, their combination with RO results in better recovery rates and lower energy consumption. While SAR values indicate a slight to moderate risk for sodium accumulation, appropriate sodium management is necessary to preserve soil structure. Additionally, low PAR values confirm that the water poses no risk to soil permeability, making it highly suitable for sustainable irrigation practices.

5. Reference Bibliographique

[1] El-Ghzizel, S., Zeggar, H., Elmidaoui, A., & Taky, M. (2024). Nanofiltration powered by renewable energy for softening of slightly brackish-nitrated groundwater: Sustainability study. *Journal of Water Process Engineering*, *60*. https://doi.org/10.1016/j.jwpe.2024.105223.

Boudhar, A., Boudhar, S., Oudgou, M., & Ibourk, A. (2023). Assessment of Virtual Water Flows in Morocco's [2] .Foreign Trade of Crop Products. *Resources*, *12*(4). https://doi.org/10.3390/resources12040049

[3] Hazra, M., Ouzbair, M., Maolida, I., Elrhaouat, O., Tahaikt, M., Elmidaoui, A., Taky, M., & Belhamidi, S. (2024). Evaluation Study of Ammonium Removal from Groundwater by Electrodialysis: Case Study of Real Groundwater from the City of Kenitra in Morocco. *ChemistryOpen*, *13*(5). https://doi.org/10.1002/open.202300163

Bel Haj, H., Ben Zhir, K., Aboulhassan, M. A., & El Ouarghi, H. (2023). Impact assessment of treated [4] wastewater reuse for irrigation: Growth potential and development of lettuce in Al Hoceima province, .Morocco. E3S Web of Conferences, 364. https://doi.org/10.1051/e3sconf/202336401002

Duque, A. F., Campo, R., Rio, A. V. Del, & Amorim, C. L. (2021). Wastewater valorization: Practice around [5] the world at pilot-and full-scale. In *International Journal of Environmental Research and Public Health* .(Vol. 18, Issue 18). MDPI. https://doi.org/10.3390/ijerph18189466

[6] Yang, J. Monnot, M. Eljaddi, T. Ercolei, L. Simonian, L. and Moulin, P. (2021).Ultrafiltration as tertiary treatment for municipal wastewater reuse," *Sep Purif Technol*, vol. 272, Oct. 2021, doi: 10.1016/j.seppur.2021.118921.

[7] Elazhar, F. Elazhar, M. El Filali, N. Elmidaoui, A. Taky, M. (2021). Potential of hybrid NF-RO system to enhance chloride removal and reduce membrane fouling during surface water desalination**,** Separ. Purif. Technol., 261, p. 118299

[8] Elazhar, F. Elazhar, M. El-Ghzizel, S. Tahaikt, M. Zait, M. Dhiba, D. Elmidaoui, A. Taky, M. Nanofiltration-reverse osmosis hybrid process for hardness removal in brackish water with higher recovery rate and minimization of brine discharges. Process Safety and Environmental Protection, 2021, 153, pp. 376–383. Doi : 10.1016/j.psep.2021.06.025.

[9] Ayres, R.S.; Westcot, D.W. FAO Irrigation and Drainage Paper; Food and Agriculture Organization of the United Nations: Rome, Italy, 1985.

[10] Hacıfazlıoğlu, M.C., Tomasini, H.R., Bertin, L., Pek, T.Ö., & Kabay, N. (2019). Concentrate reduction in NF and RO desalination systems by membrane-in-series configurations: Evaluation of product water for reuse in irrigation. Desal., 466, p. 89-96. DOI:10.1016/j.desal.2019.05.011.