



| Research Article



Evaluating Performance and Energy Efficiency of Reverse Osmosis Systems: A Comprehensive Analysis

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Annotation

Reverse osmosis (RO) has become a central technique for the desalination of seawater and brackish water, owing to its effectiveness and versatility. The level of total dissolved solids (TDS) present in the water source plays a significant role in determining the efficiency of this process. While brackish water RO (BWRO) and seawater RO (SWRO) systems may use similarly structured membranes, differences in water chemistry and system design can lead to substantial variations in performance and energy demand. This review explores the operating principles of RO systems, identifies the critical factors influencing energy consumption, and evaluates strategies aimed at improving system performance. The discussion includes membrane technology developments, pretreatment techniques, and modeling tools used to optimize operation. Findings from previous studies are analyzed to highlight trends in recovery rates, scaling issues, and system configurations. The study aims to contribute to the optimization of RO technologies and inform strategies for sustainable water treatment solutions.

Keywords: Reverse osmosis; water treatment; total dissolved solids.



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1. Introduction

As only about 2.5% of all of Earth's water is suitable for direct consumption by humans and drinking, clean water is a resource that is both limited and important. Currently, there is a notable gap between the availability and need for clean water, with approximately 25% of the global population facing a financial shortfall in water access [1,2]. Several factors, such as a rapidly increasing population, continuous industrial growth, enlarging agricultural operations, water pollution, insufficient water management, and warming temperatures, exacerbate the problem of water scarcity. A semi-permeable membrane is utilized in the reverse osmosis (RO) process uses membrane technology. Membrane systems offer higher performance to the procedures that include

thermal desalination. RO techniques are commonly employed to extract solutes from both brackish water (BW) and saltwater to yield purified water that can be used for agriculture and human consumption, etc. Traditional RO membranes are made of TFC-PA. Three layers

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compose this material: a non-woven layer made of polyester, a layer that provides support, and a layer that is [3,4]. Seawater reverse osmosis desalination (SWRO) plants typically feed waters with a total dissolved solids (TDS) content of approximately $30,000 \text{ mg L}^{-1}$, and reverse osmosis desalination plants that filter feed waters and brackish water (BWRO) have a TDS content limit of 500 to $10,000 \text{ mg L}^{-1}$. Many factors influence the effectiveness of the RO process, like the composition of feed water, properties of RO membranes, design of the RO system (phases, passes, etc.), and operating parameters. In the last two decades, the desalination method known as reverse osmosis (RO) has emerged as a technology that is frequently utilized for addressing water-related issues. Despite of essential for the SEC (specific energy consumption) decrease of the SWRO systems, vitality recuperation devices (ERDs, even though energy recovery devices (ERDs) are due to operating pressures and brine flow rates being lower than BWRO systems, energy recovery devices (ERDs) are mostly avoided with BWRO systems; thus, SEC cannot be reduced using ERDs. However, as BWRO has lower TDS than SWRO, it is generally more energy efficient even without ERDs. Besides the BWRO membrane characteristics, the feed water parameters are decisive in the layout and functioning of BWRO facilities. Because large flow recoveries (R) can be achieved, the solubility of moderately soluble salts of minerals, such as limestone (CaCO_3), gypsum (CaSO_4), barite (BaSO_4), celestite (SrSO_4), fluorite, and silica (SiO_2) may all be gotten over[21]. Because of this, scaling may occur, a significant problem associated with membrane fouling in BWRO desalination. Increasing rejection (%R) creates this issue and hence requires chemical intervention involving the use of antiscalant in pretreatment or intermediate demineralization treatment. However, the TDS and within-day temperature variation of brackish water is generally higher than that of the saltwater feed water sources. This paper aims to Comprehensive Assessment to provide a thorough review of the performance and energy efficiency of reverse osmosis systems and highlight areas for analysis and evaluation of different methods for measuring and improving the performance of these systems. This review also addresses study technologies and strategies for reducing energy consumption.

2. Reverse Osmosis Process

In 2012, John C. Crittenden[et al.],[5,6] explained in more detail the process of the RO system, which Fig. 1 is an illustration, including covers, conventional pretreatment, and after-treatment activities. The next description will elaborate on this design.

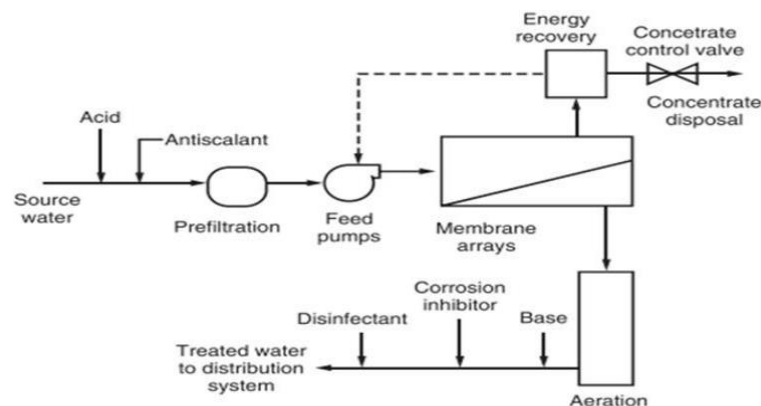


Fig.1. Diagrammatic representation of a typical reverse osmosis system.

Pretreatment

In practically all RO systems, there is a need for pretreatment of feed water. Pretreatment has one role to play in stopping the scaling caused by sparingly soluble salts. The removal of water from the feed stream throughout the process causes solutes to become concentrated. It is possible for the concentration that is produced to surpass the solubility of several varieties of saltwater. The regulation of the scale includes adjusting pH and/or adding antiscalants. The solubility of precipitates can be altered by adjusting the pH, and antiscalants can either prevent the production of crystals or slow down the pace at which precipitates are formed.

Filtration is yet another pretreatment procedure that can be used to remove particles without necessarily requiring a backwash phase. Cartridge filtration with a sieve opening of at least 5 micrometers is the bare minimum; however, prefiltration of the membrane is frequently required when employing granular or membrane filters for sources of surface water. When it comes to reducing biological fouling, one of the most typical pretreatment processes that is utilized is sterilization.

Feed pumps are utilized to pressurize the water that is being fed after pretreatment. For NF membranes, the normal supply water pressure is 5 to 10 bar (73 to 145 psi), and lower pressure and brackish water (BW) RO ranges from 10 to 30 bar (145 to 430 psi), and from 55 to 85 bar for seawater RO. Even if the concentration is minimal, particles have the potential to build may block the feed or reside on the membrane's interface. channels if there is no backwash cycle. As a minimum R, the pressure range for seawater RO is 55-85 bar (800-1200 psi).

Post-treatment

Permeate often necessitates post-treatment; this may include the removal of dissolved gases and alkalinity and adjusting the initial pH level. Membranes don't effectively remove tiny uncharged molecules, especially gases in dissolved feed. If the source water has hydrogen sulfide, it must be removed before consumption. If the stripping operation removes sulfides to eliminate sulfide compounds that are present in the column off-gas and, as a result, to avoid odors and oxidation issues, it is necessary to make the necessary arrangements. The removal of CO₂ increases pH (so that now fewer base chemicals are needed to stabilize water).

2. Literature Review

2.1. Energy Efficiency Optimization

Specific Energy Consumption (SEC): According to research, it is possible to adjust operational factors as supply water salinity, pressure, and flow rate, in order to boost water recovery by more than four times and significantly reduce SEC by up to 36 % (Abkar et al., 2024)[19].

Methods Using Models: According to the study entitled "Reduction of Energy Consumption of Brackish Water Reverse Osmosis Desalination System Via Model-Based Optimisation" (2023),[20] brackish water RO systems might save 27.97% on energy costs by modifying input conditions when model-based optimization techniques are used.

2.2. The Impact of Pretreatment on the Performance of RO

There is a direct relationship between the effectiveness of the water pretreatment process and the performance of the RO system. This is one of the most significant aspects that contributes to the process of determining the performance and lifespan of a membrane is the quality of the feedwater. The good news is that these issues might be resolved, and the RO process could continue to be viable if the feedwater were treated in advance[26].

2.3. Previous Researches

Joyce and colleagues [7,8] used photovoltaic systems to work in systems that use reverse osmosis in tiny agricultural areas. The author of the study concluded that when the supply water recovery

and intake pressure rise, the smaller RO system has a lower energy consumption than the larger system. Filters, pumps, and a membrane are used in the design depicted in Figure 2 to assemble the system in a way that maximizes power efficiency and lowers costs.

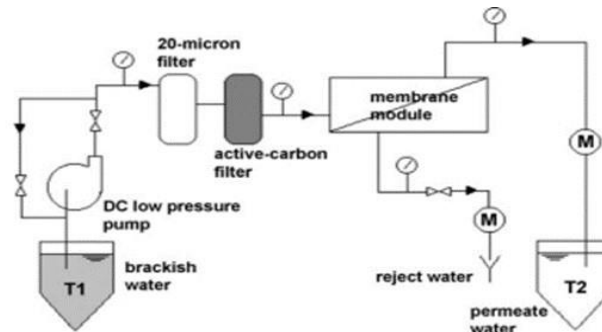


Fig. 2. An illustration of the schematic layout of a small RO experimental plant.

In order to purify brackish water, RE systems that are powered by a small number of PV have been created, despite the fact that many renewable energy-powered reverse osmosis units have been created for saltwater desalination [9,10]. An overview of the current PV-powered BWRO systems is provided in Table 3.

Table 3. An overview of a reverse osmosis (RO) system that is currently in operation and is powered by photovoltaic (PV) technology.

geographical location	TDS (g/L)	Pressure (bar)	Salt retention (%)	Recovery (%)	Clean water(m ³ /d)	Electric Array (kW)	Battery	SEC (kWh/m ³)
Portugal	The conductivity 2-5 ms/cm	4	90	2	0.02	0.15	No	25.6
Australia	5	-	-	16 or 25	0.4	0.12	No	-
Australia	3.5	10-4	92	10	0.1	0.26	No	8
Mexico	1.5-5	40	-	-	0.7-1.4	2.5	Yes	4.0-6.9
Oman	1	12	96.6	65-70	5	3.25	Yes	2.3
Israel	4	14-16	98	50	3	3.5	Yes	-

Boulaifa et al. (2019) [11,12] studied the impact and discovery of operational elements on a Moroccan RO plant over a five-year analysis. After comparing the performance station's operating parameters with analysis data that the ROSA program produced, they found that a four-degree Celsius rise in input temperature resulted in a 10% higher flux. Ansari et al. (2021) [13,14] show that performance is greatly altered by both feed pressure and salinity. A linear relationship of significant intensity was observed between feed water salinity and permeate flow rate with a constant feed composition; the lower the yield of brine relative to higher the feed rate.

The study found that a mathematical model was used for a BW30-400 membrane-type Filmtec to conduct an experimental investigation into the effectiveness of an RO system for brackish water that has a capacity for production of 50 m³/d. The system was operated under varying feed pressure and salinity conditions. Within the context of permeate and brine flow, the connection between feed pressure and flow is virtually linear and direct. It has been discovered that the permeate flow is nonlinearly and adversely dependent on the salinity of the supply water. The amount of salt that is rejected is significantly influenced by the feed salinity as well as the supply pressure. At a pressure of 13 bars, the highest percent of salt rejection was reported to be 98.8 percent. When the input pressure was increased from 5 to 13 bar, there was a 73.3% decrease in the salinity of the permeate that was recorded. The finest possible quality of water, which is 12 ppm, is achieved by applying a feed pressure of 13 bars to water that has a salinity of 1000 ppm. A relationship that is generally

linear was discovered to exist between the quantity of water that is recovered by the membrane and the feed pressure required for brine salinity.

This relationship was shown to be favorably connected. Furthermore, it was demonstrated that the permeability of water is affected by a variety of parameters, including salinity, feed pressure, temperature, and water recovery. It was calculated that the coefficient of water transfer that this RO system possesses in the pilot plant was 2.8552 L/ (m².h.bar), which is equivalent to 7.93×10^{-7} (m/ (bar)). This was obtained with a 92% accuracy rate.

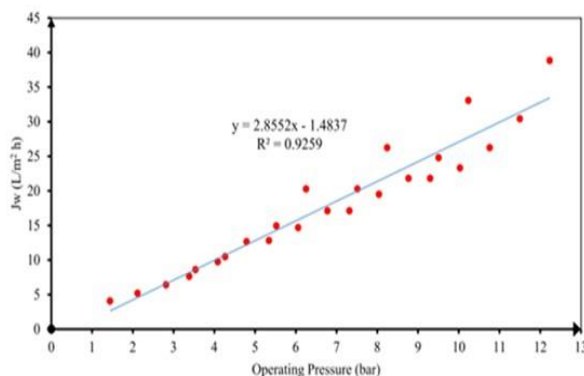


Fig. 3. A significant impact of operational pressure on water flow, PH value, and temperature at 7.2 and 15 degrees Celsius.

(M. Talaeipour and others, 2017) [15,16] studied the production of drinking water by desalinating brackish water using a membrane method. The study looks at the desalination procedures used on brackish water in Iran's Qom Province. Membrane techniques, including nanofiltration membranes and the reverse osmosis (RO) process, both alone and in combination, were used to achieve this goal. Chemical and physical properties of the water, such as electrical conductivity (EC), salt content, the total amount of dissolved solids (TDS), the element Na⁺, and Cl⁻. The rejected percentage of each measurement was examined and analyzed utilizing reverse osmosis and nanofiltration independently, as well as their combination technique. The Luna household desalination equipment was used to carry out the treatment procedure. Membrane systems, that the NF90-2540, TW30-1821-100 (RO), and the model hybrid (NF/RO), were put on a desalination process home-size pilot (Luna water-based 100 GPD) and used to filter all collected brackish water samples. The ROSA simulation software model was then used to investigate how pressure affected the membranes' permeability quality. The findings indicate that the salinity rate elimination in the NF, RO systems, and hybrid techniques was 50.21 percent, 72.82 percent, and 78.56 percent, in that order. The ROSA models, which refer to the procedure of reverse osmosis system evaluations, were used throughout the evaluation to analyze the efficiency of reverse osmosis and nanofiltration hybrids via power drive. Three desalination techniques were tested for performance to eliminate physicochemical features as a proportion of rejected plants used for experimentation. These include an RO membrane salinity of 72.02, a TDS of 60.26, electrical conductivity of 60.33, a chlorine was of 43.08, and a sodium was of 54.41; the salinity of the NF system was 50.21, TDS was 43.41, electrical conductivity was 43.62, chlorine was 21.1, and sodium was 36.15. The following parameters and ions in Fig.4 were also rejected in the hybrid system: TDS (76.52), EC (76.42), Cl (63.95), salinity (78.65), and Na (70.91) (Fig.4).

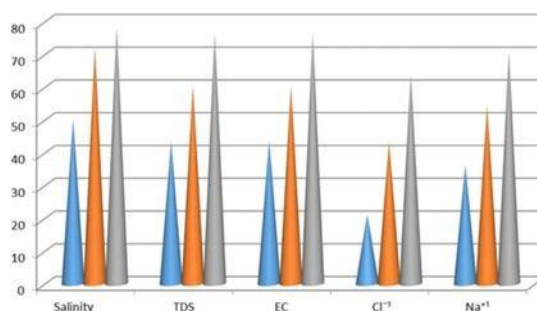


Fig.4. shows the rejection % of researched parameters and ions utilizing NF, RO, and hybrid procedures.

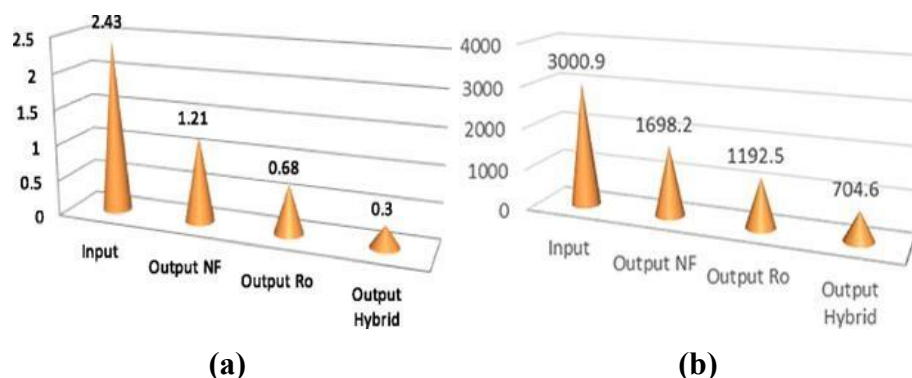


Fig.5. (a) EC ($\mu\text{mhos/cm}$) change in accompanying NF, RO, and hybridization (NF/RO),(b) TDS (mg/L) change following desalination NF, RO, and hybridization (NF/RO).

N.K. Khanzada and colleagues 2016 [17,18] presented a study titled "The preliminary treatment technology effectiveness reverse osmosis (RO) for the treatment of brackish water obtained from inland sources" to evaluate the rejection efficiency of multi-pre-treated RO membranes at various water recovery rates (30, 35, 40, 45, and 50 percent) and the total dissolved solids (3500, 4000, and 4500 m/L) on a pilot scale. The reverse osmosis (BWRO) filters for brackish water, notably the Filmtec LC-LE-4040 and the Hydranautics CPA5-LD-4040, are examined by employing 0.25 M sodium chloride and magnesium chloride as draw solutions (DS),⁵ in addition to 1 m cartridge filters and 0.02 m ultra-filtration (UF) membranes.

The percentage rejection efficiency of all RO membranes is depicted in Figure 6. These figures show how well both membranes of the RO system work with a range of pre-treatment procedures at various recovery processes against a range of trans-membrane pressures (TMP) for input TDS at concentrations of 1,3500 mg/L. The filtering trials that were conducted using the Filmtec membrane produced a minimum salt. When employing a cartridge-type filter (CF-RO), the maximum amount of total dissolved solids (TDS) in the permeate was 175 mg/L, and it was 68 mg/L when using the preliminary treatment ultrafiltration (UF-RO). A comparable set of arrangements using osmosis with forward flow as an initial treatment (FO-RO) produced TDS levels of 234 and 120 mg/L are optimum for permeate, with 93 and 96% rejection of salt using sodium chloride and magnesium chloride as DS (Fig. 6). This is a significant improvement over the previous results.

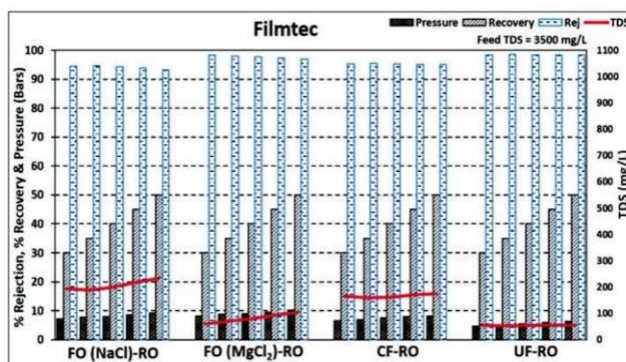


Fig.6. Rejection and TDS use Filmtec filtration membranes for (FO-RO, UF-RO, and CFRO) technologies at several recoveries and pressures with an intake TDS of 3500 mg/L.

From the Hydranautics membrane, it was stated that a minimum of 85% salt rejection was achieved using a cartridge filter (CF-RO) as a pre-treatment, as well as the fact that pre-treatment was accomplished through the utilization of ultrafiltration (UF-RO) to achieve a salt rejection rate of 97%. It was discovered that the maximum permeate total dissolved solids (TDS) for the former was 500 mg/L, whereas the latter had 98 mg/L of TDS over its whole volume. Using osmosis with forward flow as a pre-treatment, the highest filtrate total dissolved solids levels of 775 and 130 mg/L were recorded, with the lowest salt rejection of 77% with sodium chloride and 96% with magnesium chloride as the draw solution (Fig. 7).

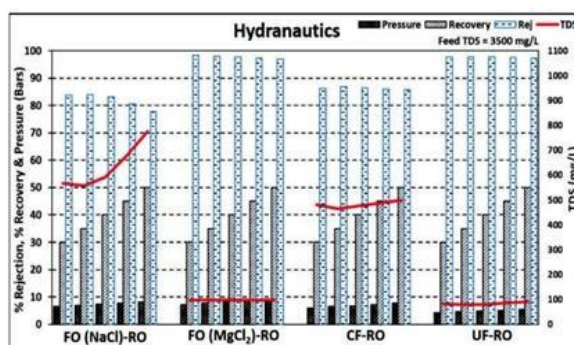


Fig.7. Rejections and total dissolved solids for the FO-RO, UF-RO, and CF-RO systems with Hydranautics membrane across various recovery and pressures with feed TDS of 3500 mg/L.

Testing in feed condition II, the salt rejection of the Filmtec membrane-based test in conjunction with a cartridge filter (CF-RO) was 95% at its lowest point and, for ultrafiltration as a preliminary treatment process (UF-RO), 97% at its highest, with a permeate TDS of up to 186 and down as far as 110 mg/L in sequence (Figure 8).

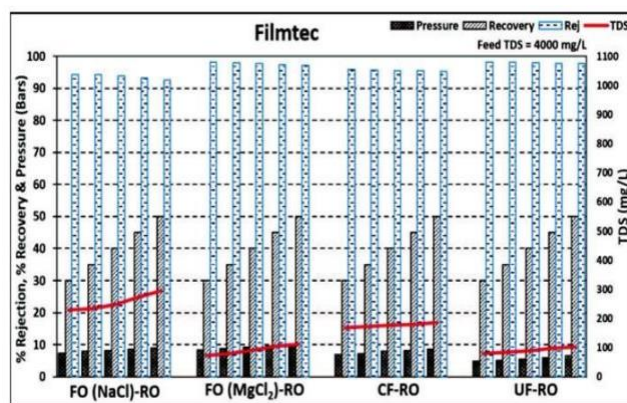


Fig.8. The rejection and TDS at different pressures and rates of recovery for the FO-RO, UF-RO, and CF-RO systems with input TDS of 3500 mg/L, all based on the run data with Filmtec membrane.

An increase in the amount of total dissolved solids (TDS) of the supply water has an impact on the RO membrane's ability to reject contaminants during the rejection process, with all of the possible options for initial treatment negatively. The best rejection reduction was with FO-RO with sodium chloride as a draw solution, while the use of the Hydranautics membrane with CF-RO provided a similar improvement. The monovalent ionic nature of NaCl is inevitable. As a result of its poor rejection, sodium chloride as DS and the permeable dissolved solids (TDS) in FO-RO increased significantly(Figure 9).

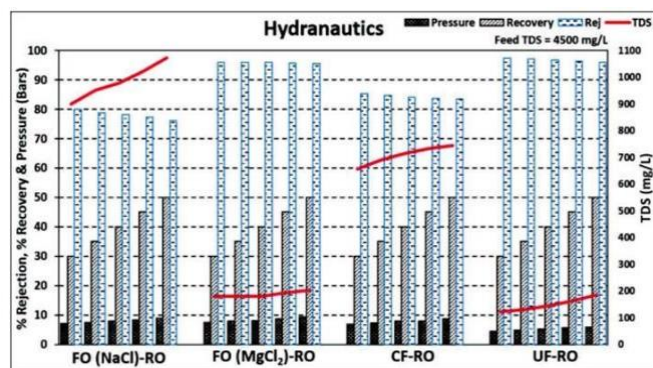


Fig.9. The rejection and TDS for the FO-RO, UF-RO, and CF-RO techniques at varying recoveries and pressures, in addition to the Hydranautics membrane at various recoveries and pressures with 3500 mg/L of feed TDS.

Both the processes of FO and UF stand for forward osmosis and ultrafiltration, respectively. They have been reported to be successful preliminary treatments that are also resistant to fouling. However, both of these processes have substantial operational expenses, which range from excessive operational pressures for UF to the use of magnesium chloride in the FO process's draw solution (DS). FO can justify its operating expenses when applied to brackish water featuring different and dynamic constituents that offer high fouling potential. MgCl₂ has shown superiority as a draw solution over NaCl due to its divalent characteristics and osmotic ability. Over a wide variety of Filmtec membranes, LC-LE-4040, it was superior to the Hydranautics membrane CPA5-LD-4040 under a large variety of pressures and amounts of TDS. It was established that the optimal values for recovery processes regarding Filmtec membranes and Hydranautics were consequently 40% and 45% for all the feed circumstances.

Marwa and others (2023)[22] assessed the efficiency of the process of reverse osmosis, which was enhanced through an experimental method in which magnesium chloride and Sodium chloride water solutions were treated using a reverse osmosis system to see how operating conditions affected the rejection of salt and penetration by water.

According to the results shown in Figure 10, when the temperature of the feed water is raised from 15 to 35 degrees Celsius, the salt concentration of the permeate rises as a result of this change. In this way, the relationship between the temperature of the intake and the sensitivity of the spiral-wound membranes is demonstrated. It is recognized that a separate mechanism may not be required to preserve reverse osmosis selectivity for different salt inputs.

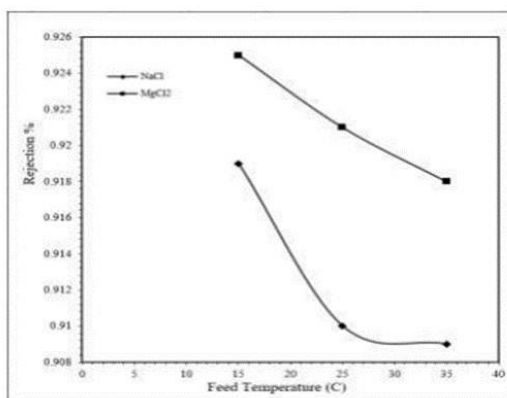


Fig.10 . The relationship between rejection and supply temperature.

The flow of permeability and the rejection of salt enhance as the effective pressure rises, additionally, the reverse osmosis system reacts to the operational pressure in a more substantial manner. At 5 bar, the salt removal achieves 96%. The product's quality will diminish if the pressure exceeds a certain maximum level (Fig.11).

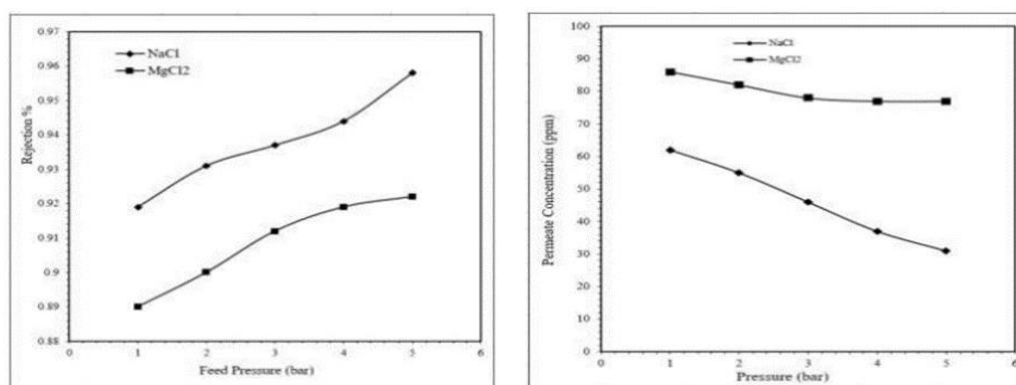


Fig. 11. The relationship between permeate concentration and pressure was investigated.

In contrast to the popular assumption, increasing the rate of feed passed by a certain ideal point will cause a reduction of the net transmembrane pressure difference, subsequently decreasing the water production rate. Numerous studies indicate that increased operating pressures and feed flow rates. Lower pressure or higher pump flow rate might mean that "column concentration on a very significant part of the wall degrades at a rate beyond which saturation occurs"(Alsarayreh et al., 2020). Membrane wall concentration and pressure, feed concentration as well as module size increase with increased power (Kotb et al., 2015) [23]. The flow rate and pressure rate that are present in the permeate stream are increased by high-pressure operation(Al Obaidi et al., 2018). Although raising the pump pressure increases the recovery rate, simultaneously, it will tend to make it easier for pollutants to pass through membrane pores(Idrees, 2020) [24,25]. As the temperature drops, Water viscosity and membrane resistance are reduced, whereas the membrane desalination system's input solution rises (Liliane et al., 2019) [26, 27].

Conclusion

This study provides an exhaustive review of the efficiency of Reverse Osmosis (RO) systems, taking into consideration both their efficiency and the amount of energy that they use to carry out their operations. This study aims to determine the major criteria and indicators that are applied in the evaluation of these systems. This will be accomplished by conducting a comprehensive analysis of the available research and literature. Additionally, the study will explore the elements that influence the efficiency of these in terms of energy consumption. The purpose of this comprehensive overview is to analyze the advancements and limitations of reverse osmosis water desalination, with a particular emphasis on strategies to increase performance and reduce energy. Within the field of

water treatment and technologies for desalination, it is anticipated that it will serve as an important asset for researchers, engineers, and other experts in the sector.

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