Original Article

Selection of optimal draw solution recovery technology for forward osmosis desalination system using analytical hierarchy process

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ABSTRACT

Water scarcity poses a significant threat to global food and water security, prompting a need for practical solutions. With 97% of Earth's water situated in oceans, desalination emerges as a viable option. Among desalination technologies, forward osmosis (FO) using membrane-based technology stands out for its potential to reduce costs and energy requirements. The focus on energy consumption in FO has prompted an exploration of optimal technology selection through the Analytical Hierarchy Process (AHP), a multi-criteria decision-making method. Value judgments were collected through a questionnaire in consultation with two experts. Environmental aspects emerged as the most critical factor, weighted at 0.3963. The AHP analysis revealed nanofiltration (NF) as the optimal system, attaining a total weight of 0.2612. The NF scored highest in terms of environmental impact (C3), operating and maintenance costs (S6), and energy requirements (S4). Conversely, membrane distillation ranked as the least preferred alternative, with a total score of 0.1335, mainly due to lower maturity of technology (S3), higher capital costs (S5), and negative environmental impact (C3). Sensitivity analysis was conducted to investigate how changing weights for sub-criteria might affect the preferred technology. Notably, Reverse Osmosis became the most favored technology when efficiency (S1) and S3 weights were set at 0.3 and 0.2, respectively. Conversely, thermal separation gained preference when the weights for resistance to scaling and fouling (S2) and S5 were set at 0.3. Changes in S4, S6, and C3 have showed the most minor sensitivity.

Keywords: membrane, nanofiltration, thermal separation, water scarcity

INTRODUCTION

Water scarcity is an emerging global issue. It is characterized by an insufficient water supply to meet demand (Tzanakakis et al. 2020). This issue results either from unfavorable environmental conditions or inadequate technology (United Nations – Water n.d.). Approximately 2.3 billion people inhabit water-stressed environments, with contaminated water causing 3.4 million annual fatalities. Only 2.5% of Earth's water is freshwater, with a mere 1% accessible to humanity. The United

Nations is dedicated to ensuring universal access to water and sanitation, integral components of its sustainable development goals.

Desalination, the process of extracting salts and pollutants from seawater, brackish water, or wastewater, presents as a promising solution (Feria-Diaz et al. 2021). Progress in membrane technology has made membrane filtration processes, driven by pressure or concentration gradients, more cost-effective and environmentally friendly compared to thermal desalination using steam (Chaoui et al. 2019).

Among membrane technologies, reverse osmosis (RO) has been considered the optimal choice for seawater desalination. However, RO membranes face durability and efficiency challenges related to scaling (Feria-Diaz et al. 2021). Conversely, forward osmosis (FO) attracted attention due to its lower energy requirements and reduced membrane fouling compared to RO, making it a promising option in desalination.

Overall, membrane filtration technologies offer improved cost efficiency compared to traditional thermal desalination technologies, driving their increased adoption in the field (Chaoui et al. 2019). In forward osmosis, water from the feed of low concentration flows through the semipermeable membrane alongside the draw solution (DS) of high concentration. The disparity in osmotic pressure between the two solutions leads to the separation of water from unwanted solutes while diluting the draw solution. The solution containing unwanted solutes is discharged as wastewater, which can be treated later. Meanwhile, the diluted draw solution undergoes further treatment in a recovery system to obtain the desired clean water. Most energy consumed in forward osmosis desalination is expended in the draw solution recovery phase. Therefore, selecting the appropriate technology is imperative as it profoundly affects the efficiency and economic viability of the desalination system.

Various draw solution recovery technologies, including thermal separation for volatile compounds, are employed but with high energy costs. Membrane-based methods such as reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and membrane distillation (MD) are widely used. High-temperature RO is effective for thermo-responsive draw solutions, while FO-NF hybrid systems achieve high water recovery. The NF is more cost-effective than RO, and UF filters small molecules. Membrane distillation offers high water recovery and low investment costs but may encounter scaling and maintenance issues. Considerations for selecting a desalination technology include energy demand, economic viability, and water quality.

The Analytical Hierarchy Process (AHP), developed by Thomas L. Saaty in 1970, organizes information. Saaty and Ozdemir (2014) underscore the importance of carefully considering the expertise needed for a decision and highlight that, in many cases, a single expert judge may suffice. The problem in this study concerns the selection of the optimal draw solution recovery technology for forward osmosis desalination. Expert consultations and literature review revealed four potential solutions: RO, UF, NF, and MD. Criteria under consideration encompass economic viability, energy requirements, water quality, and system efficiency.

Water scarcity threatens 50% of the world's population by 2050, with 97% of water being salt water. Desalination systems often a promising solution; however, they often rely on high energy consumption and economically inefficient methods. Technologies include thermal separation, electrodialysis, and membrane-based methods like RO, FO, and MD. The majority of the energy consumed in FO is allocated to draw solution recovery. Selecting the best draw solution recovery technology will maximize FO desalination systems.

The study aims to identify the optimal draw solution recovery technology for forward osmosis in desalination systems using the AHP methodology. Specifically, the study employs pairwise comparisons to determine the weight of each criterion and sub-criterion, considering technical, economic, and environmental aspects. The ranking of alternatives is based on the global weights of the criteria and subcriteria. In addition, sensitivity analysis was conducted to determine the most influential factors and how the weights affect the ranking of alternatives.

The study employed the Analytical Hierarchy Process (AHP) to compare TS, RO, MD, NF, and ED. These technologies were analyzed comprehensively considering technical aspects, economic viability, and environmental impact. Each criterion and technology were compaired in a pairwise manner through consultations with experts with at lease ten years of of experience in the relevant field. These experts have not only accumulated substantial experience but have also produced significant studies in the fields of forward osmosis, membrane systems, and desalination. Their contributions to these areas validate their expertise and justify their inclusion in the study. For this research, two experts were interviewed to enrich the depth of analysis further.

The study did not seek to specify the characteristics of the forward osmosis membrane, including the membrane type, operating conditions (pressure and temperature), and reaction time. Moreover, the specifics of the technologies considered, such as the kind of membrane, were not specified. Achilli et al. (2010) noted that NaCl is commonly used due to its solubility, low toxicity, and scaling prevention but found it one of the least effective draw solutes. They observed that $MgCl_2$ performed better with a high recovery rate, suggesting it may be the best draw solute for water and wastewater treatment. Arcanjo et al. (2020) used $MgCl_2$ and NaCl in an FO-MD hybrid system, finding that $MgCl_2$ reduced FO reverse salt flux and was completely rejected by the membrane distillation process. With literature review and conversation with the experts, this study was limited to considering $MgCl_2$, as the draw solution for the forward osmosis process.

METHODS

Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) is a multi-criteria decision analysis method utilized for comparing the weights of each criterion relative to each other in determining the best alternatives. Developed by Thomas Saaty in 1970, Analytic Hierarchy Process (AHP) is most effectively applied in selecting the optimal alternative. The process is summarized in Figure 1.

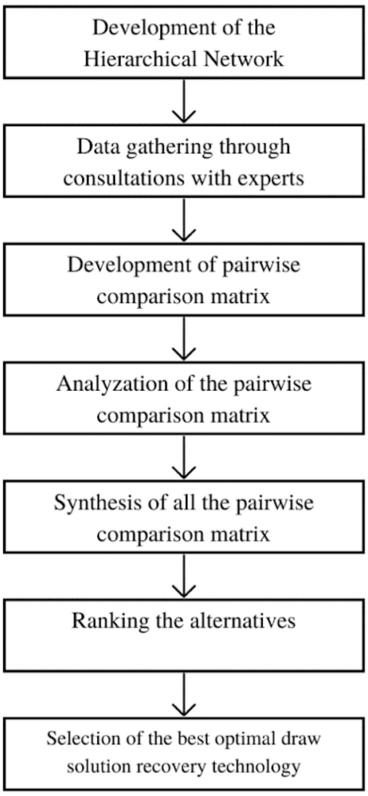

Figure 1. Overview of the analytical hierarchy process (AHP).

The preliminary step in AHP involves the construction of a hierarchical network with three levels (Figure 2). The first level represents the goal. In this study, the goal is defined as selecting the optimal draw solution recovery technology. The second level consists of the criteria and sub-criteria, while the third level comprises the alternatives. Following a review and expert consultation, the identified criteria include Technical Aspect (C1), Economic Aspect (C2), and Environmental Aspect (C3). Six sub-criteria were determined: efficiency (S1), resistance to scaling and fouling (S2), maturity of technology (S3), energy requirement (S4), capital costs (S5), and maintenance and operating costs (S6). C3 does not have sub-criteria.

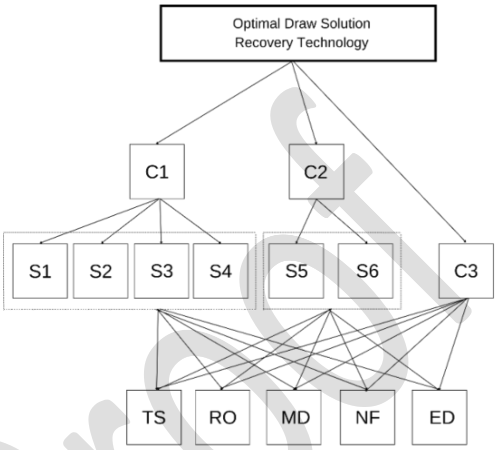

Figure 2. Hierarchical network for analytical hierarchy process (AHP). C1 – Technical Aspect; C2 – Economic Aspect; C3 – Environmental Aspect; S1 – Efficiency; S2 – Resistance to Scaling and Fouling; S3 – Maturity of Technology; S4 – Energy Requirement; S5 – Capital Costs; S6 - Operating and maintenance costs; TS – Thermal Separation; RO – Reverse Osmosis; MD – Membrane Distillation; NF – Nanofiltration; ED – Electrodialysis.

Pairwise Comparison

Value judgments for pairwise comparison were gathered from the experts. A questionnaire was formulated describing the study's objectives, criteria, sub-criteria, and alternatives. Experts rated each criterion/sub-criterion and alternatives relative to each other using Saaty's scale of relative importance (1980), as shown in Table 1. Pairwise comparison matrices were constructed based on the collected expert value judgments with an example shown in Table 2. The geometric mean of the value judgments was used in the matrices due to multiple experts' involvement.

Table 1. Saaty's scale of relative importance.

Definition	Equivalent
Equal Importance	1
Equal to moderate Importance	3
Strong importance	5
Very strong importance	7
Extreme importance	9
Intermediate values	2, 4, 6, 8, 10

Determination of Criteria, Sub Criteria, and Alternatives

Upon conducting a literature review and expert consultation, the environmental impact of the draw solute recovery system was identified as primarily concerning CO_2. Thus, the environmental aspect focuses only on greenhouse gas emissions in carbon dioxide equivalents, as shown in Table 3. The alternatives were determined through literature review and expert consultation. Initially, ultrafiltration was considered. However, the pore size was the only significant difference between ultrafiltration (UF) and nanofiltration (NF). Moreover, NF showed more promising results with $MgCl_2$ as the draw solute, UF was omitted as an alternative. The final alternatives selected were thermal separation (TS), reverse osmosis (RO), membrane distillation (MD), nanofiltration (NF), and electrodialysis (ED). The hierarchical network is shown in Figure 2. Definitions of factors are summarized in Table 3.

Table 2. Example of a pairwise comparison matrix. C1 to C5 – example criteria; a_{12} – value judgments comparing C1 and C2; a_{13} – value judgment comparing C1 and C3; a_{14} – value judgment comparing C1 and C4; a_{15} – value judgment comparing C1 and C5; a_{23} – value judgment comparing C2 and C3; a_{24} – value judgment comparing C2 and C4; a_{25} – value judgment comparing C2 and C5; a_{34} – value judgement comparing C3 and C4; a_{25} – value judgement comparing C3 and C5; a_{45} – value judgement comparing C4 and C5; w_1 – calculated weight of C1; w_2 – calculated weight of C2; w_3 – calculated weight of C3; w_4 – calculated weight of C4; w_5 – calculated weight of C5.

Criteria	C1	C2	C3	C4	C5	Priority Weight
C1	1	a_{12}	a_{13}	a_{14}	a_{15}	w_1
C2	$1/a_{12}$	1	a_{23}	a_{24}	a_{25}	w_2
C3	$1/a_{13}$	$1/a_{23}$	1	a_{34}	a_{35}	w_3
C4	$1/a_{14}$	$1/a_{24}$	$1/a_{34}$	1	a_{45}	w_4
C5	$1/a_{15}$	$1/a_{25}$	$1/a_{35}$	$1/a_{45}$	1	w_5

Table 3. Criteria and sub criteria used in analytical hierarchy process (AHP).

Criterion	Sub Criterion	Definition
Technical aspect (C_1)	Efficiency (S_1)	Effectivity of the technology in separating water from the draw solute
	Resistance to Scaling and fouling (S_2)	Frequency of occurrence of scaling and fouling in the membrane
	Maturity of technology (S_3)	Degree of how long the technology has been established and continually improved.
	Energy requirement (S_4)	The amount of energy it takes to separate the water from the draw solute
Economic aspect (C_2)	Capital Costs (S_5)	Initial costs for the equipment
	Operating and maintenance costs (S_6)	Costs for the personnel who will operate and maintain the technology.
Environmental aspect (C_3)		Impact to the environment through GHG emission in carbon dioxide equivalents (kg, CO_2-eq).

RESULTS

Selection of Optimal Recovery Technology

Two questionnaires were administered to the experts. The first focused on their judgment regarding preselected criteria and alternatives, while the second aimed to gather value judgments through performing pairwise comparisons. The results of the first questionnaire were discussed in the methods section since it is essential in creating the hierarchical network. The second questionnaire was administered after the results of the first questionnaire were completed.

Table 2 shows the local and global weights of each criterion and sub-criterion. It can be observed from Table 4 that among the criteria, the environmental aspect (C3) has the most weight at 0.3963, followed by the technical aspect at 0.3963 and the economic aspect at 0.2810. Local weights refer to the weight of each sub-criteria relative to the other sub-criteria within that criterion. Within the technical aspect (C1), efficiency (S1) has the highest local weight (0.4180), while the maturity of technology (S3) has the least weight (0.0494). The economic aspect sees operating and maintenance costs (S6) with a higher weight of 0.8173 than capital costs (S5) at 0.1827. Global weight refers to the weight of the sub-criteria in comparison to the other sub-criteria, regardless of the criteria they are under. With C1 having the second highest score and S1 having the highest score in C1, S1 gained the highest global weight among the sub-criteria. The maturity of technology (S3) has the least global weight. Having no sub-criteria and the highest weight among the criteria, C3 has the highest global weight.

Table 5 shows the different grades for each alternative in every sub-criterion. The higher the grade, the more the technology is preferred in that sub-criteria. Regarding S1, reverse osmosis (RO) has the highest grade of 0.5923. Meanwhile, thermal separation (TS) has the lowest grade of 0.0643. Regarding resistance to scaling and fouling (S2), TS has the highest grade of 0.4428, and RO has the lowest grade of 0.0932. In S3, RO has the highest grade of 0.5276, and membrane distillation (MD) has the lowest grade of 0.0573. Regarding energy requirements (S4), nanofiltration (NF) has the highest grade of 0.3621, and RO has the lowest grade of 0.0670. In S5, TS has the highest grade of 0.5062, and MD has the lowest grade of 0.0389. In S6, NF and electrodialysis (ED) have the highest grade of 0.2854, with MD having the lowest grade of 0.0886. Lastly, in C3, NF has the highest grade of 0.3122, and MD has the lowest grade of 0.1443.

Table 6 shows the overall grade of each technology, along with their ranks. The technology with the highest grade most preferred, the one with the lowest is the least preferred. The NF has the highest overall grade of 0.2621 and ranking highest grade in S4, S6, and C3.

Table 4. Local and global weight of criteria and sub-criteria used in determining the optimal technology.

Criteria	Weight	Sub Criteria	Local Weight	Global Weight
Technical Aspect (C1)	0.32273	Efficiency (S1)	0.4180	0.1349
		Resistance to Scaling and Fouling (S2)	0.2433	0.0785
		Maturity of Technology (S3)	0.0494	0.0159
		Energy Requirement (S4)	0.2893	0.0934
Economic Aspect (C2)	0.28097	Capital Costs (S5)	0.1827	0.0513
		Operating and Maintenance Costs (S6)	0.8173	0.2296
Environmental Aspect (C3)	0.39630			0.3963

Table 5. Summary of grade of each alternative for each criterion and sub criterion.

	Sub-criteria and Criteria						
Alternative	S1	S2	S3	S4	S5	S6	C3
Thermal Separation (TS)	0.0643	0.4428	0.2422	0.0837	0.5062	0.2244	0.1639
Reverse Osmosis (RO)	0.5923	0.0932	0.5276	0.0670	0.0560	0.1161	0.1487
Membrane Distillation (MD)	0.1763	0.2155	0.0573	0.1323	0.0389	0.0886	0.1443
Nanofiltration (NF)	0.0943	0.1130	0.1117	0.3621	0.2877	0.2854	0.3122
Electrodialysis (ED)	0.0728	0.1355	0.0612	0.3549	0.1112	0.2854	0.2310

Table 6. Overall grade and rank of each technology.

Alternative	Grade	Rank
Thermal Separation (TS)	0.1976	3
Reverse Osmosis (RO)	0.1904	4
Membrane Distillation (MD)	0.1335	5
Nanofiltration (NF)	0.2612	1
Electrodialysis (ED)	0.2173	2

Sensitivity Analysis

The study conducted sensitivity analysis to observe rankings change by adjusting the global weight of specific sub-criteria while keeping the other sub-criteria and criteria adjusted with a constant preference ratio. The global weight of the target sub-criteria varied from 0 to 1 in intervals of 0.1. Figures 3 to 9 display the results of this analysis.

Regarding S1, nanofiltration (NF) remained the preferred technology when the grade is 0.2 and below, as shown in Figure 3. However, reverse osmosis (RO) became the preferred technology when the grade of S1 reached 0.3. The behavior of the ranking regarding change in the grade of S1 can be graphically observed in Figure 3.

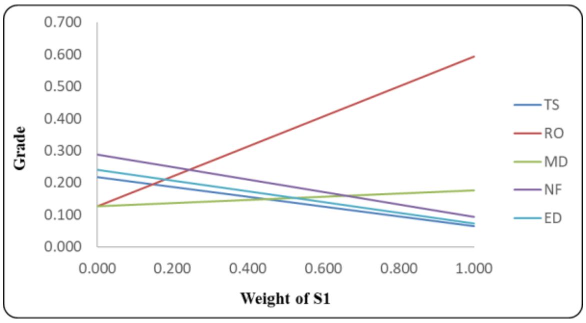

Figure 3. Sensitivity analysis for efficiency (S1). TS – Thermal Separation; RO – Reverse Osmosis; MD – Membrane Distillation; NF – Nanofiltration; ED – Electrodialysis.

Nanofiltration (NF) remained the most preferred technology at a low global weight of S2, as shown in Figure 4. It was observed that thermal separation (TS) would become the most preferred technology when the weight of S2 was increased to 0.3. Thermal separation had the highest grade in terms of resistance to scaling and fouling, making it the optimal choice for this aspect. The behavior of the ranking regarding change in the grade of S2 can be graphically observed in Figure 4.

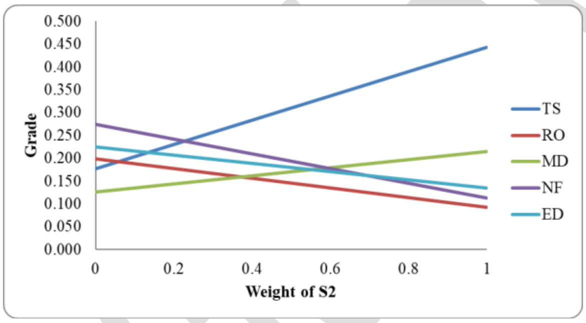

Figure 4. Sensitivity analysis for scaling and fouling (S2). TS – Thermal Separation; RO – Reverse Osmosis; MD – Membrane Distillation; NF – Nanofiltration; ED – Electrodialysis.

Changes in S3 were observed to cause RO to become the optimal technology more quickly than S1, as shown in Figure 5. When the grade reached 0.2, RO became the optimal technology due to its highest score in terms of maturity. The behavior of the ranking regarding change in the grade of S3 can be graphically observed in Figure 5.

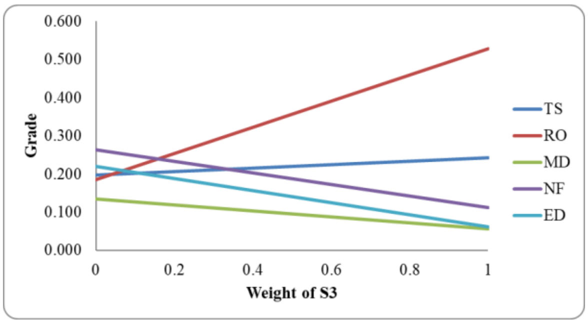

Figure 5. Sensitivity analysis for maturity of mechnology (S3). TS – Thermal Separation; RO – Reverse Osmosis; MD – Membrane Distillation; NF – Nanofiltration; ED – Electrodialysis.

The optimal technology remains NF at all values of S4. However, it can be noted that membrane distillation (MD) ended up as the third technology when the global weight of S4 is set to 0.7. It occurred because the grades of TS and RO significantly decreased as S4 approached 1. The behavior of the ranking regarding change in the grade of S3 can be graphically observed in Figure 6.

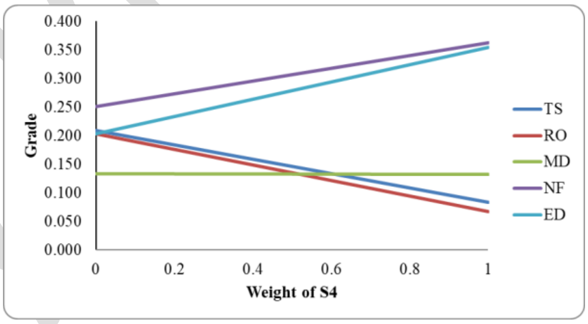

Figure 6. Sensitivity analysis for energy requirement (S4). TS – Thermal Separation; RO – Reverse Osmosis; MD – Membrane distillation; NF – Nanofiltration; ED – Electrodialysis.

Thermal separation went up from the fourth position to the second when the global weight of S5 was 0.1. Eventually, it became the preferred technology when the global weight reached 0.3. It is also evident that this technology is susceptible to capital costs. This sensitivity can be explained by the significant difference in scores regarding S5. Thermal separation achieved a grade of 0.5062, whereas NF lagged with a score of 0.2877. Among the technologies, only TS exhibited a drastic change in ranking. The behavior of the ranking regarding change in the grade of S5 can be graphically observed in Figure 7.

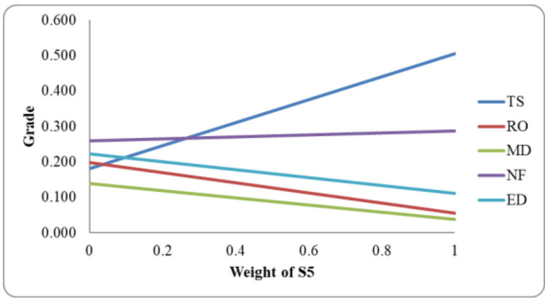

Figure 7. Sensitivity analysis for capital costs (S5). TS – Thermal Separation; RO – Reverse Osmosis; MD – Membrane distillation; NF – Nanofiltration; ED - Electrodialysis.

The rankings were least sensitive to changes in S6 and C3. At all values of S6 and C3, NF remains the most preferred technology, and MD is the least preferred. It can be attributed to the grades of the technology in S6 and C3. Nanofiltration has the highest grades, with MD having the least. The behavior of the ranking regarding change in the grade of S6 and C3 can be graphically observed in Figure 8 and Figure 9, respectively.

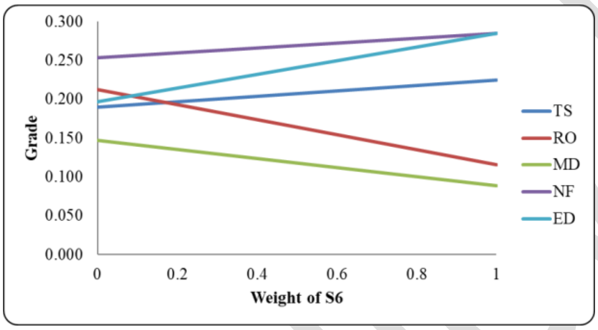

Figure 8. Sensitivity analysis for operating and maintenance cost (S6). TS – Thermal Separation; RO – Reverse Osmosis; MD – Membrane distillation; NF – Nanofiltration; ED – Electrodialysis.

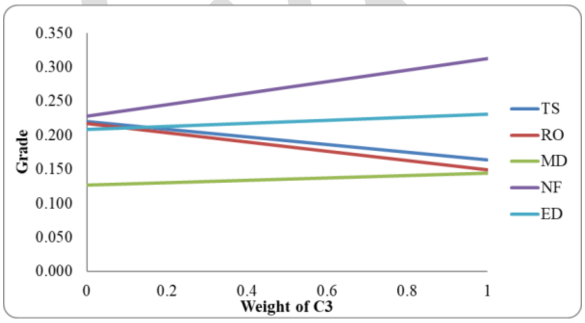

Figure 9. Sensitivity analysis for environmental aspect (C3). TS – Thermal Separation; RO – Reverse Osmosis; MD – Membrane distillation; NF – Nanofiltration; ED – Electrodialysis.

DISCUSSION

Selection of Optimal Recovery Technology

Nanofiltration achieved the highest grades in terms of energy requirement (S4), capital costs (S5), operating and maintenance cost (S6), and environmental impact (C3). Studies have supported the economic viability and environmental impact of NF. Kim et al. (2017) compared Forward Osmosis-Reverse Osmosis (FO-RO) and Forward Osmosis-Nanofiltration (FO-NF) systems, assessing the differences in their environmental and economic performances in hybrid systems. Four draw solutes were considered, namely, MgCl2, NaCl, Na2SO4, and MgSO4. It was determined that FO-RO systems are more efficient, having a consistent 99% rejection rate across all the draw solutes, unlike FO-NF systems, which have a rejection rate of 46% to 94%. However, in terms of energy requirements, the FO-RO system consumes more energy (2.75 kWh/m3) than the FO-NF system (approximately 2.25 kWh/m3) when using MgCl2 as the draw solution. Additionally, the FO-NF system showed a promising result in its global warming impact, with 2.25 kg CO2 – eq compared to FO-RO 2.75 kg CO2 – ep. Bordbar et al. (2022) used life cycle assessment (LCA) in an NF-RO process. This study compared five cases of desalination systems: recirculation multi-stage flash (R-MSF), hybrid RO/R-MSF, NF/R-MSF, single pass RO, and NF/RO system, respectively. It can be observed that nanofiltration is integrated into cases two and four to develop cases three and five. It was found that integrating NF into these processes resulted in a decrease in kg CO2 eq emissions. Integrating NF to case two resulted in a reduction from 7.39 kg CO2 eq to 6.38 kg CO2 eq. In case four, the reduction was 2.16 kg CO2 eq to 1.74 kg CO2 eq despite the addition of equipment. The decrease in these emissions can be attributed to the decrease in the use of thermal energy. Using nanofiltration causes a decrease in the reduction of pressure required in RO.

It was also noted that most of the cost in an FO-NF process can be attributed to the chemical costs. However, Corzo et al. (2018) compared FO-NF with UF-RO and noted that FO-NF costs less in terms of chemical use. FO process can cut costs since it does not require chemical cleaning. The losses in draw solute incur a significant contributor to chemical costs for an NF membrane. However, it was noted that $MgCl_2$ has a fertilizing property, which can further compensate for the costs. It was found that magnesium chloride as the draw solute would reduce operational costs. According to Dutta et al. (2019), NF can also reduce the maintenance cost.

Membrane Distillation (MD) has been ranked last, with a grade of 0.1135. MD received the lowest scores in terms of maturity (S3), capital costs (S5), and the environmental aspect (C3). Roy et al. (2018) noted that MD is an emerging technology that can potentially replace thermal distillation processes. They mentioned ongoing studies exploring possibilities for improving the recovery rate of MD processes, which may include advancements in membrane fabrication to optimize performance. Chaoui et al. (2019) also highlighted that MD is relatively new compared to other membrane-based technologies. Using fuzzy AHP and Grey Relational Analysis, Eusebio et al. (2016) found that FO-MD scored lowest in maturity.

Cabrera-Castillo et al. (2021) conducted a comparison between Forward Osmosis-Membrane Distillation (FO-MD) and Forward Osmosis-Reverse Osmosis (FO-RO) as well as single RO systems. Their findings align with the results of this study. FO-MD was found to have higher capital costs compared to FO-RO and single-RO systems. The need for boilers influences the capital costs in FO-MD systems operating on steam, while FO-MD systems operating on thermal fluid face increased costs due to the heaters. Site development for an FO-MD system is also slightly higher compared to FO-RO.

Additionally, FO-MD membranes are estimated to be costlier due to their lesser commercialization and relative immaturity compared to FO-RO. In contrast to RO systems that rely on pressure, operation and maintenance costs in FO-MD systems were noted to be mainly associated with using steam to produce high-quality water. Although FO-RO systems require a pumping system, the cost is significantly lower than the heating used in FO-MD systems.

Given that MD is relatively new, the membrane replacement cost is significantly higher than that of other membrane systems like FO-RO. Nevertheless, this may be a temporary scenario, as the commercialization of FO-MD could reduce membrane costs. Such scenarios are not addressed in the study but offer opportunities for further exploration.

Glover et al. (2022) conducted a life cycle assessment (LCA) to compare the carbon footprint of a membrane bioreactor-membrane distillation (MBR-MD) wastewater treatment system. They compared it with a baseline system that integrated RO and UF systems. They assessed environmental impacts using the ReCiPe Midpoint (E) impact assessment method. The study found that most of the impact from the baseline and MBR-MD systems is attributable to air emissions. In the MBR-MD system, most of the impact results from the integrated MD system, although this impact has been reduced through the MBR system. The MBR-MD system exhibited a 218-1400% higher environmental impact than the baseline. However, when waste heat is used in MD, the environmental impact of the MBR-MD system is 53.7% lower than that of the baseline system, which integrates RO and UF systems. Elshafei et al. (2022) examined various AHP techniques that could be applied to optimize the establishment of green buildings. The study mentioned that they combined Life Cycle Assessment (LCA) with AHP to account for the environmental impact of each alternative.

Given that environmental impact is one of the criteria (C3) used in this study, future research could explore using AHP with LCA to select the optimal recovery technology. MD has the lowest score in terms of MD. However, there are opportunities to reduce these costs. FO-MD can operate on low-grade heat sources, such as waste heat, due to its ability to function in small temperature gradients. Industrial heat sources from nearby plants or smelters could be potential alternatives, although these need to be specified in this study. The Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis could also be paired with AHP. Eusebio et al. (2016) employed Fuzzy AHP and Grey Relational Analysis (GRA). Fuzzy AHP was used to determine the weights of criteria and sub-criteria, while GRA was employed to establish the grades of the alternatives. Exploring the application of these methods in combination with AHP for future studies is worth considering, especially in determining other factors that may influence the results. It may allow the consideration of factors such as potential for improvement for technologies such as MD.

Reverse Osmosis has the highest grade in terms of efficiency and maturity. It was previously discussed that RO can function with 99% efficiency across different draw solutes, including $MgCl_2$ (Kim et al. 2017). In the study by Do Thi et al. (2021), it was highlighted that RO has the capability to produce water of high purity, removing toxic substances present in brackish water. Unlike in thermal separation, which has the lowest efficiency score, toxic materials were present, as noted by Deiling (2015). Kim et al. (2013) examined a Forward Osmosis-Thermal Separation (FO-TS) hybrid system using various draw solutes. They found that in all the draw solutes used, traces of toxic materials were found and thus resulted in undrinkable water. RO has the lowest grade regarding resistance to scaling and fouling (S2) and energy requirement; both scores can be attributed to RO operating under high pressure. Roy et al. (2018) mentioned that the pressure in the Forward Osmosis-Reverse Osmosis (FO-RO) system results in unwanted pollutants, causing scaling and fouling. Im et al. (2019) also mentioned that scaling and fouling are still problematic in RO.

Regarding S2, Im et al. (2019). also mentioned that the FO-RO system has a relatively higher energy requirement than a two-stage RO system. It agrees with the finding of Kim et al. (2017) when Forward Osmosis-Nanofiltration (FO-NF) was compared to FO-RO, noting that FO-RO consumed more energy than FO-NF. Moreover, Othman et al. (2022) mentioned that a typical RO functions at up to 1000 psi in high pressure. This condition results in high energy requirements and fouling in the membranes. Deiling (2015) mentioned that RO tends to have the most fouling (among all membrane technologies) because the hydrodynamic pressure will carry the unwanted materials on the membrane's surface. It was also noted that RO consumes energy as it functions under high pressure. Unlike in MD, the energy required in an RO system is high-grade to provide the needed pressure.

Considering its heavy reliance on expert judgment, Paulson and Zahir (1994) explored into the uncertainties that can arise in AHP. They pointed out that these uncertainties stem from both external and internal sources. External sources pertain to how value judgments were obtained, while internal sources are related to the expert's limited knowledge of the topic despite their years of experience. Recognizing these uncertainties, Finan and Hurley (1999) suggested a method known as transitive calibration. In this method, experts are asked how they would define the scale initially established by Saaty in terms of percentages. This value is then used to calibrate the rest of the expert's responses. While the method is complex and demands substantial statistical analysis, it can be used when there is no time constraint to yield results with minimal uncertainties.

Sensitivity Analysis

Sensitivity analysis was conducted to assess how rankings could shift by adjusting the overall weight of a particular sub-criteria while maintaining a consistent preference ratio for the other sub-criteria and criteria. Reverse Osmosis emerges as the preferred technology when S1 reaches 0.3 and S3 becomes 0.2. Once S2 and S5 reach 0.3, TS becomes the preferred technology. According to the results of the AHP, RO achieved the highest grade in terms of efficiency, gradually surpassing NF, which dropped to third position. Studies by Kim et al. (2017) and Bordbar et al. (2022) have noted that although NF offers advantages in environmental impact and maintenance cost, RO remains the most efficient technology.

Furthermore, RO holds a considerable advantage over other technologies in terms of efficiency. Efficiency is crucial factor in producing high-quality water. As mentioned by Do Thi et al. (2021), RO operates efficiently, even in the removal of other toxins. Reverse osmosis has established itself as the most mature technology for desalination. Chaoui et al. (2019) and Roy et al. (2018) mentioned that the RO system attracted interest due to the potential for commercializing its products. This is an example of how maturity of technology can influence its global weight, as shown by the adjustment, it only needed to reach 0.2. The preferred technology remained unchange when S4, S3, and C3 were varied, showing minimal sensitivity, with NF retaining its status as the preferred technology. As the weights of S4, S3, and C3 increased from 0 to 1, the grades of NF and ED significantly increased, allowing them to maintain their ranks. In contrast to S4, an increase in the weight of S6 led to a positive change in the grade of TS. However, this change was insufficient to surpass the increasing grades of NF and ED. When the global weight of S6 reached 1, NF and ED jointly claimed the top position both with grade of 0.2854 in maintenance and operating costs. The ranking exhibited minimal changes in response to changes in the grade of C3. It can be observed that when C3 is 0, ED ranks as the fourth technology. Eventually, it became the second preferred technology when the global weight of C3 was set to 0.2. Despite the positive changes in the grade of MD, it remained the least preferred technology. Negative changes were only observed for TS and RO. Although MD scored the lowest in C3, it demonstrated a positive change, attributed to its low scores in other criteria. As C3 approached 1, other sub-criteria approached a value of 0, including those for which MD had relatively lower scores, causing a positive change in MD.

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ETHICAL CONSIDERATIONS

No human or animals were involved or harmed in the conduct of this study.

DECLARATION OF COMPETING INTEREST

The authors declare that there are no competing interests among any authors.

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