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Performance evaluation of a Sea water reverse osmosis system at different operating scenarios

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AbstractThe reverse osmosis (RO) system performance is mainly influenced by four different parameters, including the feed water salinity, the feed water temperature, system recovery and the membrane age. In the current analysis, by employing the LG Chem. software (Q+ projection software v2.4) and the Taguchi method using the Minitab 19 software, the most effective parameter of the proposed RO system and the best level of each parameter were defined. Initial trials were performed to authenticate the LG Chem. software (Q+ projection software v2.4) by comparing the predicted results with the available data in the literature. The obtained results showed that the system recovery the parameter that most affects the produced permeate flow rate, and the average flux produced from the proposed RO system. Moreover, the feed water temperature is the dominant parameter that mainly influences the produced permeate salinity and the concentration of boron of the permeate obtained from the system. Finally, the feed water salinity is the driving parameter that most impacts the inlet feed pressure of the proposed RO system.

Keywords: Reverse Osmosis , Desalination , Salinity, Recovery , Taguchi method , average Flux , Membrane age , LG Chem.

Nomenclature

Symbols

Q_p	Permeate transport rates, m^3/h
Q_s	Salt transport rates, m^3/h
X	Water permeability coefficient
S	Membrane area, m^2
Z	Salt permeability coefficient
T_{CF}	Temperature correction factor
P_f	Feed water pressure, bar
P_p	Permeate water pressure, bar
C_{PF}	Concentration polarization factor
S_{fw}	Feed water salinity, ppm

Abbreviations

RO	Reverse osmosis
ED	Electro dialysis
IX	Ion exchange
SWRO	Sea water reverse osmosis
SEC	Specific energy consumption
ERDs	Energy recovery devices
TDS	Total dissolved solids
TFN	Thin film Nano
SW	Sea water
ERU	Energy recovery unit

Symbols

S_{pw}	Permeate water salinity, ppm
π_f	Feed osmotic pressure, bar
π_p	Permeate osmotic pressure, bar
N_E	Minimum required number of trials
N_P	Number of parameters
N_L	Number of levels for each parameter
n	Total number of trials
y	Response of the given parameter level combination
T_{fw}	Feed water temperature, ºC
R	System recovery, %
$\propto$	Membrane age, year

Abbreviations

PX	Pressure exchanger
SDI	Silt density index
S/N	Signal to noise ratio

1. INTRODUCTION

Natural freshwater supplies are scarce and water shortage has become a serious problem in many countries as a result of unsustainable use and rising pollution. Desalination systems are therefore utilized to produce fresh water from a variety of water sources, such as wastewater, seawater and brackish water. Fresh water can be extracted in limitless quantity from Seawater by desalination. Sea and brackish water are usually desalinated using four common techniques such as thermal evaporation (distillation), reverse osmosis (RO) membrane separation, electro dialysis (ED) and ion exchange (IX). In the case of RO desalination, freshwater is produced from saline source water by pressure-driven passage through semipermeable membranes. The osmosis process happens as pure water flows from a dilute saline solution through a semipermeable membrane into a higher concentrated saline solution. The semipermeable membrane allows pure liquid and some ions to pass but retains the bulk of the dissolved solids (ions). Due to natural osmosis water will flow from the compartment with the low concentration of dissolved solids to the compartment with the high concentration of dissolved solids as an inherent law of nature to maintain equilibrium. The flow of water will continue through the membrane in that one direction until the concentration is equalized on both sides of the membrane. At equilibrium, the concentration of dissolved solids is the same in both compartments and there is no more net flow from one compartment to the other. However, the compartment that once contained the higher concentration solution now has a higher water level than the other compartment as shown in Fig. 1(a). The difference in height between the two compartments corresponds to the osmotic pressure of the solution that is now at equilibrium. If a pressure force is applied to this column of salt water, the path of water flow through the membrane can be reversed. If a pressure greater than the osmotic pressure is applied to a compartment containing a high-concentration solution, fresh water flows through the membrane in the opposite direction to that of the osmosis as shown in Fig. 1(b). Therefore, the water in one compartment is purified or “demineralized,” and the solids in the other compartment are concentrated or dewatered as the membrane is not permeable to salt [1]. Due to the added resistance of the membrane, the applied pressure required to achieve reverse osmosis are significantly higher than the osmotic pressure of the source water, which in turn is proportional to its salinity.

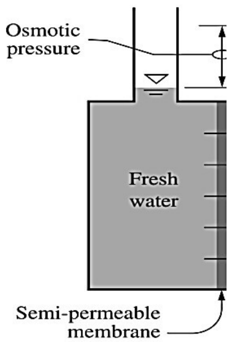

Fig. 1(a) Osmosis process [1].

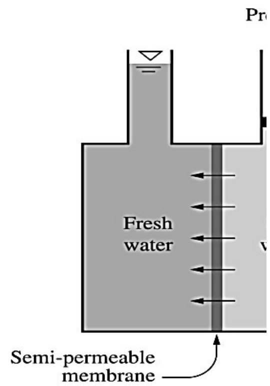

Fig. 1(b) reverse osmosis[1].

Among the various available techniques, the reverse osmosis (RO) is considered to be the most reliable, energy efficient and cost-effective in the production of fresh water [2]. It is reported that about 50% of manufacturing plants around the world use RO Systems due to the high quality of the product water, high system reliability, longevity, low footprint and energy consumption [3].The performance of Operating Sea water reverse osmosis (SWRO) system depend on many Parameter such as feed water Salinity, feed temperature, feed pressure, SWRO System recovery and membrane age. A lot of research has been conducted to study the RO phenomenon, how to enhance the efficiency of RO systems and what are the most efficient design and operating parameters. Jungbin Kim et al. [4] studied and analysed the performance of SWRO plants in an attempt to understand their specific energy consumption (SEC). More than 70 datasets of large-scale SWRO application were investigated. The study explained the increasing number of large-size SWRO plants, the SEC decrease by using isobaric energy recovery devices (ERDs), and the use of different SWRO arrangements to meet the energy and quality requirements. SEC-related parameters, such as feed conditions, target conditions and equipment quality, were also evaluated. They concluded that, high feed water total dissolved solids (TDS) increases energy Consumption, while the temperature effect on energy demand is not entirely clear. Moreover, high-efficiency equipment can reduce SEC, but overall SEC cannot be clarified by these factors alone. SEC is also affected by the required water salinity and flow rate. A further research was performed by M. Elsayed et al. [5] to experimentally investigate the effect of RO operation parameters such as feed water salinity ranging from 2000 to 3000 ppm, feed water temperatures ranging from 29 to 41℃, and feed flow rates ranging from 1.25 to 1.75 L/min. Their results showed that permeate salinity and system recovery are highly affected by feed water salinity. Moreover, increasing the feed temperature increased the permeate salinity, while feed pressure and salt rejection are decreased. Based on the experimental investigation, empiric correlations are obtained for permeate flow rate, permeate salinity, system recovery, feed pressure, and salt rejection as functions of feed temperature, feedwater flow rate, and feed salinity.Young Geun Lee et al. [6] studied the permeate flow rate and TDS concentration of three kinds of commercial RO membranes under different operating conditions [i.e., feed pressure (45–65 kgf/cm^2) and temperature (5–30 °C)]. Based on the experimental data, membrane resistance models including temperature and pressure correction factors were developed for the rapid diagnosis of SWRO membrane performances. Based on the procedure in this study, the performance of any type of RO membranes can be rapidly examined by simple model parameter inputs. Furthermore, the developed diagnosis tool for performance test of SWRO membranes can be practically applied to build database of membrane performance for designing the SWRO process with minimum data as well as to reduce the cost and effort for data acquisition.

In the current analysis, the effect of feed water salinity, membrane age and system recovery on permeate flow rate, permeate salinity, feed pressure, average flux, and boron concentration is inspected and assessed. LG Chem. software (Q+ projection software v2.4) [7] is used to simulate the effect of feed water salinity and temperature, system recovery and membrane age on the RO system performance. Then, for the first time, the Taguchi method is applied to assess the optimum design and operating conditions that attain the optimum permeate quantity and quality.

2. PHYSICAL MODEL

A detailed description of the examined RO system implemented in the current work is presented in Fig. 2. The system consists of RO train of (420) seawater membrane element (LG 400 R) assembled in 60 pressure vessels, each vessel contain 7 membranes. LG Chem's NanoH_2OTM seawater RO membranes are integrated with innovative thin film Nano composite (TFN) technology that reduces desalination costs while providing superior water quality. They provides industry leading salt rejection of 99.85% and produce 20% more flow than membranes manufactured with conventional technologies. Moreover, LG SW 400 R membranes offer a combination of high rejection and low energy requirements to allow lower total costs for seawater systems operating with medium to high-salinity seawater. The detailed dimensions and specifications of LG SW 400 R membranes are listed in Table 1.

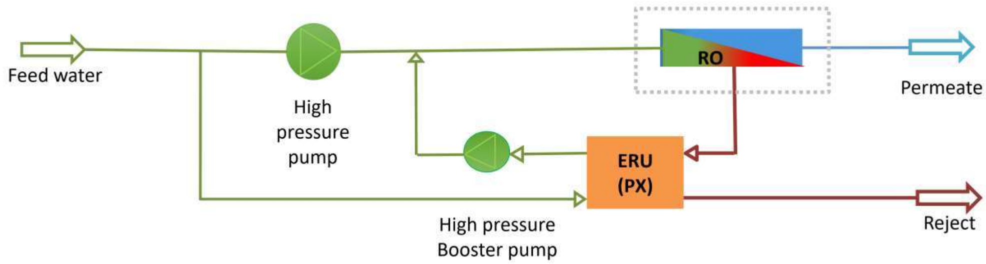

Fig. 2 The physical assembly of the RO system implemented in the current work.

Table 1. Detailed dimensions and specifications of the studied RO system.

Parameter		Value	Unit
Active Membrane Area	:	37	m^2
Permeate Flow Rate	:	34.1	m^3/d
Minimum Salt Rejection	:	99.7	%
Stabilized Salt Rejection	:	99.85	%
Boron Rejection	:	93	%
Element Length	:	1016	mm
Element Diameter	:	200	mm
Max. Applied pressure	:	82.7	bar
Max. Chlorine concentration	:	< 0.1	ppm
Max. Operating temperature	:	45	ºC
pH Operation Rang	:	2-11	
Max. Feed water turbidity	:	1	NTU
Max. Feed water SDI (15 mins)	:	5	
Max. Feed flow	:	17	m^3/h
Min. Ratio of concentrate to permeate flow for any element	:	5:1	
Max. Pressure drop (ΔP) for each element	:	1	bar

3. THEORETICAL ANALYSIS

The goal of this study is to identify the optimum design and operating conditions that attain the maximum possiple performing of the the proposed RO system. The RO system performance is mainly affected by four different parameters, including the feed water salinity, the feed water temperature, system recovery and the membrane age. In the current study, the most effective parameter of the proposed RO system and the best level of each parameter can be determined by applying the Taguchi method, instead of simulating each possible combination of the governing parameters. In the current analysis, the effect of feed water salinity, membrane age and system recovery on the permeate quantity, permeate quality and power consumption is inspected and assessed. LG Chem. software (Q+ projection software v2.4) is used to simulate the effect of feed water salinity and temperature, system recovery and membrane age on the RO system performance. Then, for the first time, the Taguchi method is applied to assess the optimum design and operating conditions that attain the optimum permeate quantity and quality. Q+ projection software basic equations used to analyze the RO system are given as [8]:

$$Q_p = X \times S \times T_{CF} \times \left[(P_f - P_p) - (C_{PF} \times \pi_f - \pi_p)\right] \quad (1)$$

$$Q_s = Z \times S \times T_{CF} \times (C_{PF} \times S_{fw} - S_{pw}) \quad (2)$$

Where Q_p and Q_s are the permeate and salt transport rates, respectively. *X, S*, and *Z* are water permeability coefficient, membrane area and salt permeability coefficient, respectively. Also, T_{CF}, P_f, and P_p are the temperature correction factor, the feed water pressure, and the permeate water pressure, respectively. Finally, C_{PF}, S_{fw}, S_{pw}, π_f, and π_p are the concentration polarization factor,feed water salinity, permeate water salinity,feed osmotic pressure, and permeate osmotic pressure, respectively.

Taguchi method is an optimization technique that uses the standard orthogonal arrays of the operating parameters and their corresponding levels to form a matrix of trials headed for getting maximum information from the minimum number of tests, which saves the computational time and costs [14]. The minimum number of trials needed for this system is given as [9]:

$$N_E = 1 + N_P(N_L - 1) \quad (3)$$

Where N_E, N_P, and N_L represent the minimum required number of trials, the number of parameters, and the number of levels for each parameter, which should be the same for all the parameters.

The signal to noise ratio (S/N) is used in this method for the analysis of the data obtained from different trials to assess the most affecting parameter on the efficiency of the system. There are three types of S/N ratio analysis: larger is better, nominal is best, and smaller is better. The 'larger is better and smaller is better'concepts are applied in the current analysis as the objective is to maximize the system efficiency. Consequently, the S/N ratio is calculated as per equation (4) and (5) for larger is better and smaller is better respectively [10].

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right) \quad (4)$$

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}{y_i}^2\right) \quad (5)$$

where n is the total number of trials, and y is the response of the given parameter level combination. It should be noted that the level with maximum value of S/N ratio is the optimum level of each parameter.

4. SOFTWARE VERIFICATION.

Initial trials were performed to validate the LG Chem. software (Q+ projection software v2.4) by comparing the predicted results with the available data in the literature for which the same system geometry, boundary conditions, and material properties were used. Such comparisons extensively test the accuracy and reliability of the employed software before moving forward. LG Chem. software (Q+ projection software v2.4) verfication was accomplished by comparing the results with the corresponding results of Jungbin Kim et al. [8] as can be seen in Fig. 3(a - d).They study the performance of RO train with a capacity of 10,000 m^3/d consist of 120 Pressure vessels ,with 7 membrane element per Pressure vessel using LG software and modeling program using MATLABR2018b. It should be noted that NaCl was the only type of salt considered. As seen in the figure, a good agreement was found between the current predicted results and those numerically obtained by [8].

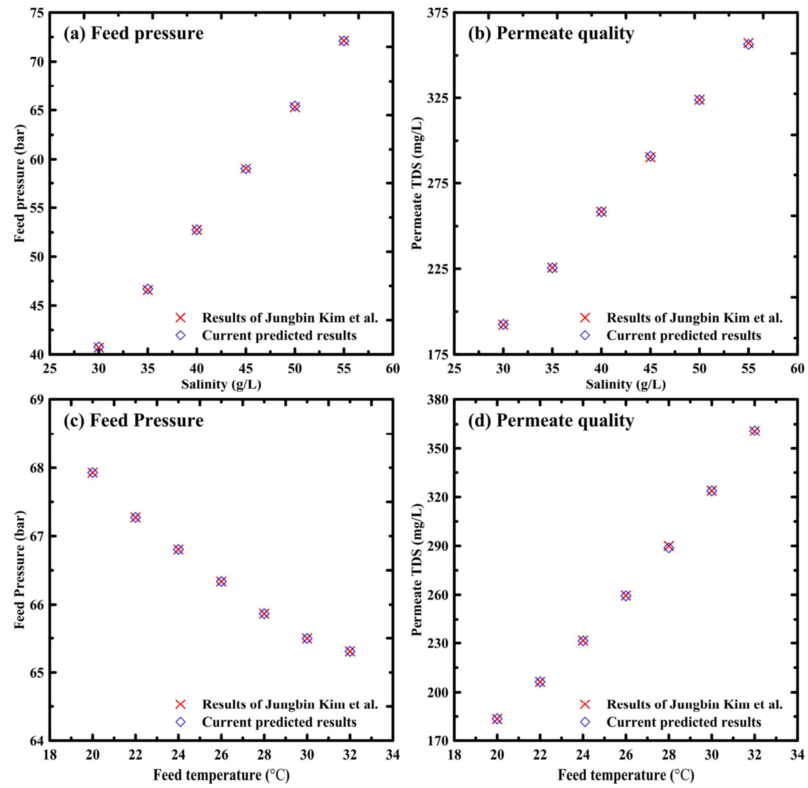

Fig. 3 Software verification (a) Feed Salinity Vs. Feed Pressure (b) Feed Salinity Vs. Permeate quality (c) Feed Temperature Vs. Feed Pressure (d) Feed Temperature Vs. Permeate quality.

5. RESULTS AND DISCUSSIONS

As mentioned above, the RO system performance is mainly influenced by four different parameters, including the feed water salinity, the feed water temperature, system recovery and the membrane age. In the current analysis, by employing the Taguchi method using the Minitab 19 software, the most effective parameter of the proposed system and the best level of each parameter are defined. For each mentioned parameter, five various levels are considered as defined in Table 2. Accordingly, on the basis of Eq. (3), at least 17 trials would be appropriate for this group of parameters (4) and levels (5). Thus, L_{25} (5^6) standard orthogonal array is chosen for this study. Firstly, the LG Chem. software (Q+ projection software v2.4) is used to calculate the output parameter at each trail. Five different performance parameters, including permeate flow rate, permeate salinity, feed pressure, average flux, and boron concentration, are considered as output parameters in the current analysis. Next, the S/N ratio is calculated for each of the operating parameters at each level using 'larger is better' concept (Eq. (4)) and 'smaller is better' concept (Eq. (5)) to determine the rank of each level. The S/N ratio values of each trial are then used to obtain the corresponding values for different levels of each parameter. Each parameter is rated from 1 to 4, based on its effect on the output parameter, noting that the higher the S/N ratios, the more efficient the system is.

Table 2. Governing parameters and their levels in Taguchi analysis.

Operating parameters		Level				
Label	Description	1	2	3	4	5
A	Feed water salinity (S_{fw}), ppm	25000	30000	35000	40000	45000

B	Feed water temperature (T_{fw}), °C	15	20	25	30	35
C	System recovery (R), %	36	37	38	39	40
D	Membrane age ($\propto$), year	1	2	3	4	5

Initially, the effect of the feed water salinity(S_{fw}),the feed water temperature (T_{fw}), the system recovery (R), and the membrane age ($\propto$) on the system-produced permeate flow rate is investigated in order to determine the most effective parameter between them. The 'larger is better' concept is applied in the current analysis as the objective is to maximize the produced permeate flow rate. The S/N ratios for different levels of each parameter and the respective rank are obtained as shown in Table 3. For further clarification, the variation of the S/N ratio values for different levels is presented in Fig. 4. The analysis shows that the system recovery (R) is the parameter that most affects the produced permeate flow rate from the proposed RO system. On the other hand, the influence of the the feed water salinity, the feed water temperature and the membrane age is not as significant as the system recovery as can be seen in Table 3 and Fig. 4. System recovery (R) is defined as the ratio between the permeate flow and the feed flow and is usually selected from 36% to 40 % depending on the required permeate flow. Based on the obtained results it is noticed that the largest permeate flow rate is obtained at 40% system recovery.

Table 3. Response table for S/N ratios for each parameter and the respective rank.

	Level	Operating parameter			
		A	**B**	**C**	**D**
S/N ratio	**1**	47.15	47.15	46.69	47.15
	2	47.15	47.15	46.93	47.15
	3	47.15	47.15	47.16	47.15
	4	47.15	47.15	47.38	47.15
	5	47.15	47.15	47.60	47.15
Delta		0.00	0.00	0.92	0.01
Rank		**4**	**3**	**1**	**2**

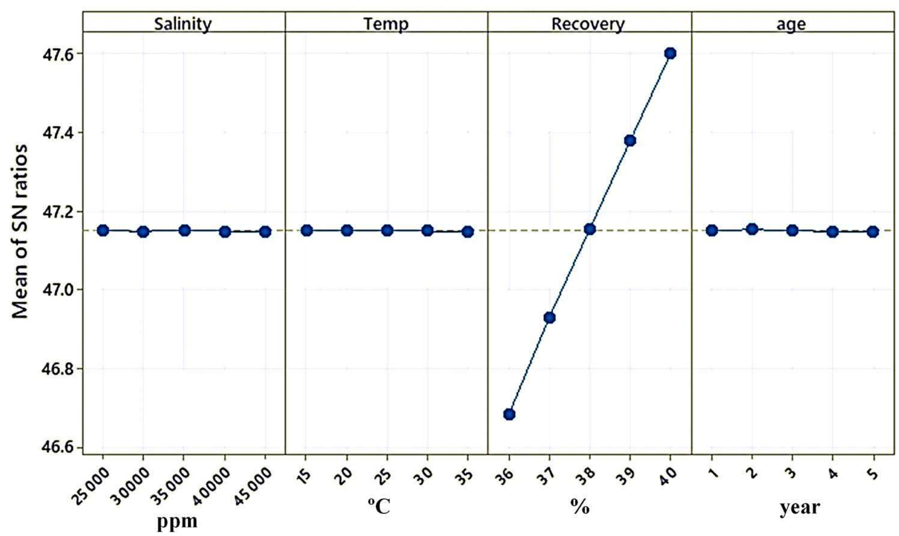

Fig. 4 The S/N ratio values for different levels of feed water salinity, the feed water temperature, system recovery and the membrane age.

Second, the effect of the feed water salinity (S_{fw}),the feed water temperature (T_{fw}), the system recovery (R), and the membrane age ($\propto$) on the produced permeate salinity is inspected and the most effective between them is identified. The 'smaller is better' concept is applied in the current analysis as the objective is to minimize the produced permeate salinity. The S/N ratios for different levels of each parameter and the respective rank are obtained as shown in Table 4 and Fig. 5. The obtained results shows that feed water temperature (T_{fw}) is the parameter that most affects the produced permeate salinity, followed by the feed water salinity and the membrane age, while the influence of the system recovery is not as significant as the other operating parameters. These observation can be explained by the fact that increasing the feed water temperature decreases the viscosity which consequently rises the membrane permeability salt passage. This situation results in an increase in the permeate salinity. In addition, the increase in the membrane age from 1 to 3 years rises the flow losses through it which decreases the produced permeate quantity. However, in order to maintain the same permeate quantity, the feed pressure should be increased to a higher value, which would increase the salt passage and increase the salinity of the permeate. Taguchi analysis shows that the minimum permeate salinity is attined as follows: feed water salinity 25000 ppm, the feed water temperature 15 ºC, system recovery 40% and the membrane age one year.

Table 4. Response table for S/N ratios for each parameter and the respective rank.

	Level	Operating parameter			
		A	**B**	**C**	**D**
S/N ratio	**1**	-41.95	-39.96	-45.19	-43.84
	2	-43.71	-42.54	-45.06	-44.40
	3	-45.18	-45.04	-44.96	-44.96
	4	-46.43	-47.46	-44.85	-45.52
	5	-47.54	-49.80	-44.76	-46.09

Delta	5.59	9.84	0.43	2.25
Rank	**2**	**1**	**4**	**3**

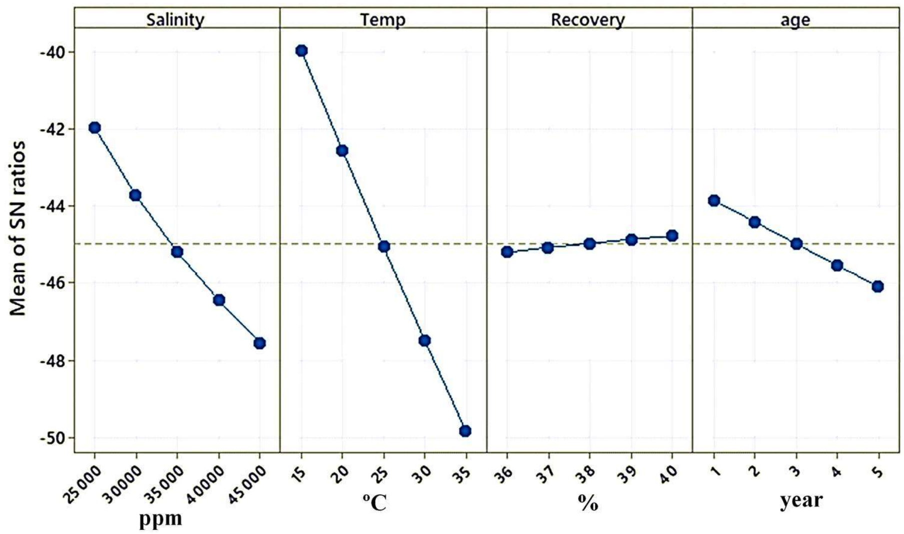

Fig. 5 The S/N ratio values for different levels of feed water salinity, the feed water temperature, system recovery and the membrane age.

Third, the behaviour of the inlet feed water pressure is examined at different levels of the feed water salinity (S_{fw}), the feed water temperature(T_{fw}), the system recovery (R), and the membrane age ($\propto$). The 'smaller is better' concept is also applied in the current analysis as the objective is to minimize the inlet feed pressure provided by the high pressure pump. The S/N ratios for different levels of each parameter and the respective rank are obtained as shown in Table 5 and Fig. 6. It is found that the feed water salinity (S_{fw}) is the dominant parameter that mainly affects the inlet feed pressure provided by the high pressure pump, followed by the feed water temperature, the system recovery and the membrane age as can be seen in Fig. 6. These findings can be explained by the fact that an increase in the salinity of the feed water contributes to an increase in the feed osmotic pressure, which therefore raises the temperature of the inlet water and reduces the needed feed pressure. Taguchi analysis shows that the lowest feed pressure could be achieved as follows: feed water salinity 25000 ppm, the feed water temperature 35 ºC, system recovery 40% and the membrane age one year.

Table 5. Response table for S/N ratios for each parameter and the respective rank.

	Level	Operating parameter			
		A	**B**	**C**	**D**
S/N ratio	**1**	-31.60	-34.74	-33.78	-33.83
	2	-33.04	-34.33	-33.96	-33.96
	3	-34.23	-34.04	-34.18	-34.13
	4	-35.31	-33.79	-34.23	-34.22
	5	-36.33	-33.61	-34.37	-34.36

Delta	4.74	1.12	0.59	0.53
Rank	**1**	**2**	**3**	**4**

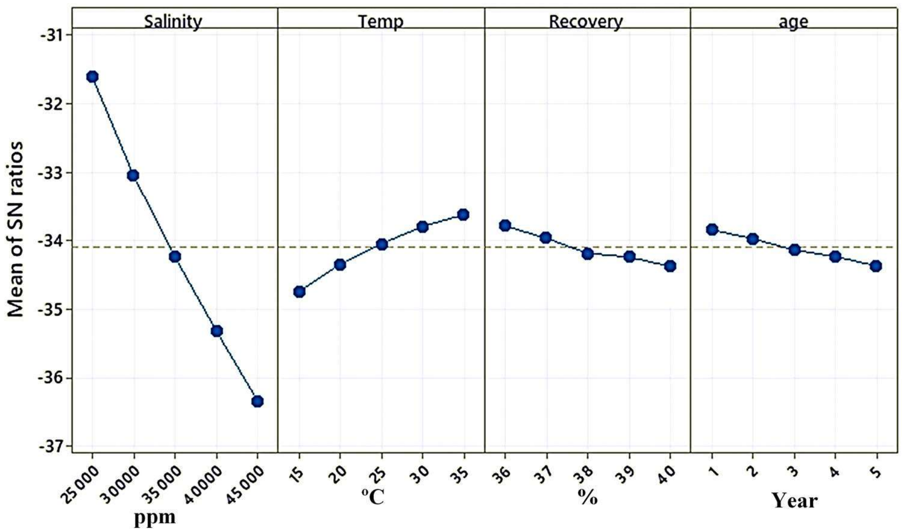

Fig. 6 The S/N ratio values for different levels of feed water salinity, the feed water temperature, system recovery and the membrane age.

Fourth, the influence of the feed water salinity (S_{fw}), the feed water temperature(T_{fw}), the system recovery (R), and the membrane age ($\propto$) on the system average flux is evaluated to define the governing parameter between them. The 'larger is better' concept is applied in the current analysis as the objective is to maximize the system average flux. The S/N ratios for different levels of each parameter and the respective rank are obtained as shown in Table 6 and Fig. 7. The analysis shows that the system recovery (R) is the parameter that most affects the average flux produced from the proposed RO system. Alternatively, the influence of the the feed water salinity, the feed water temperature and the membrane age is not as significant as the system recovery as can be seen in Fig. 7. The membrane permeate flux is defined as the permeate flow that RO membrane produces devided by the membrane unit area. Thus, it is only depend on the System recovery and the selected area of membranes.

Table 6. Response table for S/N ratios for each parameter and the respective rank.

	Level	Operating parameter			
		A	**B**	**C**	**D**
S/N ratio	**1**	23.29	23.30	22.83	23.29
	2	23.29	23.30	23.08	23.30
	3	23.30	23.29	23.30	23.29
	4	23.30	23.30	23.52	23.29
	5	23.29	23.29	23.75	23.29
Delta		0.00	0.00	0.92	0.01

Rank	**4**	**3**	**1**	**2**

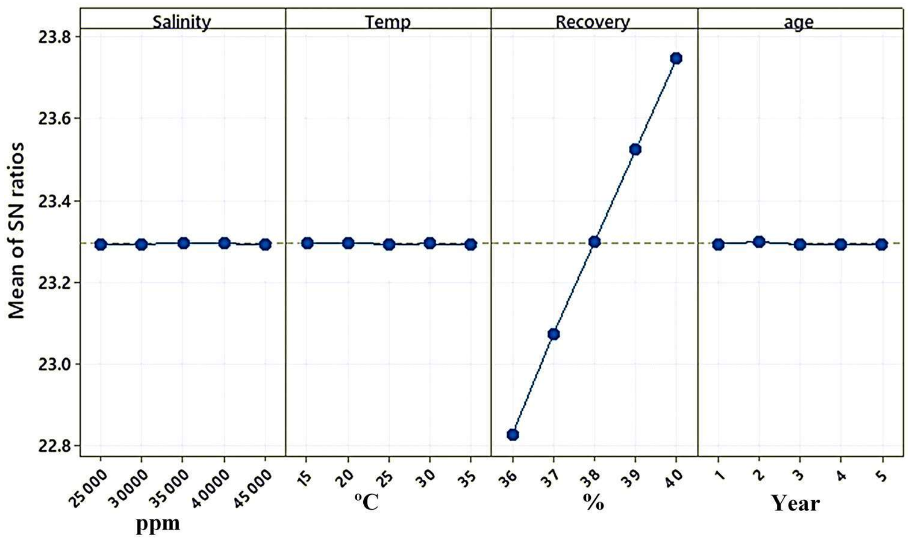

Fig. 7 The S/N ratio values for different levels of feed water salinity, the feed water temperature, system recovery and the membrane age.

Finally, the concentration of boron of the permeate is inspected at different levels of the feed water salinity (S_{fw}), the feed water temperature(T_{fw}), the system recovery (R), and the membrane age ($\propto$). The 'smaller is better' concept is also applied in the current analysis as the objective is to minimize the boron concentration. The S/N ratios for different levels of each parameter and the respective rank are obtained as shown in Table 7 and Fig. 8. It is found that the feed water temperature(T_{fw}) is the dominant parameter that mainly affects the concentration of boron of the permeate, followed by the membrane age, the system recovery and the feed water temperature, as can be seen in Fig. 8. This could be explained by the fact that , as the temperature of the feed water increases, the membrane salt passage increase which subsequently rises the boron concentration of the permeate.

Table 7. Response table for S/N ratios for each parameter and the respective rank.

	Level	Operating parameter			
		A	**B**	**C**	**D**
S/N ratio	**1**	0.1876	3.7891	0.1413	1.2642
	2	0.2409	1.8376	0.3032	0.7996
	3	0.3481	0.1152	0.3506	0.3637
	4	0.4743	-1.3517	0.4649	-0.1099
	5	0.5183	-2.6210	0.5092	-0.5484
Delta		0.3307	6.4102	0.3678	1.8126
Rank		**4**	**1**	**3**	**2**

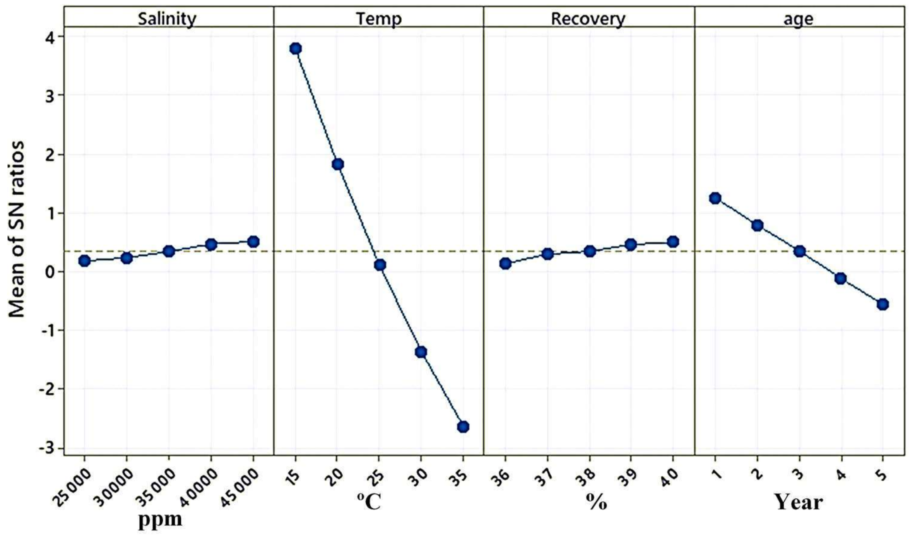

Fig. 8 The S/N ratio values for different levels of feed water salinity, the feed water temperature, system recovery and the membrane age.

6. CONCLUSION

The results of the RO system Performance analysis using Taguchi method and LG Chem. software shows the effect of the feed water salinity (S_{fw}), the feed water temperature(T_{fw}), the system recovery (R), and the membrane age ($\propto$) on the system-produced permeate flow rate, permeate salinity, Feed Pressure,RO system average flux and Permeate Boron Concentration. System recovery (R) is the parameter that most affects the produced permeate flow rate On the other hand, the influence of the the feed water salinity, the feed water temperature and the membrane age is not as significant as the system recovery.Feed water temperature (T_{fw}) is the parameter that most affects the produced permeate salinity, followed by the feed water salinity and the membrane age, while the influence of the system recovery is not as significant as the other operating parameters.Feed water salinity (S_{fw}) is the dominant parameter that mainly affects the inlet feed pressure provided by the high pressure pump, followed by the feed water temperature, the system recovery and the membrane age. the system recovery (R) is the parameter that most affects the average flux produced from the proposed RO system. Alternatively, the influence of the the feed water salinity, the feed water temperature and the membrane age is not as significant as the system recovery.Feed water temperature(T_{fw}) is the dominant parameter that mainly affects the concentration of boron of the permeate, followed by the membrane age, the system recovery and the feed water temperature.

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