

Research Article

Optimising Membrane Performance in High-Recovery Seawater Reverse Osmosis Systems to Reduce Biofouling Using Modelling and Simulation

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Article Info	Abstract
Article History	The increasing demand for freshwater due to human activities underscores the need for alternative water sources. Desalination of seawater and water reclamation are reliable methods for producing potable water. Among desalination techniques, seawater reverse osmosis (SWRO) is widely adopted due to its lower energy consumption compared to thermal desalination, smaller footprint, reduced waste generation, and consistent performance. Efficient pre-treatment is vital to ensure high-quality feed water and protect RO membranes, which are prone to fouling, scaling, and chemical damage. The HYDRACapMAX80 ultrafiltration module offers high permeate flux and effectively removes total suspended solids and organic contaminants. A two-pass, two-stage SWRO system was developed, achieving a recovery rate of 45%, salt rejection of 99.1%, and energy consumption of 3.26 kWh/m ³ . Post-treatment yields permeate water that meets WHO standards, with TDS at 407 ppm, calcium at 6.4 ppm, sodium at 145 ppm, chloride at 204 ppm, fluoride at 0.39 ppm, and a pH of 7.2. System performance was tested under varying salinity and temperature conditions. Higher salinity and lower feedwater temperatures increased TDS and energy consumption, but maintained acceptable performance. This system demonstrates energy-efficient desalination while delivering high-quality drinking water.
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1. Introduction

The primary constraint of the seawater reverse osmosis desalination process is its low product water recovery rate, generally 35% to 40%, compared with the 85% to 90% recovery rate of the brackish water reverse osmosis method. The low water recovery in the reverse osmosis process is due to its tendency to foul. The poor permeate recovery rate necessitates substantial capital investment in installing SWRO plants, particularly when the feed seawater is highly saline. Moreover, elevated salinity levels in high RO feed

seawater augmented the power consumption necessary for operating high-pressure pumps, hence diminishing process energy efficiency. Membrane fouling is a major challenge in membrane-based desalination technologies, originating from multiple sources, including particulate matter, colloids, inorganic and chemical compounds, and biological growth. Suspended and colloidal particles in seawater tend to aggregate and form a layer on the membrane surface, increasing hydraulic resistance and reducing transmembrane pressure (TMP), ultimately leading to a decline in water flux.

Additionally, dissolved organic compounds can interact with one another and with the membrane surface, further contributing to fouling by forming a dense layer that impedes water transport and reduces overall membrane efficiency. Colloidal particles that create a cake layer of clay, organic matter, and inorganic metals can also induce fouling. Furthermore, when microbial cells from bacteria, fungi, or algae aggregate on the membrane surface, forming a biofilm, this is referred to as biological fouling. Inorganic scaling arises from the accumulation of soluble salts, such as CaCO_3 and CaSO_4 , when their concentrations exceed water's solubility limits.

2. Literature Review

Anti-scaling agents are a useful tool for reducing this problem. Although chemical cleaning with acid and/or base solutions is frequently used to remove fouling, it usually works only on small deposits. Particles may accumulate in the RO membrane pores and on its surface if the fouling layer is not sufficiently removed and the feed water is of low quality. To avoid fouling-related problems, such as decreased water flux, increased transmembrane pressure (which increases energy consumption), shortened membrane lifespan, and more frequent maintenance requirements, proper pre-treatment of seawater before it reaches the RO membranes is crucial [1, 2].

Algal blooms, commonly known as red tides, are seasonal phenomena in marine environments characterised by the rapid, excessive proliferation of algae, often leading to visible discolouration of coastal waters. Beyond altering water appearance, these blooms can have severe ecological and public health impacts. They can significantly reduce dissolved oxygen levels in the water, creating hypoxic circumstances that threaten marine life, including fish, crustaceans, and other marine organisms. Furthermore, certain harmful algal blooms (HABs) produce toxins and elevated levels of chemicals such as ammonia and nitrate, which may accumulate in seafood and pose health risks to humans who consume

affected fish or shellfish [3]. Oman's coastal waters, situated along the open Arabian Sea, are highly susceptible to red tide occurrences. These harmful algal bloom events are most commonly observed during seasonal transition periods, mainly from January to March and again from August to October, when shifts in temperature, sunlight, and ocean circulation create optimal conditions for bloom formation. In recent years, both the frequency and severity of algal blooms in this region have increased. This escalation is driven by an arrangement of environmental factors, including the steady rise in sea surface temperatures, alterations in coastal current patterns, and elevated nutrient loads entering the marine environment. Nutrient upgrading results from both natural processes, such as upwelling, and human-induced activities, involving agricultural runoff, improper wastewater discharge, and coastal development. Together, these conditions enhance the growth and accumulation of algae, making red tide events a recurring challenge for desalination plants and coastal ecosystems [4, 5].

2.1. Pre-treatment Feed Seawater Analysis

Before designing the pre-treatment ultrafiltration system, it is essential to determine the physicochemical properties of the feed seawater. This ensures that the system is appropriately tailored to produce filtrate of the required quality for the downstream reverse osmosis (RO) membranes. The feed seawater characteristics at the plant intake site were obtained from [6], and the main physicochemical parameters are summarised in Table 1.

Table 1. Quality of feed water entering the ultrafiltration system

Minimum Temp(°C)	35	BOD₅ (ppm)	5	Al (mg/L)	0.05
Turbidity (NTU)	8	TOC (ppm)	4	Alkalinity (mg/L as CaCO₃)	400
Total suspended solid(ppm)	16	pH	8.3	Ca (mg/L as CaCO₃)	2000
Total dissolved solids(ppm)	37883	Fe (mg/L)	0.05	Total Hardness (mg/L as CaCO₃)	6000
COD (ppm)	10	Mn	0.02	LSI*	2.245

* LSI- Severe scaling risk

2.2. Design of Pre-Treatment Ultrafiltration System

This simulated facility is based on the ACWA Power Barka I SWRO plant, which produces 661 m³/h of desalinated water from each of its three trains and operates at a reverse osmosis recovery rate of 41.5%. The total feed water required for the process is 4775 m³/h. The ultrafiltration system, illustrated in Figure 1, was analysed with respect to the number of racks and modules, filtrate flux, recovery rate, and filtration duration. The system is designed to produce filtrate with turbidity below 0.1 NTU, total suspended solids

(TSS) below 0.5 mg/L, and a silt density index (SDI) below 3, meeting the quality requirements for downstream RO membranes [7].

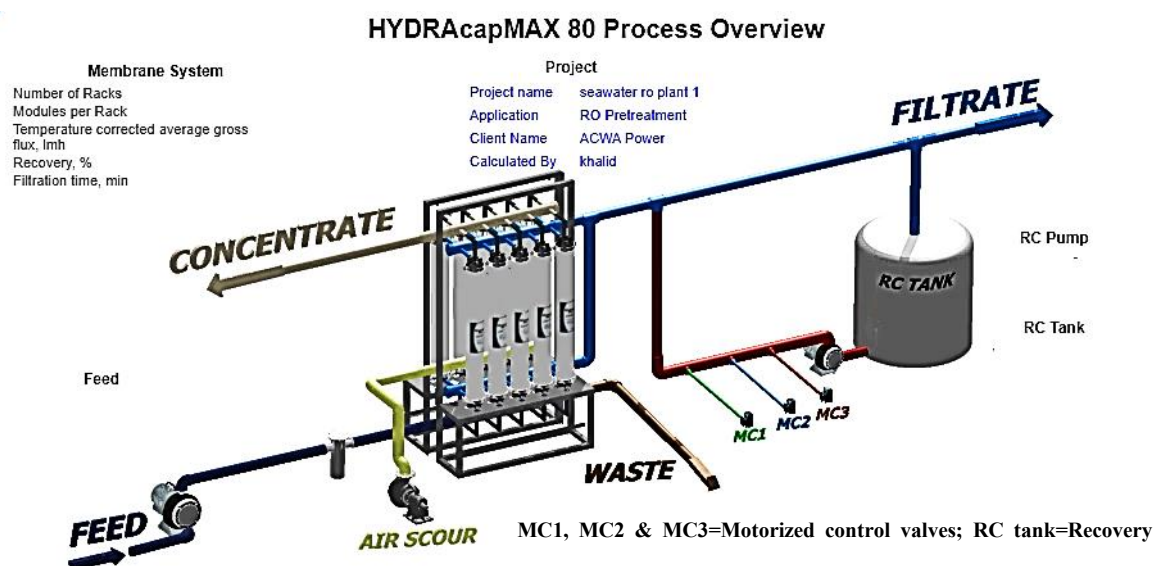


Figure 1. Ultrafiltration system for pre-treatment unit

2.3. RO Desalination Process

This system replicates the operational procedure of the ACWA Power Barka-1 reverse osmosis facility. Comprising three trains of 149 pressure vessels, each pressure vessel had seven Hydronix membrane elements. The feed water, after pre-treatment, is conveyed by high-pressure pumps to the RO system. The membrane integration involved a single-stage first pass, whereas the second pass had two phases, with the latter primarily focused on boron removal. The reverse osmosis desalination plant operates at 65-70 bar and 25-40°C, achieving a recovery rate of 44% in the initial pass. The second pass recovery rate is 95% owing to the high-quality feed derived from the first pass [8].

2.4. RO Feed Seawater Analysis

The design of a reverse osmosis (RO) seawater desalination system requires a detailed analysis of the feed seawater. For large-scale RO plants, such as those in Oman, the source water is typically acquired via a direct open intake system. As a result, the feedwater quality displays temporal fluctuations due to natural factors, including seasonal temperature variations, rainfall, and tidal effects, as well as anthropogenic influences, such as improper wastewater disposal and the discharge of fertiliser-laden agricultural runoff into the marine environment. For the initial design scenario, the feedwater is assumed to have standard seawater quality. The pH is 8.1, and the total dissolved solids (TDS) average 37,905 mg/L. The major cationic constituents include calcium (Ca^{2+}) at 445 mg/L, magnesium (Mg^{2+}) at 1,387 mg/L, sodium (Na^{+})

at 11,651 mg/L, and potassium (K^+). The principal anionic constituents are chloride (Cl^-) at 20,913 mg/L, sulfate (SO_4^{2-}) at 2,931 mg/L, and bicarbonate (HCO_3^-) at 123.1 mg/L.

3. Methodology

3.1. Design of RO Desalination System

3.1.1. One-Pass System

The one-pass reverse osmosis desalination system comprised three trains, each including 149 pressure vessels with seven membrane elements. Nonetheless, a single-pass system proved impractical, as the average permeate flux exceeded the maximum allowable permeate flux limit following operation. The permeate flux reached 34.1 lt/m²/hr, exceeding the allowed average flux of 34 lt/m²/hr for this type of pressure vessel, thereby risking elevated fouling rates. To achieve the necessary permeate volume of 661 m³/hr, affiliated with the ACWA Power Barka-1 RO plant, an increased number of membrane elements is required.

3.1.2. One Pass, Single Stage With Recirculation Stream

As the permeate flux exceeded the maximum allowable flux rate of the RO membrane element, a cost-effective solution is to reduce the flux by partially recirculating a portion of the rejected water, thereby decreasing the volume of rejected water produced. The typical recirculation ratio is from 10% to 20%. Consequently, the system was re-simulated using brine recirculation rates of 80 m³/hr and 160 m³/hr to diminish the average permeate flux. Nonetheless, the maximum permeate flux rate remained elevated, necessitating a second pass to mitigate potential membrane fouling [9, 10].

3.1.3. Two Passes, Single-Stage RO System

The selection of the membrane type for the second pass is crucial, typically employing a brackish-water membrane due to the lower salt concentration of the feed, which is determined by the results of the first pass. The ideal membrane type is selected based on operating pressure and superior product quality. The selected membrane type must be a brackish water membrane characterised by high salt rejection and low differential pressure. Upon confirming the appropriate membrane type for the second pass, the next stage involved determining the quantity of pressure vessels and membrane elements required for the system. When determining the appropriate quantity of membrane elements, it is essential to consider the average flux, maximum flux rate, and concentrate rate per pressure vessel, all of which must adhere to the standard

limits for the selected membrane type [11]. Furthermore, the permeate pressure must consistently exceed the permeate back pressure, typically set at 1 bar, to ensure the passage of permeate to the post-treatment unit and, subsequently, to the product tank.

3.1.4. Two-Pass, Two-Stage RO System

Implementing a second-stage process can significantly improve product water recovery, as the rejected stream currently accounts for approximately 55% of the seawater feed. This additional stage enables further utilisation of the treated seawater, reducing brine disposal and mitigating the associated environmental impacts of desalination. Increasing the number of pressure vessels in the second stage also results in a moderate increase in the product flow rate. However, careful consideration must be given to selecting an appropriate membrane type and determining the optimal number of pressure vessels for this stage. Due to the high salinity of the feed entering the second stage (68,644 mg/L TDS), the permeate recovery in this step remains relatively low.

3.2. Design Optimisation

The optimisation of the intended SWRO system aimed to enhance product yield, minimise reject water production, and decrease power consumption, which constitutes the primary operational expense. The reject stream from the second pass was first recycled and combined with the feed entering the first pass because its TDS concentration was lower than that of the reject from the first pass.

3.2.1. Increase Membrane Recovery Rate

Another potential optimisation method examined is augmenting the system recovery rate to improve system productivity. A study was conducted on a two-pass, two-stage SWRO desalination system at various recovery rates, manually controlling permeate flow to explore the potential to enhance system recovery. Given that conventional SWRO systems exhibit a recovery rate of 35-40%, and the simulated system achieves a recovery rate of 45%, akin to the ACWA Power RO plant, the viability of increasing the recovery rate to 50% was examined. Operating the system at a 50% recovery rate is unfeasible, as the peak flux values for both the first and second passes exceed the maximum design limits of 34 lt/m²/hr and 56 lt/m²/hr, respectively [12, 13].

3.2.2. Use Pressure Exchanger as Energy Recovery Device (ERD)

Subsequently, the simulated SWRO system showed that power consumption exceeded the average

power consumption per cubic meter of permeate water produced. The last two passes of a two-stage reverse osmosis system lacking an energy recovery device exhibit a power consumption of 6 kWh/m³, in contrast to the global average of 5-3.5 kWh/m³. A widely used Energy Recovery Device (ERD) in desalination systems is the pressure exchanger. This isobaric, positive-displacement mechanism recovers waste energy from the discharged brine and transfers it directly to the incoming feed stream via a cylindrical rotor equipped with longitudinal ducts. The pressure exchanger effectively maximises pressure recovery from the reject stream, thereby reducing the overall pumping power required. Typical operating specifications for the pressure exchanger include a leakage rate of approximately 1%, volumetric mixing of 5.5%, a high-pressure pump differential pressure of 0.8 bar, and a booster pump pressure of around 2.44 bar [14].

Despite significant advancements in seawater reverse osmosis (SWRO) technology, biofouling remains a critical operational challenge, leading to increased energy consumption, reduced membrane lifespan, and higher maintenance costs. Current studies primarily focus on chemical cleaning strategies and improvements to membrane materials, yet comprehensive approaches integrating optimised system design, operational parameters, and fouling control remain limited. Moreover, the interplay between feedwater characteristics, hydraulic conditions, and membrane performance is often underexplored, resulting in suboptimal recovery rates and inefficient energy utilisation. This study addresses these gaps by systematically analysing design optimisation strategies for mitigating biofouling in SWRO systems, focusing on performance enhancement through multi-stage recovery configurations, energy recovery devices, and process modelling. The research aims to establish a data-driven framework that links membrane design choices to operational efficiency, thereby advancing more sustainable, cost-effective desalination practices.

4. Results and Discussions

4.1. Ultrafiltration Pre-Treatment System

Based on the feed water quality presented in the referenced study and the required feed flow rate for the proposed SWRO system, the process design and operational parameters were evaluated accordingly. The UF pre-treatment system was designed with 7 racks, each containing 91 UF modules. The feed flow entering the HYDRAcapMAX80 UF membranes, supplied by three feed pumps, is 4306 m³/h, producing a filtrate flow of 4208 m³/h and achieving a recovery rate of 97.73%. The rejected waste stream from the UF

system is 97.86 m³/h, which includes 8.1 m³/h of chemical waste used for UF operations and membrane chemical cleaning [15]. The HYDRAcapMAX80 is a high-flux membrane, operating at an average flux of 72.81 lt/m²/hr, compared to the 60 lt/m²/hr average flux of the Norit X-Flow SeaGuard UF membranes used in the Palm Jumeirah SWRO Plants in the UAE [12-15]. The filtration cycle lasts 28 minutes, which is favourable when compared to the 3.5 minutes required for cleaning or air scouring, resulting in a total cycle time of 31.5 minutes. For comparison, the Palm Jumeirah UF system operates with a filtration time of 25 minutes, while the Shuwaikh SWRO Plant in Kuwait has a filtration duration of 26 minutes [16].

The UF process commenced with the injection of seawater into the seven racks via three feed pumps to segregate filtrate at a rate of 4208 m³/hr from reject water containing pollutants from the intake system, backwashing, and the chemical cleaning (CIP) process. Air scour is applied during backwashing every 28 minutes for 3.5 minutes to maintain the high flux of the UF membranes. Disinfection is achieved using sodium hypochlorite at 12 wt%, with a daily usage of 79.73 litres, to prevent bacterial growth in the UF modules. Chemical cleaning is performed using sulfuric acid (H₂SO₄) at 96 wt% and low pH, consuming approximately 47.7 litres per day, and sodium hydroxide (NaOH) at 50 wt% and high pH, with a daily consumption of 88.3 litres. This cleaning, performed with filtered water, is conducted every 3 days. The UF membranes achieve rejection rates of 99% for total suspended solids (TSS) and 96% for total organic carbon (TOC) [17].

4.2. RO Desalination Process

4.2.1. One-Pass, Single-Stage System

In simulating the initial process configuration of a single-pass, single-stage direct open-intake SWRO plant integrated with an ultrafiltration pre-treatment system, the required number of membrane elements was calculated to be 1046.35, corresponding to approximately 149.4 pressure vessels, assuming 7 elements per vessel. The next step in the SWRO simulation involves selecting an appropriate membrane type. Given that the feedwater is high-salinity seawater with significant fouling potential, it is essential to select a membrane that provides strong salt rejection and adequate permeate flow. Among the six available membrane types, the SWC4 MAX is the only membrane capable of producing 661 m³/h of permeate from a 1469 m³/h feed, matching the performance of the Barka ACWA Power SWRO facility and utilising the same number of pressure vessels (149 PV). The ACWA Power Barka I SWRO plant (Phase I + Phase II) has a total desalination capacity of 102,284 m³/day, equivalent to 27 MGD. It is the commonly used and

reported production capacity for the Barka I RO facility [18]. Although all membranes achieve similar permeate production, the design limit requires that the maximum flux does not exceed 34 $\text{lt}/\text{m}^2/\text{hr}$. Only the SWC4 MAX and SWC4-LD membranes meet this criterion. However, given feed pressure requirements, the SWC4-LD membrane is selected for the first-pass pressure vessels due to its lower feed pressure than the SWC4 MAX. Other membrane types, despite potentially having higher permeate flow rates, would exceed the 34 $\text{lt}/\text{m}^2/\text{hr}$ flux limit, increasing the risk of rapid biofouling [19].

Table 2. Comparison of membrane types for first pass

Membrane type	Feed pressure (bar)	Permeate TDS (mg/L)	Highest flux ($\text{L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$)
SWC4 MAX	61	185	33.1
SWC4 – LD	59	208	34
SWC5 MAX	55.3	295.3	39.4
SWC5 – LD	55.6	264.1	40.4
SWC4 MAX	53.8	449.5	46.5
SWC6 – LD	53.7	447	47.9

From the 1469 m^3/h feed seawater, it was possible to recover 661 m^3/h of product water, corresponding to a 45% recovery at an operating pressure of 61 bar. The product water quality from this RO system is satisfactory, with a salt rejection rate of 99.51% and total dissolved solids (TDS) reduced to 185 mg/L , as illustrated in the image below. However, this simplistic design is not practical because the maximum flux of 34 $\text{lt}/\text{m}^2/\text{hr}$ equals the design limit and is significantly higher than the average operating flux of 17 $\text{lt}/\text{m}^2/\text{hr}$. Therefore, it was necessary to increase the number of pressure vessels to enlarge the membrane area available for filtration [20].

4.2.2. One Pass, Single Stage with Recirculation Stream

To decrease the average permeate flux in a single-pass system and to prevent escalating desalination plant costs with additional pressure vessels, the initial corrective measure was to enhance the feed entering the RO membranes by recirculating a portion of the brine stream. A recirculation stream was incorporated into the design to recirculate 10% (80 m^3/hr) to 20% (160 m^3/hr) of the brine stream. Incorporating a recirculation stream into the design, with a rate of 80 m^3/hr , resulted in the average flux remaining unchanged at 17 ($\text{L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$), while the maximum flux experienced a partial reduction from 34 ($\text{L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) to 32.1 ($\text{L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). Upon increasing the recirculation ratio to 20% or 160 m^3/hr , the average flux marginally decreased to 15.9, while the maximum flux diminished to 31.2. Although these flux values remain high,

operating at this rate could accelerate biofouling, particularly in the presence of elevated concentrations of organic foulants from algal blooms in the feed seawater. Consequently, it became necessary to increase the number of pressure vessels, leading to the simulation of a two-pass, single-stage reverse osmosis system configuration [21, 22].

4.2.3. Two Passes, Single-Stage RO System

In the second pass, fourteen types of brackish water membranes were considered. These membranes treat the product water from the first pass. A two-pass system was simulated to evaluate the performance of each membrane in terms of feed pressure, permeate flow, permeate total dissolved solids (TDS), maximum flux, and the highest beta value. All membranes achieved a permeate recovery rate close to 90%. However, with respect to the maximum flux and beta parameters, which should not exceed $55 \text{ (L} \cdot \text{m}^{-2} \cdot \text{h}^{-1})$ and 1.5, respectively, most membrane types exceeded the design limits during the second pass. It is critical to maintain the beta value, which reflects concentration polarisation at the membrane surface, below 1.2 times the saturation concentration and ensure its maximum does not exceed 1.5 times the saturation limit within the pressure vessel. This precaution maintains high salt rejection and prevents membrane damage from scaling [23]. Among the membranes evaluated, only two types met the design criteria and produced high-quality permeate: CPA6-LD, with a maximum flux of $53.6 \text{ (L} \cdot \text{m}^{-2} \cdot \text{h}^{-1})$ and a beta of 1.3, and CPA6-MAX, with a maximum flux of $51.8 \text{ L/m}^2/\text{hr}$ and a beta of 1.4, as summarised in Table 2. CPA6-LD is preferred over CPA6-MAX due to its higher average permeate flow, resulting in improved overall recovery.

The determination of the appropriate quantity of pressure vessels for the second pass was predicated on various operational constraints, including feed flow per vessel, concentrate flow, and flux. The reverse osmosis system, comprising a high number of pressure vessels, significantly decreases the concentrate flow rate when simulating 55 pressure vessels, each containing 7 membrane elements. Conversely, the selection of a limited quantity of pressure vessels, specifically 35 PV, resulted in an elevation of both average and maximum flux inside the system beyond conventional parameters. In the simulation of the two-pass reverse osmosis system with 35 pressure vessels for the second pass, the average flux per vessel was $76.2 \text{ (L} \cdot \text{m}^{-2} \cdot \text{h}^{-1})$, while the maximum flux was $79.4 \text{ (L} \cdot \text{m}^{-2} \cdot \text{h}^{-1})$, significantly above the maximum flux limit of $56 \text{ (L} \cdot \text{m}^{-2} \cdot \text{h}^{-1})$. A system of 45 pressure vessels was determined to be optimal for the specified flow, with the second pass achieving a high recovery rate of 90%, corresponding to $595 \text{ m}^3/\text{hr}$ at an operating pressure of 18.89 bar. Verification of the quantity of pressure vessels by mathematical methodology indicates that

the required number of membrane elements is 315.14. The number of pressure vessels, each with 7 membrane elements, is 45.

4.2.4. Two Passes, Two-Stage RO System

A primary disadvantage of a two-pass single-stage reverse osmosis (RO) system is its comparatively low permeate recovery, resulting in roughly 55% of the feedwater being rejected. This reduces water recovery efficiency and amplifies the operation's environmental impact. A secondary reverse osmosis system is implemented to improve permeate recovery. The principal problems in creating the second stage were selecting a suitable membrane type and determining the optimal number of membrane pieces. This phase aims to optimise product recovery, so the selection criteria prioritised membranes exhibiting elevated permeate flux. Upon simulating the suggested design with different membrane types, the SWC6-LD membrane was determined to be the most appropriate, as it produced the highest permeate flow rate (Table 3).

Under standard seawater circumstances (TDS = 37,905 mg/L), the SWC6-LD membrane exhibits a high salt rejection rate of 99.6%. In this system, the SWC6-LD membrane is employed to process the brine reject from the initial stage, resulting in a salt passage of 2.66%, corresponding to a total dissolved solids (TDS) concentration of 1,823 mg/L. This product water is unsuitable for direct consumption; however, it undergoes secondary treatment to reduce its salt concentration further, ensuring compliance with drinking water requirements.

Table 3. Comparison of different membrane types of performance for the second stage

Membrane type	Permeate flow (m ³ /hr)	Permeate TDS (mg/L)
SWC4 MAX	61.7	1313
SWC4 – LD	67.3	1076
SWC5 MAX	71.7	1563
SWC5 – LD	80	1258
SWC4 MAX	79.5	2097
SWC6 – LD	91.2	1823

Similar to the first stage, each pressure vessel in the proposed second stage contains seven membrane elements. The required number of pressure vessels was determined based on key criteria, including maintaining a minimum concentrate flow of 2.7 m³/h per vessel, ensuring feed flow does not exceed 19.3 m³/h per vessel, keeping the average membrane flux below 17 (L·m⁻²·h⁻¹), and limiting the maximum

pressure vessel (PV) flux to $34 \text{ (L} \cdot \text{m}^{-2} \cdot \text{h}^{-1})$. Using a mathematical approach, the total number of membrane elements was calculated to be 1,574.1, yielding an optimal configuration of 75 pressure vessels. The desalination process was simulated with pressure vessel quantities ranging from 45 to 85, as shown in table 4, to maximise permeate production while minimising feed pressure and meeting design constraints for feed flow, concentrate flow, and flux per PV.

While fewer pressure vessels are economically favourable, a configuration with 45 vessels and a total feed flow of $808 \text{ m}^3/\text{h}$ resulted in a feed flow per vessel of $21.69 \text{ m}^3/\text{h}$, exceeding the maximum design limit [24]. The simulations showed that increasing the number of pressure vessels improved permeate flow and reduced operating pressure, but beyond 75 vessels up to 85 no significant gains in permeate production or reduction in feed pressure were observed. Therefore, 75 pressure vessels, each containing seven membranes, were selected as the optimal configuration for the specified feed flow, balancing efficiency, cost, and performance.

Table 4. Determining the optimal number of pressure vessels for the second stage

No. of pressure vessel	Feed pressure (bar)	permeate flow (m^3/hr)	Feed flow per PV (m^3/hr)	Concentrate flow /PV (m^3/hr)	Average Flux/PV ($\text{L} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$)
85	53.6	96.3	11.95	4.4	9.5
75	54.1	91.2	13.44	12.23	4.8
65	54.5	72.1	15.38	14.11	4.9
55	55.2	59.2	17.99	16.67	5.1
45	55.9	43	21.69	20.38	5.1

4.3. Analysing the Performance of the Proposed Design with Variable Parameters

Before examining the parameters influencing the suggested design, it is crucial to verify the simulation results by comparing them with outcomes from analogous simulation studies. The permeate quality of the engineered two-pass, double-stage seawater reverse osmosis (SWRO) system was evaluated against that of an SWRO facility developed by [25, 26], which was replicated in IMSDesign software under equivalent feed seawater conditions. The comparison results are summarised in Table 5. The reference design produced permeate with a TDS of 263.75 mg/L , while the proposed design produced permeate with a TDS of 350.85 mg/L . The reference system achieved a salt rejection rate of 99.3%, compared to 99.07% for the proposed system. These values are within an acceptable range, confirming the validity and reliability of the proposed design.

Table 5. Comparing the permeate quality of the proposed designed system with the reference design

Parameter	Feed seawater (mg/L)	Reference permeates (mg/L)	Design permeates (mg/L)	Final product water (mg/L)
Calcium	445.3	0.76	0.516	6.47
Magnesium	1387.3	2.36	1.609	1.63
Sodium	11651.2	94.67	129.45	145.34
Potassium	431.3	4.37	5.98	6
Bicarbonate	121.6	1.59	2.16	24.18
Sulphate	2931.6	5.39	7.159	7.24
Chloride	20913.9	153.13	203.97	207.74
TDS	37905	263.75	350.85	407.48
Fluoride	4	-	0.095	0.39
Boron	2	-	0.82	0.82
pH	8.2	-	6.8	7.26

4.3.1. Effects of Increasing Feed Temperature

To assess the effect of seasonal variations in feed water temperature on the proposed two-pass, two-stage SWRO desalination plant, simulations were conducted at different temperatures. Using high-quality feedwater with a total dissolved solids (TDS) concentration of 37,905 mg/L, the system was assessed at feedwater temperatures of 25°C, 30°C, and 35°C. The results show that permeate quality decreases with increasing feedwater temperature. At 30°C, the permeate TDS was 350.85 mg/L, while it increased to 429 mg/L at 35°C and decreased to 233.57 mg/L at 25°C, as summarised in Table 6 [27]. This trend is expected, as higher temperatures generally increase membrane permeability, allowing more salts to pass through, thereby reducing salt rejection efficiency. Conversely, lower temperatures reduce permeability, thereby improving permeate quality.

The system was also simulated using high-salinity seawater with a total dissolved solids (TDS) concentration of 45,656 mg/L at feedwater temperatures of 25°C, 30°C, and 35°C. The results show that RO membrane salt rejection decreases as feedwater temperature rises. Permeate salinity increased from 348.37 mg/L at 25°C to 429.32 mg/L at 30°C and 525.35 mg/L at 35°C, as shown in Table 7. Additionally, higher feedwater temperatures corresponded to increased feed pressure requirements, ranging from 54.0 bar at 25°C to 54.1 bar at 30°C and 54.3 bar at 35°C. This trend is consistent with the observation that elevated temperatures enhance membrane permeability, leading to greater salt passage and necessitating higher operating pressures to maintain performance [28].

Table 6. Effect of feed water temperature on permeate quality in Low-TDS seawater desalination

Parameter	Feed Concentration (mg/L)	Permeate @ 35°C (mg/L)	Permeate @ 30°C (mg/L)	Permeate @ 25°C (mg/L)
Calcium	445.3	0.633	0.516	0.340
Magnesium	1387.3	1.970	1.609	1.070
Sodium	11651.2	158.59	129.45	80.18
Potassium	431.3	7.32	5.98	3.98
Bicarbonate	121.6	2.64	2.16	1.43
Sulphate	2931.6	8.77	7.159	4.76
Chloride	20913.9	249.90	203.97	135.79
Total Dissolved Solids (TDS)	37905	429.00	350.85	233.57
Fluoride	4.0	0.103	0.095	0.087
Boron	2.0	0.88	0.82	0.79
pH	8.2	6.9	6.8	6.6

Table 7. Variation in permeate water quality of high TDS seawater at different temperatures

Parameter	Feed (mg/L)	Permeate at 35°C (mg/L)	Permeate at 30°C (mg/L)	Permeate at 25°C (mg/L)
Calcium	677	0.954	0.779	0.632
Magnesium	1387	1.954	1.596	1.294
Sodium	14109	190.337	155.499	126.129
Potassium	762	12.84	10.49	8.511
Bicarbonate	270	5.88	4.8	3.89
Sulphate	3599	10.93	8.93	7.239
Chloride	24782	300.45	245.468	199.11
TDS	45656	525.35	429.32	348.37
Fluoride	7	0.169	0.138	0.112
Boron	5	1.6	1.446	1.259
pH	8.2	7	6.9	6.8

4.4. Optimisation Process

4.4.1. Increasing Pressure of High-Pressure Pump

The optimisation procedure sought to enhance the system recovery rate, as pressure is the principal driving factor in reverse osmosis (RO) desalination, making production proportional to the applied pressure. The system was evaluated at various operating pressures, ensuring that the applied pressure exceeded the osmotic pressure, which correlates directly with the concentration of dissolved solids in the feed water [29]. The manual adjustment of feed pressure was investigated at several pressure levels to identify the optimal operating pressure for the system. Nonetheless, manual pressure adjustment is only practicable in a single-

pass system. Regrettably, the IMSDesign simulation program does not facilitate pressure augmentation in the suggested two-pass, two-stage system. Table 8 shows the permeate recovery rates for pressure fluctuations between 53 bar and 59 bar.

Table 8. Variation in permeate flow at different feed pressures

Feed Pressure (bar)	Recovery Rate (%)	Permeate Flow (m ³ /hr)
53.0	39.82	576.60
54.3	45.00	661.00
55.0	47.76	706.18
56.0	51.88	773.49
57.0	56.07	841.93
58.0	60.32	911.18
59.0	64.62	980.00

The determined feed pressure for the system was 54.3 bar, resulting in a 45% recovery rate and a permeate flow of 661 m³/h. Reducing the feed pressure to 53 bar decreased the recovery rate to 39.82% with a permeate flow of 576.6 m³/h, while increasing it to 55 bar raised the recovery rate to 47.76%, producing 706.18 m³/h of permeate. The maximum permeate flow of 911.18 m³/h, corresponding to a recovery rate of 60.32%, was achieved at 58 bar (Table 8). However, further increases beyond 59 bar would increase permeate flow, but risk membrane damage, as first-pass permeate flux would exceed the 34 (L·m⁻²·h⁻¹) design limit. An evaluation of the costs and benefits of using higher feed pressure as an optimisation strategy indicates that it is largely impractical. The approach is incompatible with two-pass systems, limiting further salinity reduction, and can shorten membrane lifespan due to higher mechanical stress. Additionally, it increases chemical consumption for cleaning and scaling prevention, particularly in the second-stage pressure vessels. Considering these operational and economic constraints, increasing feed pressure is a less feasible optimisation strategy [30].

5. Conclusions

The proposed seawater reverse osmosis (SWRO) desalination plant integrates advanced technologies to enhance efficiency, water quality, and sustainability. A key feature is the ultrafiltration (UF) pre-treatment system with 637 HYDRAcapMAX80 modules, treating 4,306 m³/h of feed at 5 bar, achieving 97.73% recovery, removing 99.6% of TSS and 96% of TOC, including harmful algal blooms, thereby minimising membrane fouling. The SWRO process employs a two-pass, two-stage configuration with 149

pressure vessels in the first pass, 45 in the second pass, and 75 in the second stage, and incorporates pressure exchangers and turbochargers, reducing energy consumption from 6.0 to 3.26 kWh/m³. Compared to the ACWA Power SWRO plant, the proposed system attains higher recovery and lower energy use. Performance simulations across salinities of 37,905-45,656 mg/L TDS and temperatures of 25- 35°C confirm consistently high-quality permeate, although higher salinity and temperature increase feed pressure, which, while improving recovery, is impractical in the long term due to reduced membrane lifespan, increased chemical consumption, and challenges in second-pass operation. Overall, the integration of UF pre-treatment, an optimised SWRO configuration, and advanced energy recovery provides a technically and economically viable solution for sustainable seawater desalination.

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