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Brackish Water Desalination by Nanofiltration – Effect of Process Parameters

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ABSTRACT

Brackish water is an important source of water resources with lower salt content than seawater. Desalination is a very important treatment to remedy the scarcity of fresh water throughout the world. In this work, it has been proposed to desalinate brackish groundwater using a commercial nanofiltration membrane. The experiments were carried out on the basis of a factorial design using three factors and two levels of study for each variable. For this purpose, it selected the feed pressure (X1) of the membrane module at (60 and 100 psi), feed water salinity (X2) at levels of (3.4 and 6.01 mS/cm) and operating temperature (X3) at levels (20 and 28 °C) to evaluate its effect on the percentage flux recovery and salt retention. The results showed that the most significant variable is the feed pressure, achieving higher flow recovery and the percentage of salinity rejection at the 100 Psi level. This showed that by increasing the pressure from (60 to 100 psi), there was a considerable increase in flow recovery (42 to 72%) and salt rejection (24.6 to 28.4%). Likewise, by increasing the temperature from 20 to 28 °C, the recovered flow rate increased from (49.78 to 63.2%) and the percentage of salt separation showed an increase from 25.95 to 27.05%. Similarly, by increasing the starting conductivity of the brackish water from (3.4 to 6.01 mS/cm) the percentage of flow recovery has decreased from (61.46 to 51.525%). Likewise, the permeate flow rate increased linearly with feed pressure from 132 L/h (P = 40 Psi) to 420 L/h (108 Psi). In conclusion, this research confirms the suitability of the commercial NF membrane studied for brackish water desalination.

Keywords: brackish groundwater, desalination, nanofiltration, experimental design.

INTRODUCTION

Freshwater scarcity has become one of the major concerns of global communities, especially in developing countries with large populations (Wajima and Sekihata, 2023). Water is not only an essential material for humans (70% of our body by weight), but also an important resource for human activities, such as agriculture, commerce, industry, domestic use, etc (Tian et al., 2021). Currently, almost half of the world's population lives in areas that experience water scarcity for at least one month per year, and this number is expected to increase to 5.7 billion people by 2050 (Shannon et al., 2008). By 2025, 60% of the world's population will live in water-scarce areas (Daly et al., 2020). Desalination is the process of removing salts and minerals (contaminants) from seawater or brackish water to obtain clean water suitable for human consumption and industrial and domestic use (Shenvi et al., 2015). Water resources of moderate salinity, such as brackish groundwater, are a valuable alternative for water supply. Brackish water, whose salinity is between 500 mg/L and 10,000 mg/L. They are further subdivided into two categories of low salinity, which process feed water with a salinity of between 500 and 2 500 mg/L, and high salinity, which process water with a salinity of between 2 500 and 10 000 mg/L. Brackish water is an important resource with a lower salt content than seawater, and desalination is an alternative to alleviate the global water crisis. According to statistics, brackish water accounts for 1% of the Earth's total water, which is an important potentially available water resource (Lu and Huang, 2019). Brackish water desalination has been widely used in some arid regions where the availability of potable water is limited. Brackish water desalination currently accounts for more than 20% of the world's total desalination capacity, while seawater desalination accounts for more than 60% of the total capacity (Panagopoulos, 2021). The desalination process necessarily involves high energy consumption, which makes its minimization a major challenge for desalination technologies (Kammoun et al., 2020). An alternative to reduce energy consumption and increase the level of salt removal is to use water with lower salinity (brackish water). Currently, there are three main types of water desalination technologies (Lin, 2020). The first is pressure desalination, which includes reverse osmosis (RO) and nanofiltration (NF); the second category is applied voltage desalination, which is electrodialysis (Fritzmann et al., 2007). While the third desalination technology is thermal distillation, which involves the vaporization of feedwater and its subsequent condensation to obtain distilled water (Caldera and Breyer, 2023). In pressure desalination technology, hydraulic pressure is used to pass water from the feed solution through a semi-permeable membrane that rejects solutes. Reverse osmosis is effectively used to produce drinking water from groundwater sources containing dissolved impurities, such as fluoride, lithium, strontium, boron, arsenic, etc. (Pervov and Spitsov, 2023). However, the energy consumption of reverse osmosis is high, membrane fouling and high pressure operation is another problem to be solved (Mickols et al., 2021; Tan et al., 2023). Depending on the salinity and ionic composition of the feedwater, a recovery of 35 to 90% is expected in NF and RO desalination systems, so that the typical recovery in seawater desalination using RO systems is 35 to 50%, while high recoveries of 70 to 90% can be achieved in brackish water desalination (Strathmann, 2010). Electrodialysis (ED) uses an electric field to transport ions across highly charged ion exchange membranes. When alternating cation and anion exchange membranes are used in a stacked configuration, the saline feedwater is desalinated and effectively concentrated in adjacent compartments (Patel et al., 2024). It currently represents only a small part of the brackish water desalination market (Eke et al., 2020). Thermal distillation requires even more thermal and electrical energy, which makes it very expensive and produces a large amount of greenhouse gases (Eke et al., 2020; Srimuk et al., 2020). Thermal processes have a high level of investment and operating costs and are considered fossil fuel intensive. Therefore, the evaluation of an environmentally friendly and energy efficient technology is highly desirable for brackish water desalination and water softening. Since the salinity level of brackish water is much lower than that of seawater, its osmotic pressure is also much lower than that of seawater, which makes desalination of brackish water much easier and more economical. Nanofiltration (NF) is a relatively recent membrane technology whose characteristics lie between ultrafiltration and reverse osmosis (RO). Among water treatment technologies, pressurized membrane processes such as microfiltration (MF), ultrafiltration (UF), reverse osmosis (RO) and nanofiltration (NF) have proven to be the most energy efficient and technologically sound, in particular, NF membranes better reject multivalent ions and organic molecules with much higher flux than RO membranes (Khan et al., 2023). The nanoscale pores of an NF membrane are usually smaller than 2 nm (Mohammad et al., 2015) and the molecular weight limit (MWCO) is usually between 150 and 800 Daltons (Wang and Lin, 2021). Compared to reverse osmosis, NF membrane has low operating pressure and high permeation flux, so the operating cost is relatively lower (Deepti et al., 2020). Performance of nanofiltration membranes is highly dependent on feed water quality and operating conditions, this results in higher productivity and longer membrane life due to minimized membrane fouling (Madaeni et al., 2015). Studies with brackish water have shown that nanofiltration can remove up to 98% of calcium and magnesium salts and up to 66% of sodium chloride (Galanakis et al., 2012).Studies have mentioned, nanofiltration membranes typically have high rejections of multivalent inorganic salts and small organic molecules at modest applied pressures. In particular, nanofiltration (NF) membranes reject multivalent salts and organic molecules (> 200 Da) (Wang et al., 2018), making them an ideal technology for seawater treatment economically and with high performance compared to reverse osmosis (RO) (Pino et al., 2020).

In this experimental work, the treatment of brackish water by means of a nanofiltration module has been studied and the performance of the permeate flow recovery percentage and salt rejection percentage has been evaluated by varying the conditions of brackish water feed pressure, water conductivity and operating temperature. Pareto analysis and analysis of variance (Anova) of the factors studied were also performed.

MATERIALS AND METHODS

Groundwater characterization

The actual brackish water was extracted directly from the well located in the district of Lurin, Lima, Peru. The characteristics of the brackish water are shown in Table 1. represents concentration of parameters, including salinity, total dissolved solids, electric conductivity, the main ions of interest being Mg^{2+}, Ca^{2+}, Na^{+}, Cl^{-}, NO_3^{-} y SO_4^{2-}. For the analysis of cations such as Ca^{2+}, Mg^{2+}, Na^{+} the following technique was used ICP-OES (Agilent Technologies, Inc., EE.UU.).

Analytical methods

The performance of the brackish water desalination system was investigated in terms of permeate quality and quantity. Conductivity (mS/cm) and TDS (mg·L^{-1}) readings of the permeate and reject streams were taken with a portable ADWA AD 330 conductivity meter. Permeate and concentrate flows (Q_p and Q_r) are recorded with flow meters. Feed and reject pressure readings were also taken through pressure gauges installed in the system

Table 1. Groundwater characterization

No.	Parameter	Unit	Average values
1	Conductivity	mScm^{-1}	6.01
2	pH	…………	7.3
3	Turbidity	NTU	0.28
4	Total dissolved solids	mg/L	2 709
5	Total, hardness	mgL^{-1}	1381.5
6	Calcium	mgL^{-1}	386,6
7	Magnesium	mgL^{-1}	99.7
8	Sodium	mgL^{-1}	554.3
9	Chloride	mgL^{-1}	1307.62
10	Sulphate	mgL^{-1}	469.59
11	Nitrate	mgL^{-1}	137.92

Nanofiltration membranes

A VNF1-4040 polyamide spiral wound membrane (4.0 inch diameter, 40 inch length) and a stainless steel pressure vessel were selected to construct the nanofiltration membrane system and purchased from the company Vontron Technology Co., Ltd., China. The main technical specifications are shown in Table 2, according to the manufacturer's data reported in the literature and previous studies (Liu et al., 2022; Xu et al., 2020)

Nanofiltration unit

The pilot equipment is shown in Figure 1, the main specifications of the membrane are shown in Table 1. A container with a capacity of 150 liters has been installed for the storage and supply of water to the system, as well as two containers for the reception of permeate and concentrate. A pump with a capacity of 10 bar has been installed to transport the feed liquid. The maximum pump output flow is 5 L/min, the system contains a valve to control the permeate flow, three pressure gauges (feed, permeate and reject) and two flowmeters (permeate and reject). A 10-micron filter was installed to protect the high-pressure pump and the nanofiltration membrane. The new membrane was conditioned by filtration with deionized water at a concentration of 10 ppm to stabilize the permeate flux. The feed tank is charged with 150 liters of brackish water, then the water is conveyed to the nanofiltration membrane by pump action, the permeate flow rate is regulated by the valve installed in the reject stream. The test is started at 50 psi and then the reject stream pressure is increased every 10 minutes until 100 psi is reached in the reject stream. Flow and pressure readings are observed directly on the experimental module. The pilot scale system was operated in a continuous regime, collecting permeate and reject in separate vessels, as can be seen in Figure 1 permeate and concentrate flow rates (Q_p and Q_r) were recorded by flowmeters as shown in Figure.

Calculations

The calculation formulas used in these analyses to find the desalination percentage, solute rejection percentage and permeate flow rate are shown in the following equations.

Table 2. The specifications of the membrane

Model	Manufacturer	Maximum operating pressure Psi	Effective area (m^2)	Allowed pH range for feed water	Maximum feed water temperature °C	Molecular weight Cut-Off (MWCO) [Da]
VNF1–4040	Vontron	600	2.6	3–10	45	260

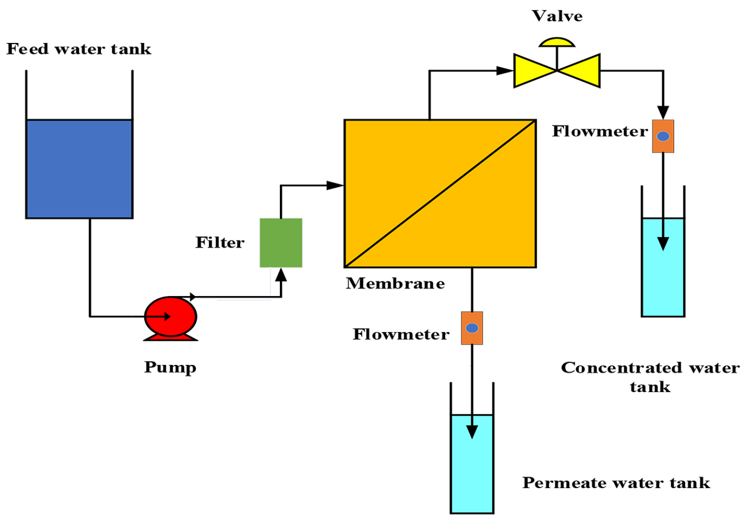

Figure 1. Nanofiltration experimental equipment

Demineralization rate (DR)

The percentage of desalination is evaluated using the Equation 1

$$DR = \left(\frac{\delta_0 - \delta_t}{\delta_0}\right) \times 100\% \tag{1}$$

where: δ_0 and δ_t (mS/cm²) are the electric conductivity of permeate and feed water respectively.

Salt of rejection

Ion rejection was determined from the feed and permeate concentration of the samples collected during the experiments; it is calculated by means of Equation 2.

$$(R) = \left(\frac{C_f - C_p}{C_f}\right) \times 100\% \tag{2}$$

Water recovery

$$Q(\%) = \left(\frac{Q_p}{Q_P + Q_r}\right) \times 100\% \tag{3}$$

where: C_p and C_f are the concentration (mg/L) of permeate and feed, respectively.

$$Q_f = Q_p + Q_r \tag{4}$$

where: Q_r is the rejection flow rate.

The total and partial mass balance in the two streams (permeate and reject) can be written as follows.

$$Q_f C_p = Q_p C_p + Q_r C_r \tag{5}$$

Experimental design

The selected factors and their respective levels were established on the basis of preliminary experiences with the newly constructed equipment. Previous studies have mentioned that the most influential parameters on nanofiltration membranes are feed pressure, temperature, feed flow rate, pH and membrane pores (Ahmad and Alshammari, 2023) The experimental design used in this research was a factorial design for two levels and three factors (2^3) 16 runs (2 replicates) were performed and the average flux recovery and solute rejection have been reported as the response. The Pareto plot were carried out using minitab 18 software. Table 3 shows the factors and levels under study.

RESULTS AND DISCUSSION

Results of the studied variables

Table 4 shows the results of flow recovery and salt retention for each test performed, according to the proposed experimental design. Flow recovery is between (33.9–86.3%) and salt retention is between (21.7–31.7%).

Table 3. Factors and study levels

Factors	Units	Notation	Levels	
			-	+
Feed pressure	Psi	X1	60	100
Conductivity of the feed solution	mS/cm	X2	3.4	6.01
Feed temperature	°C	X3	20	28

Table 4. Matrix design and experimental results

No.	X1	X2	X3	Flow recovery (%)	Salt retention (%)
1	60	3.4	20	42.05	28.2
2	100	3.4	20	66.6	23.5
3	60	6.01	20	33.9	21.7
4	100	6.01	20	56.6	30.4
5	60	3.4	28	50.9	25.8
6	100	3.4	28	86.3	31.7
7	60	6.01	28	42.8	23.1
8	100	6.01	28	72.8	27.6

The descriptive statistical results were analyzed for flow recovery and salt retention, the values of which are shown in Table 5. The standard deviation for flow recovery and salt retention are 6.26 and 1.27**.**

Pareto analysis

The effect of the main factors and their interactions on the response variable can be observed by means of a Pareto diagram. The Pareto diagram was used to draw conclusions about the most significant variables and the interactions between them. Bars crossing the reference line (vertical plot) with horizontal bars (Factors and interactions) in a Pareto diagram are statistically significant. Figure 2 shows that the horizontal line (factor A), crosses the baseline at 17.92. This factor was statistically significant at the 0.05 level. Likewise, it is observed that factors C and B do not contribute significantly. It is also observed that the interaction of the factors (AC, AB, BC and ABC) does not have a significant influence on flow recovery. Figure 2 shows that the variable of greatest significance is factor B in the concentration of total dissolved solids in the permeate.

The main effects

The main effects plot (Figures 3 and 4) shows the effect of each factor on the response variable

Effect of the operating parameters

Effect of feed pressure impact

Figure 3 shows that increasing the feed pressure to the nanofiltration system has a significant effect on the percent flux recovery, as the operating pressure increases (60 to 100 Psi) very significant changes in percent flux recovery are observed. When the pressure is at the low level (60 Psi) a flow recovery of 42% is achieved and when the pressure is at the high level (100 Psi) a flow recovery of 72% is achieved. Figure 4 shows that the feed pressure shows a slight positive trend in the percentage of salt rejection (24.6 to 28.4%). The slight positive trend in membrane solute rejection is attributed to increased water flux through the membranes, leading to a decrease in permeate concentration. In addition, increased operating pressure contributes to increased mechanical compaction of the membrane, which in turn reduces the membrane pore size and increases membrane

Table 5. Standard deviation of the response variables

Response variable	N	Mean	Standard error of mean	Desv.Est.	Variance
Flow recovery	8	56.49	6.26	17.71	313.48
Salt retention	8	26.50	1.27	3.59	12.92

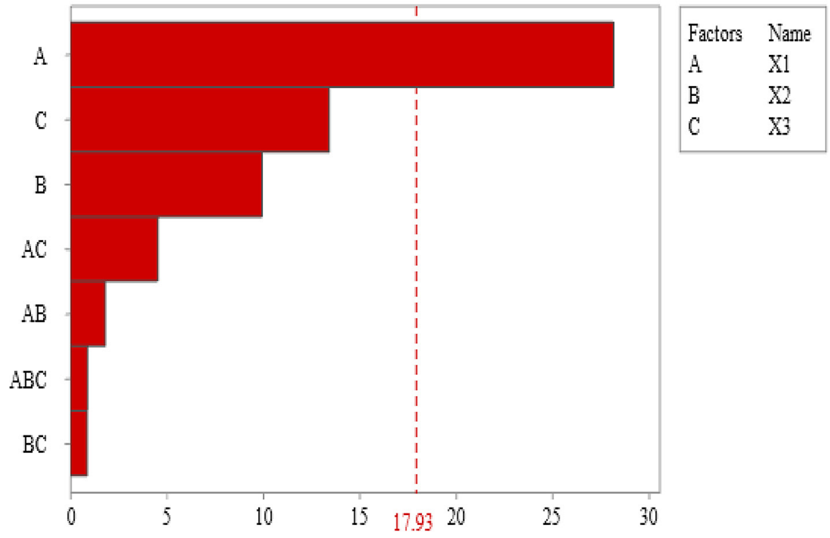

Figure 2. Pareto plot for recovery of flow

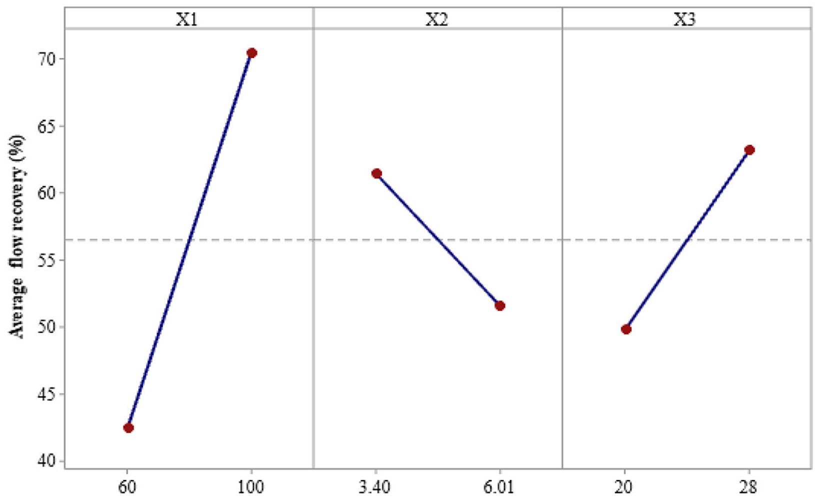

Figure 3. Primary-effects plot for flux recovery (%)

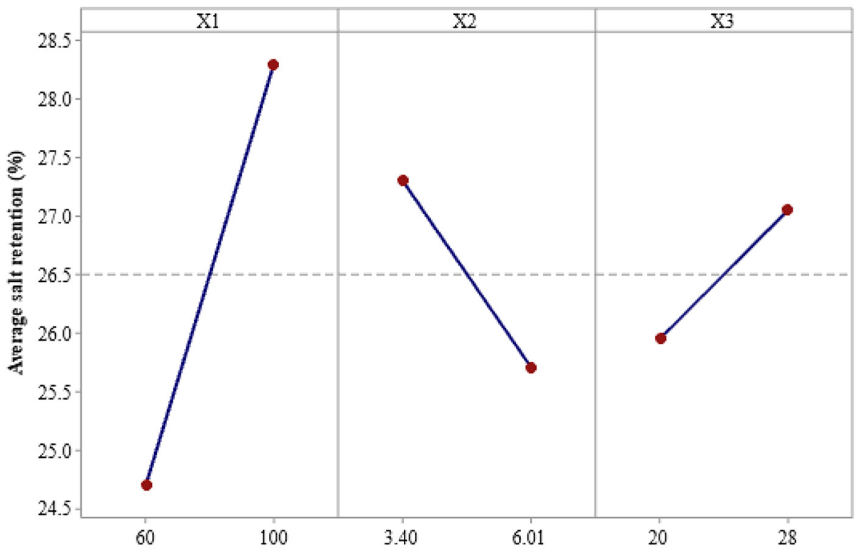

Figure 4. Primary-effects plot salt retention (%)

rejection (Bohonak and Zydney, 2005). In this sense, the increase in operating pressure increases the permeability of water through the membranes, which in turn increases the permeate flow rate. As reported in previous studies with similar membranes, the flux across membranes was found to be proportional to the transmembrane pressure. The permeate flux increases with increasing feed pressure (ΔP), which means that the rate of increase of the feed pressure exceeds that of the osmotic pressure (Jeon et al., 2023).

Effect of initial conductivity

To show the influence of the initial concentration of dissolved salts in brackish water on the percentage of flux recovery and the retention rate, the nanofiltration membrane was studied using a solution with conductivities of 3.1 and 6.1 mS/cm. The results obtained are shown in Figure 3 for a low solution conductivity level of (3.1 mS/cm), a flux recovery of 63% has been achieved and with a conductivity of 6.1 mS/cm, 52%. Figure 4 shows that the rejection of salts through the membrane has decreased as the conductivity of the feed water increases. It has been observed that at an initial conductivity of 3.1 mS/cm, a salt retention rate of 27.4% is achieved, while when the initial conductivity is 6.1 mS/cm, the salt retention rate is 25.6%. Previous studies have mentioned that the salinity of the water in the feed stream affects the feed pressure (ΔP) and salt rejection. Previous studies revealed a difference in the level of retention rates, which was manifested by a difference in the 0.01 and 0.1 M Na_2SO_4 concentrations when using the NF270 membrane.

Effect of temperature

Figure 3 shows that the increase in temperature levels (20 and 28 ºC) has a very significant effect on the flow recovery percentage, at 20 ºC a recovery percentage of 49.9% and at 28 ºC 63.2%. Previous studies have mentioned that, as the temperature increases, the solvent viscosity decreases, which reduces the membrane resistance, while the permeate flux increases (Hendaoui et al., 2018) . Figure 4 shows that the temperature has a low influence on the percentage of salt retention at 20 °C (25.9%) and at 28 °C (27.05%). They have also reported that as temperature increases, the passage of water and solute through the membrane also increases, because the viscosity of water decreases and the diffusivity of ions increases at higher temperatures (Jeon et al., 2023).

Analysis of variance (ANOVA)

The accuracy of the developed models is calculated in terms of the sum of squares, the degree of freedom (df) (Hendaoui et al., 2018). Table 6 shows the analysis of variance for percent flow recovery, the F-value of 19.59 implies that the model is significant. There is only a 0.43% chance that such a large F-value is due to noise. P-values less than 0.0500 indicate that the model terms are significant. In this case, A and C are significant terms of the model. Previous studies have shown that the statistical model developed for flow recovery is highly significant because the p-values of these models are less than 0.05 (Meshram et al., 2022; Thakur, 2020).

Permeate flow and rejection as a function of feed pressure

In order to put the nanofiltration equipment into operation, preliminary tests have been carried out using brackish water from reverse osmosis concentrates. The conductivity of the reject water was 1040 us/cm and the tests were performed at room temperature (25 °C). Figure 5 shows the effect of different pressures (40, 50, 60, 90 and 108 Psi) of operation of the nanofiltration module with respect to permeate flow and rejection. It can be observed that the permeate flux increases as the feed pressure to the nanofiltration membrane increases, likewise the rejection flux decreases as the pressure increases. It was observed that the membrane permeability increased with the applied

Table 6. Analysis of variance de recuperation of flow

Source	Sum of squares	df	Mean square	F-valué	p-valué
Model	1946.04	2	973.02	19.59	0.0043
A-X1	1586.25	1	1586.25	31.94	0.0024
C-X3	359.79	1	359.79	7.24	0.0432
Residual	248.32	5	49.66		
Cor Total	2194.36	7			

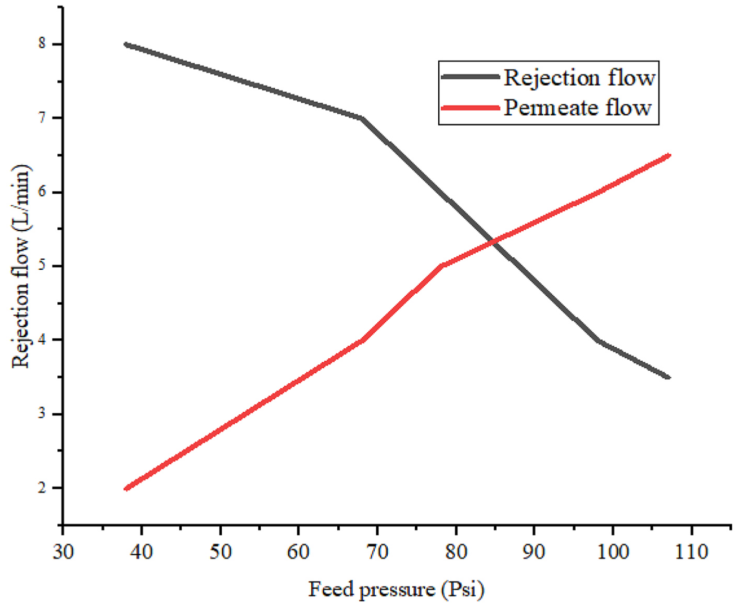

Figure 5. Effect of feed pressure on permeate flux and water rejection

feed pressure. The permeate volumetric flux varied from 2.2 L/min (P = 40 Psi) to 7 L/min (108 Psi).

Comparison of membrane performance

Table 7 shows the performance of the commercial NF membrane used (VFN1) with other membranes reported in the related literature. The result obtained with respect to the percentage retention of salts can be compared with other studies carried out under different operating conditions. Previous work by (Kammoun et al. 2020) used a commercial NF270 membrane and simulated solutions of concentrations 2222 and 3337 g/L at a feed pressure of 145 psi. In that work, retention levels quite similar to our work were obtained under different operating conditions. This information is shown in Table 7, adapted and modified from (Kammoun et al. 2020). It is observed that the retention percentage decreases with increasing feed salinity. Previous studies have reported that the flux recovery rate ranges between 30 and 70 % for the NF270 membrane, while the applied pressure is set at 8 bar (Elazhar et al., 2021). This result is aligned to our developed work (50.5 7 % average at 100 psi). The results presented for brackish water desalination using nanofiltration membranes were obtained by using feed water with a salinity between (3.4 and 6.01) mS/cm. The results obtained on the percentage of recovery and retention of salts can be valid for feed water with salinities up to 6.01 mS/cm. However, above 6.01 mS/cm, results may vary significantly. Future research will investigate this technology at higher salinities.

The selective study of the separation of sodium, calcium, magnesium and sulfate ions by means of the nanofiltration membrane was left out of this research work. Evaluating the energy consumption in relation to the salinity of the brackish feed water and its operating conditions of the nanofiltration system was beyond the scope of this work. Future work can lead to an evaluation of the performance of nanofiltration membranes for feed water salinities below 500 ppm (approximately 1 mS/cm) in terms of salt retention and recovery. The cost of the electrical energy consumed should be evaluated in future works and electrical installations with renewable energy resources, such as solar cells, should be encouraged. NF membranes will continue to find new applications in various fields, especially for water and wastewater treatment, pretreatment in seawater desalination, separation of ionic species especially polyvalent ions, organic compounds from other species in the pharmaceutical, biotechnological and food industries.

Table 7. Percentage of salt retention

Membrane	Pressure	Std - conductivity	Salt retention
NF270	145 Psi	2222 mg/L	75.7%
		3337 mg/L	55.3%
VFN1	100 psi	3.4 mS/cm	27.4%
		6.01 mS/cm	25.6%

CONCLUSIONS

The study focused on the feasibility of nanofiltration membrane as a process for brackish groundwater desalination. The research has analyzed the performance of a nanofiltration membrane (VNF-1) with emphasis on its effectiveness in evaluating the level of flux recovery and salt separation. Experimental investigations have revealed that the nanofiltration process is a suitable method for desalination of brackish groundwater. Experimental results showed that the pressure applied to the nanofiltration system is a determining parameter that significantly influences the efficiency of the process. It was observed that the percentage of water recovery increased with the applied feed pressure. The percentage of water flow recovery in the permeate stream ranged from 42% (P = 60 Psi) to 72% (100 Psi). By increasing the temperature from 20 to 28 °C, the recovered flow rate increased from 49.78 to 63.2% and the percentage of salt separation showed an insignificant increase from 25.95 to 27.05%. Since recovery was much lower at 20 °C than at 28 °C, more attention should be paid to operating conditions at low temperatures, especially during winter. Similarly, by increasing the initial conductivity of brackish water from (3.4–6.01 mS/cm) the percentage of flow recovery has decreased from (61.46 to 51.525%) and the percentage of salt retention (27.3 to 25.7%). In conclusion, this research confirms the suitability of the commercial NF membrane studied for brackish water desalination. Based on the results obtained in this work, the authors intend to evaluate the performance of the membrane in the selective separation of brackish water components.

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