Jordanian Journal of Engineering and Chemical Industries

Print ISSN: 2616 - 9584 Online ISSN: 2617 - 720X

Modelling, simulation and optimisation of a large-scale reverse osmosis based on a high-salinity brackish water desalination process. Quantifying different grades of water

Alanood A.Alsarayreh *1

1Mutah University, Faculty of Engineering, Chemical Engineering Department, P.O. Box 7, Karak 61710 – Jordan

Abstract

This study focuses on evaluating the performance of various proposed layouts of a multi-stage industrial large-scale Reverse Osmosis (RO) process, specifically designed to desalinate high salinity brackish water. The proposed layouts include the parallel, series, tapered layouts of retentate reprocessing, permeate reprocessing, and coupled retentate-permeate reprocessing. To conduct this study, a comprehensive validated model for a single RO membrane module found in the literature, which is then used to develop appropriate models for the proposed multi-stage RO system layouts. The proposed layouts are tested under unique inlet conditions to identify the design that performs optimally. The key performance indicators used for evaluation include water productivity, specific energy consumption, and product salinity. The results demonstrate variable productivity, product salinity and specific energy consumption for the proposed layouts. For each proposed layout, an optimisation study is conducted to instigate the optimal operating conditions to specifically producing a grade of water. Statistically, the optimisation results of tapered retentate permeate reprocessing layout elucidate the production of industrial water (less than 50 ppm) of 35.2% and 1.973 kWh/m3 of water recovery and specific energy consumption, respectively. Also, the same layout produces the optimum 72.32% and 1.623 kWh/m3 for bottled water (200 ppm). However, the tapered retentate permeate reprocessing layout introduces optimum 64.98% and 1.688 kWh/m3 for tap and drinking water (500 ppm), 58.128% and 1.353 kWh/m3 for irrigation water (800 ppm), and 47.474% and 1.238 kWh/m3 for livestock water (1000 ppm). Thus, this study introduced the possibility of producing different grades of water including industrial water, bottled water, tap water, irrigation water, and livestock water.

Paper type: Research paper

Keywords : Brackish water desalination; Reverse Osmosis; Modelling and Simulation, Optimisation; Several grades of water; Water productivity; Product water salinity; Specific energy consumption.

Citation: Alsarayreh.A. A.,“ Modelling, simulation and optimisation of a large-scale reverse osmosis based on a high-salinity brackish water desalination process. Quantifying different grades of water”, *Journal of Engineering and Chemical Industries*, Vol. **8**, No.2, pp:148-162 (2025).

1. Introduction

The need for freshwater has increased dramatically during the past few years in many places, especially in developing countries (Albert et al., 2021). Desalination is acknowledged as a key strategy for guaranteeing water quality. Surprisingly, desalination is also used to remove cancer-causing agents such chlorinated hydrocarbons and other toxins that are present in some water sources (Gondal, 2023). Researchers are now looking at more effective water desalination techniques as a result of this. As a possible response to the problem of water scarcity and the lack of high-quality water, brackish water desalination plants are becoming more common in a number of Middle Eastern countries (Mahmoudi et al., 2023; Ahdab and Lienhard, 2021). The scarcity of water in these countries can be ascribed to several factors.

* Corresponding author: E-mail: Alanood.sar@mutah.edu.jo ORCID: **https://orcid.org/0000-0002-9524-4221**

Received : 9 Mar 2025 Revised: 19 Mar 2025 Accepted: 23 Mar 2025.

Jordanian Journal of Engineering and Chemical Industries (JJECI), Vol.8, No.2, 2025, pp: 148-162.

The rapid growth of the population, the ongoing disposal of wastewater by various industrial sectors, and the inadequate infrastructure of water desalination systems are the primary causes. Additionally, a number of Middle Eastern countries lack significant groundwater resources, such as aquifers (Al-Obaidi et al., 2022), which are unable to sustain the population's needs. Moreover, the pressing issue of climate change further exacerbates the problem of water scarcity.

These factors have collectively contributed to the lessening of water resources, with the demand projected to rise in the near future. Up to this point, there is a necessity to improve the conventional water desalination plants in these countries besides maintaining the sustainability of water resources. More importantly, there is a critical demand to construct a high-capacity brackish water desalination based Reverse Osmosis (RO) process to fulfil the requirements of bottled water besides offering different grades of waters for industrial, irrigation, and livestock needs. In this regard, RO process constitutes 80% of the global desalination capacity, according to Jalihal and Venkatesan (Jalihal and Venkatesan, 2019). In recent decades, the utilisation of RO as a supplementary approach has steadily grown. Remarkably, this technique achieves lower energy consumption while meeting the recommended standards for potable water set by the World Health Organization, as highlighted by Al-hotmani et al. (2020).

Several investigations are existed in the open literature that examined the possibility of developing, upgrading and improving the efficiency of RO process-based brackish water desalination.

Al-Obaidi et al. (2018) established a steady-state mathematical model for a medium-sized, multi-stage, multi-pass brackish water reverse osmosis desalination plant (1200 m³/day), precisely concentrating on the Arab Potash Company's (APC) facility in Jordan. The model was validated against actual operational data for consistency and introduced a high degree of alignment. The research encompasses a sensitivity analysis based on the model developed to signify the effects of the operational variables (salinity, pressure, temperature, and flow rate) on the performance indicators. The sensitivity analysis indicated that inlet pressure and feed flow rate are serious parameters positively impacting the product salinity. This vision can aid to optimise the operational conditions for better performance. Statistically, the APC plant attained a superior low product salinity of around 2 ppm, signifying the efficacy of the multi-stage, multi-pass configuration in producing high-quality freshwater.

Alsarayreh et al. (2020) emphases on the opportunity of minimising the energy consumption of the spiral wound brackish water RO desalination plant of APC by adding an energy recovery device (ERD). Using the model developed by Al-Obaidi et al. (2018), the simulation of the process with and without the integration of an ERD was carried out. In this regard, the impacts of feed flow rate, pressure, and temperature on the specific energy consumption with and without ERD. The analysis showed that lower pressures and feed flow rates and higher temperatures can ascertain a drop of specific energy consumption. This introduced the opportunity of reducing the specific energy consumption by adding ERD of 47% to 53.8% in a comparison against to the original design without an ERD. Furthermore, an upsurge in ERD efficacy from 80% to 90% resulted in reliable energy consumption reductions across all feed flow rates. Thus, this research highlighted the significance of ERDs in upgrading the economic feasibility of desalination processes.

Referring to the research of Alsarayreh et al. (2020a), another research was conducted by Alsarayreh et al. (2020b) to explore the viability of utilising various recycled ratios of retentate of 10% to 100% from the first pass on the performance metrics of the spiral wound brackish water RO desalination plant of APC. Specifically, the focus was on how recycling high salinity brine would affect water recovery, product water quality, and specific energy consumption. The results introduced that recycling retentate can improve product capacity by approximately 3% at 100% recycle ratio. This in turn showed an optimum water recovery of 61.21% at 100% recycling. However, the specific energy consumption was increased (as a penalty) by 10.7% from 0.997 kWh/m³ (without recycle mode) to 1.105 kWh/m³ (with 100% recycle), demonstrating a trade-off between recovery and energy use. Moreover, the product water salinity was increased from 2 ppm to 2.975 ppm (still within acceptable limits for drinking water) at full recycling. Thus, it can be said that this research provided a primitive insight into optimising desalination processes, enhancing water recovery while considering energy efficiency and product water salinity.

As a complementary section of Alsarayreh’s research, Alsarayreh et al. (2021) focused on maximising water recovery and minimising specific energy consumption of the spiral wound brackish water RO desalination plant of APC by employing several brands of membranes. To conduct this study, the simulation study was carried out via upgrading the model of Al-Obaidi et al. (2018) by characterizing the membrane properties. The findings ascertained the optimum membrane type of FilmTec BW30LE-440 represented the finest performance, attaining a water recovery enhancement of 22% as it increases from 56.442% (original membrane) to 68.998% (FilmTec BW30LE-440). This ensured a lowering of product salinity from 2 ppm to 1.69 ppm. Also, the specific energy consumption was reduced by 10%. Accordingly, these results would contribute to optimise the RO desalination processes by determining the most efficient membrane type and making desalination more sustainable and economically viable.

Another research was introduced by Ansari et al. (2021) to design, construct, and experimentally assess the efficacy of a RO pilot-plant brackish water desalination system (50 m³/d) of Shahid Chamran University of Ahvaz, Iran. This elaborated the influence of feed pressure (5 to 13 bar) and salinity (1000 to 5000 ppm) on the performance metrics of water flux, water recovery, retentate flow rate, permeate and retentate salinities, and solute rejection. The results indicated an optimum salt rejection of 98.8% and 12 ppm of permeate salinity as a result to rising feed pressure from 5 to 13 bar. In this regard, a reduction of 73.3% in the product salinity was assured as a reply to rising feed pressure from 5 to 13 bar. This research can help to enhance the efficacy and reliability of RO systems, mainly in arid regions where freshwater resources are limited.

For a medium scale RO brackish water desalination system at Al-Hashemite University, Al-Obaidi et al. (2023) simulated and optimised the process to promote the overall performance and identify possible maintenance opportunities. To conduct this research, a specific model was developed to carry out a comprehensive sensitivity analysis. In this regard, the operational variables of pump pressure, temperature, and flow rate were analysed for their influence on the water productivity, salinity, and specific energy consumption. Also, a specific optimisation study was conducted to investigate the lowest specific energy consumption while preserving similar water productivity. The optimisation revealed a 19% decrease in specific energy consumption besides an improvement of 4.46% in water productivity. Regarding the maintenance opportunities, the research suggested a number of recommendations to scheduling cleaning and maintenance without needing full system shutdown. The freshwater production cost was appraised to be approximately \$0.459/m³ for the studied system.

Sadek et al. (2024) determined the optimal pressure and temperature of RO desalination system when subjected to different brackish salinity levels. The research investigated the effects of these parameters on the product salinity, specific energy consumption, and solute rejection of the desalination process. To conduct this aim, the researchers used a laboratory scale of RO process equipped with a membrane type DowfilmTec BW30-4040 to treat brackish water at the National Center of Water Research, Egypt. The experiments were conducted using a set of inlet pressure ranges between 5 to 15 bars, brackish water salinity ranges between 1000 to 5500 ppm, and operational temperature ranges between 21 °C to 35 °C. The results indicated the maximum solute rejection of 98.8% at 13 bar. The product salinity decreased by 73.3% as a response to raising feed pressure from 5 to 13 bar. Furthermore, the optimal water recovery was ascertained at pressures ranging from 15.6 to 10.8 bars and temperatures between 21°C and 35°C. In this aspect, it was elucidated that the specific energy consumption varies between 0.6 to 1.50 kWh/m³, reliant on the water salinity and water recovery. The findings of this research can help to introduce cost-effective and energy-efficient desalination strategies.

While several of the aforementioned studies develop RO networks and explore the best network size to elevate the water recovery at a particular low energy consumption, the majority of these studies focused on small and medium-sized seawater RO systems. Mostly, there have been no thorough studies of predetermined RO network layouts in large-scale RO systems specially to desalinate high salinity of brackish water. Thus, a thorough evaluation of predetermined architectures of multi-stage large size RO systems based brackish water desalination is urgently needed. The aim of this study is to pinpoint a reliable high-salinity brackish water desalination process. First, this study puts six designs of large-scale RO networks made up of 180 pressure vessels linked together in three blocks of multi-stage RO membrane modules based high-salinity brackish water desalination. Second, using a reliable RO membrane model that is freely available in the public domain and unique set of inlet conditions, the process simulation identifies insight into water productivity, salinity, and specific energy consumption for each layout of RO process. Third, to provide different grades of water (industrial water (less than 50 ppm), bottled water (200 ppm), tap water (500 ppm), irrigation water (800 ppm), and livestock water (1000 ppm) while maximising the water productivity at the lowest energy consumption, the process optimisation based model is conducted while considering a constrain of product salinity.

2. General background of modelling of RO process

When an industrial process is modelled, outcomes and process variables are realized to have an inter-correlation, and the process function is identified. Therefore, by establishing a correlation between critical operational parameters and performance indicators, the systematic model is intended to evaluate the RO membrane's performance. Stated differently, modeling makes it possible to assess how each control variable affects the process variables. Conducting simulation and optimisation studies for the relevant process would be made easier by the precise modelling.

Understanding the flow of water through the feed channel and the permeability of freshwater via the membrane pores is crucial for developing an efficient seawater RO treatment technique. Specific relationships expressing the salinity of the product, water productivity, solute rejection, and specific energy consumption should be included in the simplified model. These metrics, in fact, need to be correlated with the design parameters of membrane dimensions as well as the input factors of pressure, salinity, temperature, and feed flow rate.

Based on the model established by Al-Obaidi et al. (2018), the current study plans to use the model of Al-Obaidi et al. [15] as a basis to conduct simulation and optimisation studies for six proposed layouts of large-scale high salinity brackish water RO desalination process. The model equations and appropriate descriptions of a single module of RO process are provided in Table A.1 of Appendix A. This model constitutes a set of linear and nonlinear equations to demonstrate the relationships between the water flux and transmembrane pressure. Also, the overall performance of water recovery, solute rejection and specific energy consumption are included. Furthermore, the model accuracy is examined via contrasting the experimental data of medium-scale RO brackish water desalination published by Al-Obaidi et al. (2018) against the model estimations of a number of performance metrics. Accordingly, Table A.2 of Appendix A introduces marginal errors, which signifies the model robustness.

3 Proposed layouts of multi-stage large-scale RO process

This study proposes six large-scale industrial layouts of three-blocks RO brackish water desalination plants where each block contains three stages of pressure vessels (PVs). Specifically, the designed brackish water RO process contains 180 PVs total, and each PV contains six membranes linked in a series. Thus, all the proposed configurations would have similar total membrane areas. In fact, by employing a unique set of inlet conditions, the suggestion of various layouts of similar number of PVs would aid in introducing a broad range of water productivity and product salinity. As a result, there would an opportunity to choose the best design to meet the unique needs (drinking water, industrial water, and irrigation water). The suggested RO setups are fully described in the following sections.

3.1 Parallel layout (PL)

Figure 1 shows the proposed parallel layout (PL) of RO systems. The three blocks of RO process are linked in a series layout, where each block contains 60 PVs in a parallel layout and each PV carries six membranes in a series. Thus, the retentate of the first block is fed to the second block for further polishing and so on. As there would be a greater number of parallel PVs in the total feed flowrate, the feed flowrate for each membrane under consideration would be reduced. Thus, there would be a chance to obtain high productivity of low-quality water with the parallel design. It is true that a decrease in membrane contact time would result in greater filtration and increased productivity.

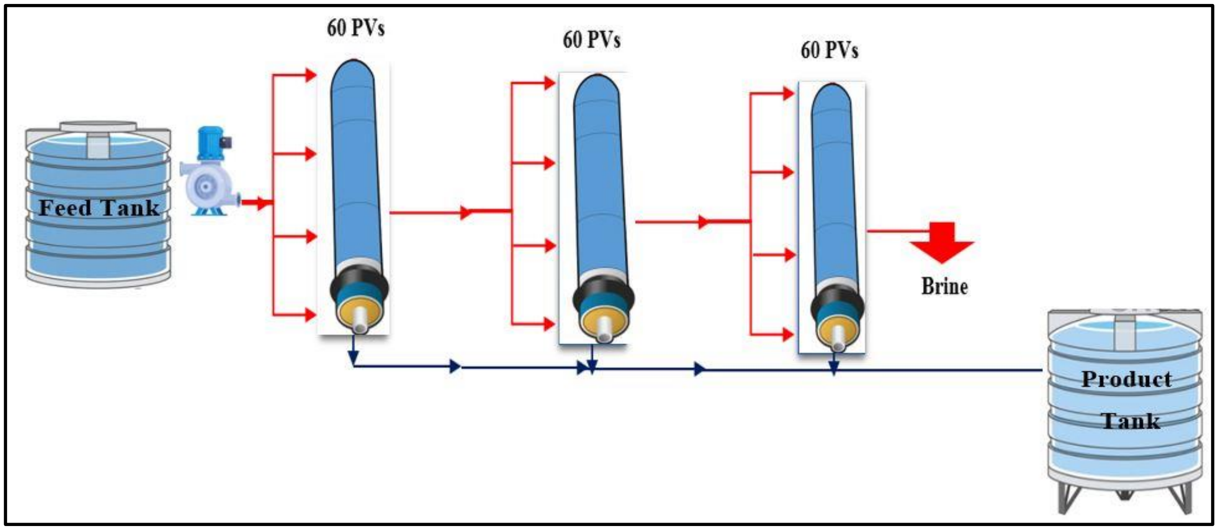

Fig. 1. A schematic diagram of parallel layout (PL)

3.2 Series layout (SL)

Three blocks of multi-stage RO systems are coupled in a series arrangement to form the series layout (SL) as depicted in **Figure 2**. In this layout, the retentate from the first block is processed in succeeding blocks, and so on through the last block. The permeates of three blocks are gathered to produce the product line. This layout characterises by the occurrences of variable operating conditions through multiple stages. Also, this layout has a high productivity due to rapid polishing of retentate through multiple stages. Compared to a single-stage system, operating many stages in series usually demands a higher energy input. The overall pressure needs rise with each new stage, resulting in higher energy consumption that may have an effect on the desalination process's operating costs. Also, this logical challenge of this layout is the dispose of high salinity brine since the retentate of a specific stage is the feed for the following one. This in turn would diminish the product flow rate as a result to fouling propensity in the tail of RO network.

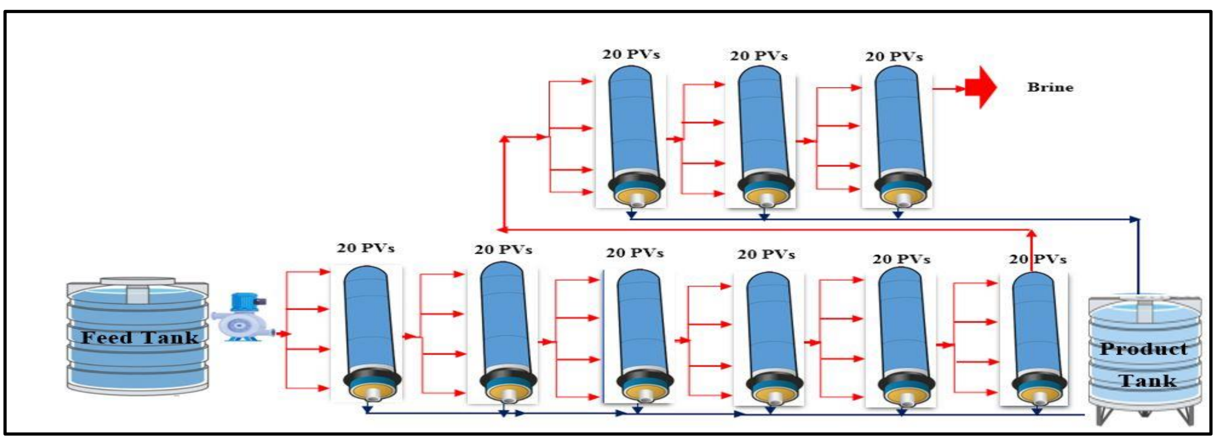

Fig. 2. A schematic diagram of series layout (SL)

3.3 Tapered retentate reprocessing layout (TRRL)

In contrast to SL, which uses a set number of PVs, the tapered retentate reprocessing layout (TRRL) exhibits a variable number of PVs across the subsequent blocks. TRRL is designed to have the total number of 180 PVs, where the first block contains 90 PVs of three stages in a series configuration, each stage contains 30 parallel PVs in each stage. The second block contains 60 PVs of 20 PVs in each stage, and the third block contains 30 PVs of 10 PVs in each stage **Figure 3**. The TRRL is typified by feeding the second block with the retentate of the first block, and so on, much like SL. In addition, the primary product stream is formed by the first block's product blending with the second block's product, and so on. According to Reiss et al., (2008), productivity can be positively impacted by the TRRL of varying numbers of pressure vessels at each stage as compared to SL.

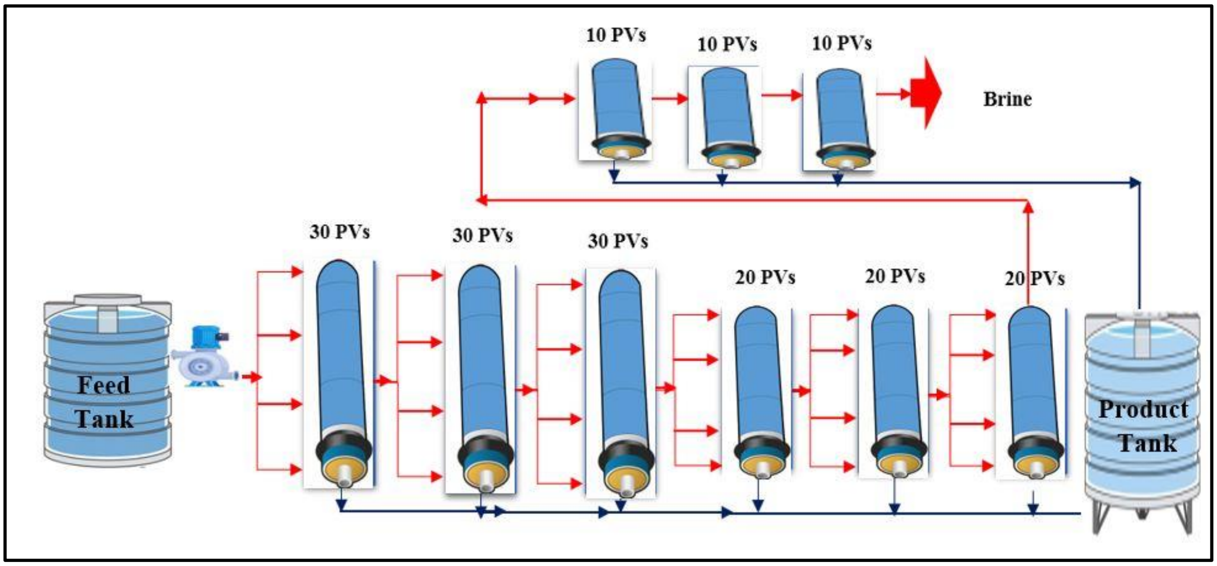

Fig. 3. A schematic diagram of tapered retentate reprocessing layout

3.4 Tapered retentate permeate reprocessing layout A (TRPRLA)

Tapered retentate permeate reprocessing layout (TRPRLA) initial block is intended to include 90 PVs connected in series, with 30 PVs in each stage. But in order to meet the upper and lower bounds on each membrane's feed flowrate, as well as the number of PVs in the second and third blocks, it's crucial to carefully choose how many PVs to keep within the relevant manufacturer's limitations. In the second block, there are three stages of 60 PVs total, with 20 PVs in each stage; in the third block, there are three stages of 30 PVs total, with 10 PVs in each of the stages. Consequently, the design of TRPRLA is founded on the idea of treating brackish water again by reprocessing the retentate from the first block in the second block. Feeding and reprocessing of collected permeates generated from the first and second blocks in the next third block come next. The product stream is thus represented by the third block's permeate. In addition, the final brine stream is formed by combining the retentate from the second and third blocks. As shown in **Figure 4**, an energy recovery device (ERD) for TRPRLA must be installed between the second and third blocks to assure active treatment of the permeate in the third block. To put up with satisfactory driving force inside the third block's membranes and throughout the ensuing stages, this is employed to rise the pressure of the reprocessing permeate (1 atm) to an improved value. Stated differently, ERD serves the purpose of extracting excess energy from the second block's high pressure retentate stream and transferring it to the first and second blocks' low pressure permeate streams before it enters the third block. When running out TRPRLA to effectively transfer energy from the high-pressure side to the lower one, the efficiency of the ERD is crucial. When the permeate stream enters block 3 for additional treatment, it will then have sufficient pressure. For this reason, TRPRLA is made to create high-quality water and improve the quality of the product. This results from reprocessing the two blocks' permeate stream in the third block, which already has a low salinity. It is reasonable to anticipate, therefore, that TRPRLA would be connected to low productivity. Because there is only one stream of products gathered from the third block, this is the primary concern with the design.

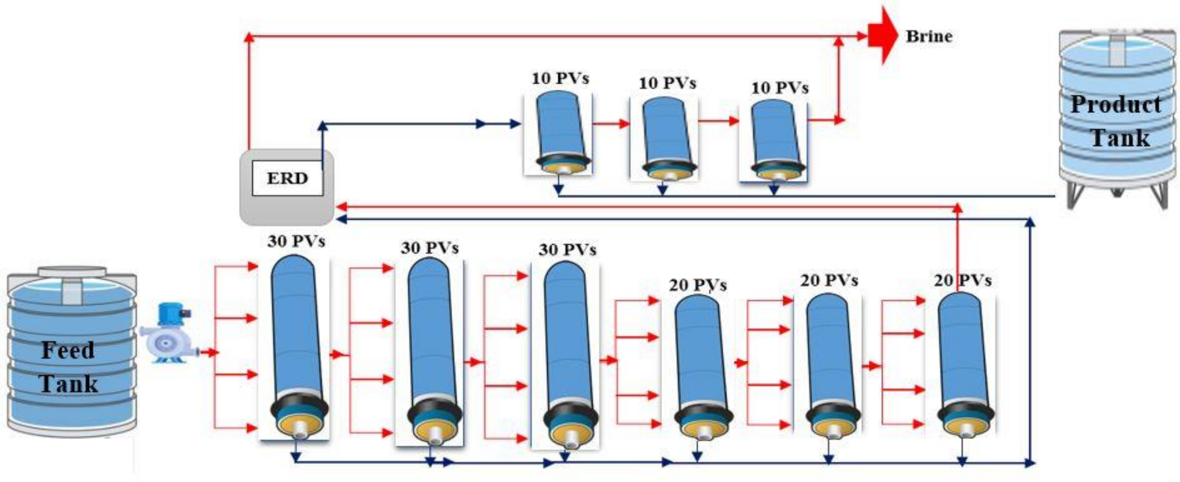

Fig. 4. A representation diagram of tapered retentate permeate reprocessing layout A

3.5 Tapered retentate permeate reprocessing layout B (TRPRLB)

The TRPRLB includes 90 PVs, 30 PVs in three stages connected in series, 75 PVs in the second block, 25 PVs in each stage, and 15 PVs in the third block, 5 PVs in each stage. TRPRLA and TRPRLB share a similar architecture, which is known as tapered retentate permeate reprocessing layout B. Instead of feeding the third block with a blended permeate of the first and second blocks as TRPRLA does, TRPRLB involves specifically reprocessing the second block permeate in the third block of the RO system. Furthermore, TRPRLB has also an ERD is introduced to absorb the excess energy from the second block's high pressure retentate stream as depicted in **Figure 5**. Another comparable feature between TRPRLA and TRPRLB is the emerging permeate of the first and third blocks, which forms the freshwater product stream of TRPRLB. Additionally, the primary disposed stream of TRPRLB is formed by the gathering of the retentate streams from the second block as they exit the ERD and the third block. It is evident that TRPRLB modifies the number of PVs in the second and third blocks in order to preserve a safe flowrate within each membrane in accordance with the manufacturer's recommendations.

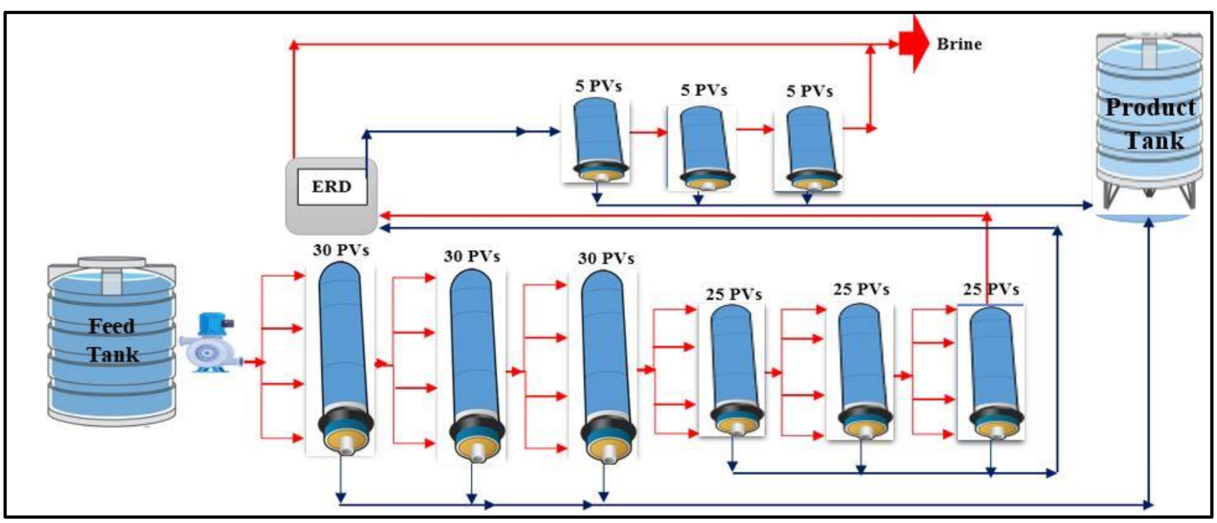

Fig. 5. A schematic diagram of tapered retentate permeate reprocessing layout B

2.4 Performance evaluation of proposed layouts via process simulation

The drive of this section is to provide an overall performance evaluation of the five multi-stage RO system layouts that have been proposed, based on the desalination of high-salinity brackish water. The product salinity, water productivity, retentate flowrate, retentate salinity, and specific energy consumption of each layout are the performance metrics that are being examined. The simulation-based model that was built has taken into account a specific set of RO system inlet characteristics. This can aid to fairly choose the optimal layout to accommodate the specific conditions of a high-salinity brackish water. Furthermore, the simulation-based model would identify the proper layout that can be used to produce a specific water type including industrial water, bottled water, tap water, irrigation water, and livestock water. This in turn would interpret the importance of realising the product salinity as an important metric in the current simulation. The simulation based model requires the availability of inlet conditions and membrane characteristics. These are provided in **Table 1**.

Table 1. Inlet conditions of brackish water and features of the used membrane

Parameter	Value and unit
Salinity of brackish water	20,000 (ppm)*
Temperature of brackish water	25 (ºC)
Pump pressure	40 (atm)
Feed flowrate	10368 (m^3/day)
Efficiency of Pump	85%
Efficiency of ERD	80%
Membrane brand and supplier	SW30HRLE-400i; DOW FILMTECK
Module layout and membrane material	Spiral wound element; Polyamide thin-film composite
Max. pump pressure	81.9 atm
Max. and min. feed flow rate	463.104 m^3/day; 86.4 m^3/day
Max. brackish water temperature	45 (ºC)
Module width (L) and length (W)	37.2 (m); 1 (m)
$A_{w\,(T_o)}$ (m/ atm s) at 25 °C	9.509x10^{-7} (m/s atm)
$B_{s(T_o)}$ NaCl (m/s) at 25 °C	5.645x10^{-8} (m/s)
Spacer type	Naltex-129
Feed spacer thickness (t_f)	5.93 x10^{-4} (m)
Length of spacer in the spacer mesh	2.77x10^{-3} (m)
Feed spacer characteristic ($A^{'}$)	7.38 (-)
Feed spacer characteristic (n)	0.34 (-)
Voidage (ε)	0.9058 (-)

*: United Nations Development Programme. Regional Bureau for Arab States and Sweden. Styrelsen för internationellt utvecklingssamarbete, 2013. Water governance in the Arab region: managing scarcity and securing the future. United Nations Publications.

Table 2 depicts the simulation results for each tested layout that considered the inlet conditions (provided in Table 1) and reflect performance metrics of the water productive, product water salinity, retentate flowrate and salinity, solute rejection, water recovery, and specific energy consumption.

Table 2. Simulation results of the five proposed layouts

Layout	Water productivity (m³/day)	Product water salinity (ppm)	Retentate flowrate (m³/day)	Retentate salinity (ppm)	Solute rejection% (-)	Water recovery% (-)	Specific energy consumption (kWh/m³)
Parallel layout (PL)	7258.372	1245.16	3109.627	63776.81	93.77	70.00	1.891
Series layout (SL)	6642.866	1154.33	3725.133	53606.64	94.22	64.07	2.067
Tapered retentate reprocessing layout (TRRL)	7029.043	1197.88	3338.956	59581.48	94.01	67.79	1.953
Tapered retentate permeate reprocessing layout A (TRPRLA)	6796.385	66.85	3571.614	57930.56	99.66	65.55	1.625
Tapered retentate permeate reprocessing layout B (TRPRLB)	6979.697	676.59	3388.303	59805.02	96.61	67.32	1.581

In comparison to other suggested layouts, Table 2 depicts that the parallel layout (PL) has the greatest water productivity of 7258.372 m³/day since it contains the greatest number of parallel pressure vessels in each stage. As a result, each membrane module has a lower feed flowrate and a longer fluid residence time, which indicates a higher permeation rate. With a water productivity of 7029.043 m³/day, the tapered retentate reprocessing layout (TRRL) ranks second in water productivity, while the series layout (SL) has the lowest water productivity at 6642.866 m³/day. The retentate reprocessing of high-salinity water in the following stages causes SL to have the lowest water productivity because it slows down water penetration. Given that each of these layouts operates under a comparable set of input conditions, the water recovery% results in Table 2 have given a consistent image of the water productivity and reflected the same response across the suggested layouts. Accordingly, the parallel layout (PL), which corresponds to the best water productivity, achieves the highest water recovery percentage of 70%. Excepting the results of SL, it should be noted that the tapered retentate permeate reprocessing layout A (TRPRLA) has elaborated the lowermost water productivity in a comparison to other proposed layouts. This can be attributed to the specific design of this layout of having one product line of high-quality water compared to other layouts.

The product water salinity of the five suggested design varies noticeably between 66.85 and 1245.16 ppm, as Table 2 displays. This discrepancy can be ascribed to the various layout designs that present various desalination techniques for the permeate, retentate, and coupled retentate and permeate reprocessing designs. The simulation findings demonstrate that the permeate reprocessing layouts outperformed the retentate reprocessing layouts in terms of results while using the established inlet conditions. To be more precise, the lowest product water salinity is produced by the tapered retentate permeate reprocessing layout A (TRPRLA) at 66.85 ppm. This is followed by the tapered retentate permeate reprocessing layout B (TRPRLB) at 676.59 ppm, the series layout (SL) at 1154.33 ppm, the tapered retentate reprocessing layout (TRRL) at 1197.88 ppm, and lastly, the worst design of parallel layout (PL) at 1245.16 ppm. In contrast to retentate reprocessing designs, which process high salinity water, the effectiveness of permeate reprocessing layouts is related to processing low salinity permeate. Thus, compared to 93.77%, 94.01%, and 94.22% for parallel layout (PL), tapered retentate reprocessing layout (TRRL), and series layout (SL), respectively, the permeate reprocessing layouts (TRPRLA and TRPRLB) introduce the maximum solute rejection of 99.66% and 96.61%, respectively.

Reduced brine discharge from membrane desalination technologies is crucial because it poses a threat to marine life and biodiversity and has a negative impact on the environment. High brine concentrations can disturb marine ecosystems by changing the salinity levels in receiving waters. According to the simulation findings provided in Table 2, Parallel layout (PL) and series layout (SL) have demonstrated the lowest and maximum retentate flowrate of 3109.627 and 3725.133 m³/day, respectively. Accordingly, the parallel layout (PL) and series layout (SL) introduce the highest and lowest retentate salinity of brine disposed to water bodies of 63776.81 and 53606.64 ppm, respectively. In this regard, it should be noted that the implementation of tapered retentate reprocessing layout (TRRL) has resulted the compromised layout regarding the negative impact on the ecosystem.

To reduce the harmful effects that high energy use has on the environment, membrane desalination methods must achieve the lowest possible specific energy consumption. Excessive energy use worsens the environmental impact of desalination operations and raises carbon emissions in addition to increasing operating expenses. Desalination plants can minimise greenhouse gas emissions and the environmental load on them by putting an emphasis on energy efficiency and reducing their dependency on fossil fuels. In light of growing water scarcity, this focus on reducing specific energy usage is in line with global sustainability goals, encouraging a more environmentally friendly method of producing freshwater and guaranteeing responsible resource use. In line of this, Table 2 signifies the prosperity of tapered retentate permeate reprocessing layout B (TRPRLB) as it introduces the lowermost specific energy consumption of 1.581 kWh/m^3 in a comparison to the series layout (SL) that depicts the maximum one of 2.067 kWh/m^3. Indeed, the existence of an ERD in the TRPRLB has positively affect the overall specific energy consumption.

4. Production of different grades of water via process optimisation

The produced water, discharged stream, and energy consumption characteristics varied primitively even though all established layouts were operating with the same number of PVs and elements and under the same operating conditions. As a consequence, the simulation results of Table 2 have validated the significance of designing the RO process, which would help in choosing the right layout. More significantly, the proposed layout's assigned difference in performance metrics provides a good excuse to use the design in a particular field to generate a certain kind of water.

This section intends to represent the optimisation of RO process to appropriately provide the optimal inlet conditions that enables to provide the specific target of water type (industrial water, bottled water, tap water, irrigation water, and livestock water). This section, in another words, attempts to identify the inlet conditions of different layouts presented in section 3 to quantify the demand of different grades of water.

Generally, the optimisation problem is mathematically built to find out the optimal pump pressure and inlet feed flowrate while constraining the product water salinity to a specific value based on water type besides maximising the water productivity (objective function). In this regard, the operational pump pressure and feed flowrate of each membrane in a pressure vessel are constrained within the manufacturer's specification presented in Table 1. The brackish water temperature and salinity, the membrane characteristics, pump and ERD efficiency are all fixed as listed in Table 2. Also, the inlet feed flowrate of the specific layout will be selected to accommodate the number of pressure vessels in the first stage. The same practice of RO process optimisation was carried out by several researchers such as Al-Hotmani et al. (2022) and Alsarayreh et al. (2020). The next section identifies the optimisation of a specific selected layout of RO process from the five proposed layouts to properly produce various grades of water.

The optimisation problem is therefore built as represented below;

Max Water productivity

$P_{f(plant)}, Q_{f(plant)}$

Subject to:

Equality constraints:

Process Model: $f(x, u, v) = 0$

Inequality constraints:

$$(10\ \text{atm}) \quad {P_{f(plant)}}^{L} \leq P_{f(plant)} \leq {P_{f(plant)}}^{U} \quad (81.9\ \text{atm})$$

The inlet feed flowrate of each RO plant is designed within the upper and lower values that will be selected based on the selected RO layout.

$${Q_{f(plant)}}^{L} \leq Q_{f(plant)} \leq {Q_{f(plant)}}^{U}$$

End-point constrains:

$$(86.4\ \text{m}^3/\text{day}) \quad {Q_{f(membrane)}}^{L} \leq Q_{f(membrane)} \leq {Q_{f(membrane)}}^{U} \quad (432\ \text{m}^3/\text{day})$$

L and U are the lower and upper limits, respectively.

4.1 Industrial water (less than 50 ppm)

The optimum inlet conditions that would enable to reduce the freshwater concentration lower than 50 ppm are discussed in this section, which enable to produce industrial water (almost stripped of its minerals). Indeed, the industrial water is currently used in a wide set of industrial systems such as heat exchanger, boilers, lead batteries, cosmetics, and laboratory experiments in addition to produce sterilized materials in the medical field. Further implications of industrial water of less than 50 ppm are the household appliances such as steam irons, car cooling system and aquariums. The optimisation formulation of the industrial water is represented below;

2613.599 m^3/day $\quad {Q_{f(plant)}}^L \leq Q_{f(plant)} \leq {Q_{f(plant)}}^U$ 13903.200 m^3/day

Inequality end-point constrain

$$10\ ppm \leq C_{p(plant)} \leq 50\ ppm$$

Table 3 presents the associated optimisation results of TRPRLA. The findings of Table 3 can be summarised in the following;

- **Table 3** shows the optimal pump pressure and feed flow rate of 27.38 atm and 11437.178 m³/day, respectively. indeed, these optimal values signify the maximum water productivity of 4026.422 m³/day while ensuring the desired product water salinity.
- **Table 3** introduces the targeted product water salinity of 20.0 ppm, that is associated within the acceptable limit of industrial water. This is in a coordinate to having a superior solute rejection rate of 99.89%. This in turn would reflect that the permeate is free from pollutants and meets the preferred purity level.
- The water recovery rate and specific energy consumption are 35.20% and 1.973 kWh/m³, respectively. In this regard, a lower specific energy consumption can represent a higher water recovery rate of the RO process.

Table 3. Optimisation results of TRPRLA at $C_{f(plant)}$ = 20000 ppm and T = 20 ºC for producing industrial water

Layout	Optimal values		Water productivity (m³/day)	Product water salinity (ppm)	Solute rejection% (-)	Water recovery% (-)	Specific energy consumption (kWh/m³)
	Pump pressure (atm)	Feed flowrate (m^3/day)					
Tapered retentate permeate reprocessing layout A (TRPRLA)	27.38	11437.178	4026.422	20.0	99.89	35.20	1.973

4.2 Bottled water (200 ppm)

This section focuses on the optimisation results of TRPRLA regarding the production of bottled water of 200 ppm from feed water of 20000 ppm and 20 °C of salinity and temperature, respectively. In this aspect, the optimisation is carried out while considering the below optimisation problem.

2613.599 m^3/day $\quad {Q_{f(plant)}}^L \leq Q_{f(plant)} \leq {Q_{f(plant)}}^U$ 13903.200 m^3/day

Inequality end-point constrain

$$100\ ppm \leq C_{p(plant)} \leq 200\ ppm$$

Table 4 introduces the capacity of having bottled water of 200 ppm from TRPRLA after regulating the pump pressure and feed flow rate to their optimum values of 42.63 atm and 6239.500 m^3/day, respectively, at constant feed water salinity and operational temperature. The most interesting findings of Table 4 are;

- To produce bottled water of 200 ppm, the optimal pump pressure is meaningfully higher at 42.63 atm and lower feed flow rate at 6239.500 m^3/day in a comparison to produce industrial water for the same RO configuration of TRPRLA (section 5.1). In this regard, lowering feed flow rate means a greater residence time of fluid inside the RO modules, which enables to have the maximum water productivity (objective function). Also, utilising a higher pump pressure is also important to generate higher water permeation. However, it should be mentioned that an increase of pump pressure would enlarge the solute flux via the membranes, which can deteriorate the product water salinity. Thus, the optimum selected pump pressure is essential to have 200 ppm as the product water salinity.
- Table 4 presents the supreme water recovery of 72.32% that can be attained with bottled water comparing to 35.20% of industrial water. The permission of increasing product water salinity to 200 ppm has enabled to raise the pump pressure and lowering feed flow rate to assure having high water recovery. This in turn has a further advantage of lowering the specific energy consumption.
- The specific energy consumption of bottled water production is lower, at 1.623 kWh/m³ comparing to 1.973 kWh/m³ of industrial water.
- The comparison of optimisation results for industrial and bottled water production signifies the trade-offs involved in attaining different product quality requirements.

Table 4. Optimisation results of TRPRLA at $C_{f(plant)}$ = 20000 ppm and T = 20 ºC for producing bottled water

Layout	Optimal values		Water productivity (m³/day)	Product water salinity (ppm)	Solute rejection% (-)	Water recovery% (-)	Specific energy consumption (kWh/m³)
	Pump pressure (atm)	Feed flowrate (m^3/day)					
Tapered retentate permeate reprocessing layout A (TRPRLA)	42.63	6239.500	4512.749	200.0	98.99	72.32	1.623

4.3 Tap and drinking water (500 ppm)

Referring to the standards of the World Health Organization, the salinity of water with salinity of less than 600 ppm is deliberated acceptable for drinking purposes (World Health Organization ,2011). Tap and drinking water of 500 ppm is produced using the proposed RO configuration of tapered retentate permeate reprocessing layout B (TRPRLB) while using 20000 ppm and 20 °C of feed water salinity and temperature. The optimisation procedure is formulated as follows;

2613.599 m^3/day $\quad {Q_{f(plant)}}^L \leq Q_{f(plant)} \leq {Q_{f(plant)}}^U$ 13903.200 m^3/day

Inequality end-point constrain

$$500\ ppm \leq C_{p(plant)} \leq 550\ ppm$$

Table 5 presents the optimisation results of TRPRLB layout. Specifically, TRPRLB produces freshwater of 500 ppm, which is quite favourable drinking water. A systematic comparison of the industrial water, bottled water and drinking water can introduce the following facts;

- It is clear that both the control variables of pump pressure and feed flowrate are varied based on the desired product water quality and the RO configuration used. In this regard, the highest pump pressure and lowest feed flow rate are required to produce bottled water from TRPRLA if compared to industrial water and drinking water. This is due to the stringent purity requirements. Industrial water production necessitates a lower pressure and higher flowrate, while drinking water production using TRPRLB falls in between these two extremes.
- The greatest water productivity of 9030.773 m^3/day is assured for producing drinking water compared to industrial water and bottled water of 4026.422 m^3/day, and 4512.749 m^3/day, respectively. However, the lowest specific energy consumption is assured using TRPRLA for the production of bottled water of 1.623 kWh/m^3 comparing to industrial water and drinking water of 1.973 kWh/m^3 and 1.688 kWh/m^3, respectively. This can be attributed to the maximum water recovery of 72.32% of bottled water comparing to 35.20% and 64.98% of industrial water and drinking water, respectively.

Table 5. Optimisation results of TRPRLB at $C_{f(plant)}$ = 20000 ppm and T = 20 ºC for producing tap and drinking water

Layout	Optimal values		Water productivity (m^3/day)	Product water salinity (ppm)	Solute rejection% (-)	Water recovery% (-)	Specific energy consumption (kWh/m^3)
	Pump pressure (atm)	Feed flowrate (m^3/day)					
Tapered retentate permeate reprocessing layout B (TRPRLB)	41.10	13896.556	9030.773	500	97.48	64.98	1.688

4.4 Irrigation water (800 ppm)

The production of irrigation water is conceivable using the RO layout of tapered retentate permeate reprocessing layout B (TRPRLB) at constant water salinity and temperature of 20000 ppm and 20 °C, respectively. The optimisation problem is formulated as follows while constraining the product water salinity between 600 – 800 ppm to accommodate having an irrigation water.

2613.599 m^3/day $Q_{f(plant)}{}^{L} \leq Q_{f(plant)} \leq Q_{f(plant)}{}^{U}$ 13903.200 m^3/day

Inequality end-point constrain

$$600\,ppm \leq C_{p(plant)} \leq 800\,ppm$$

The optimisation results of TRPRLB are provided in Table 6. Compared to tap and drinking water, the pump pressure and feed flow rate are lower for irrigation water production. Statistically, 31.59 atm, 8112.209 m^3/day are required to produce irrigation water compared to 41.10 atm, 13896.556 m^3/day to produce drinking water. This can be attributed to the firmer purity requirements for tap and drinking water, requiring greater pressure and lower flowrate to attain the desired product water quality. The water productivity is meaningfully higher for tap and drinking water production (9030.773 m^3/day) compared to irrigation water production (4715.474 m^3/day). This difference can be ascribed to the higher feed flowrate and pump pressure used for drinking water production, which help to improve the quantity of converted water into permeate. The water recovery rate is slightly lower for irrigation water production (58.128%) compared to drinking water production (64.98%). Furthermore, the irrigation water production consumes less energy of (1.353 kWh/m^3) compared to drinking water (1.688 kWh/m^3). In this regard, the specific energy consumption is positively linked to feed flowrate and pump pressure and negatively linked to water productivity (Table A.1 of Appendix A). Despite a higher water productivity of drinking water, the impact of lower pump pressure and feed flowrate throughout the irrigation water production has dominated the specific energy consumption compared to the effect of water productivity, which elucidates a lower specific energy consumption.

Table 6. Optimisation results of TRPRLB at $C_{f(plant)}$ = 20000 ppm and T = 20 ºC for producing irrigation water

Layout	Optimal values		Water productivity (m³/day)	Product water salinity (ppm)	Solute rejection% (-)	Water recovery% (-)	Specific energy consumption (kWh/m³)
	Pump pressure (atm)	Feed flowrate (m³/day)					
Tapered retentate permeate reprocessing layout B (TRPRLB)	31.59	8112.209	4715.474	800.0	96.00	58.128	1.353

4.5 Livestock water (1000 ppm)

This section focuses on demonstrating the optimisation results of tapered retentate permeate reprocessing layout B (TRPRLB) throughout the production of livestock water of 1000 ppm. The upgraded optimisation problem is formulated as follows;

$$2613.599\ \text{m}^3/\text{day} \quad {Q_{f(plant)}}^{L} \leq Q_{f(plant)} \leq {Q_{f(plant)}}^{U} \quad 13903.200\ \text{m}^3/\text{day}$$

Inequality end-point constrain

$$900\ ppm \leq C_{p(plant)} \leq 1000\ ppm$$

The optimisation results are represented in **Table 7**. This assures the production of livestock water using the optimal pump pressure and feed flowrate of 25.54 atm, and 6469.668 m^3/day, respectively. These optimal values are required to produce 3071.415 m^3/day of water productivity at 1.238 m^3/day of specific energy consumption. The observed trend in the optimisation results of the TRPRLB indicates that the obtained optimal pressure and feed flowrate are decreased sequentially as the requested product salinity increases from 500 ppm (drinking water) to irrigation water (800 ppm) to livestock water (1000 ppm). This in turn has introduced a sequence drop of water productivity. A number of observation can be elaborated in the following;

- Drinking water necessitates stringent purification standards. Thus higher pump pressure and flow rate are required to efficiently remove solutes and attain a lower salinity level of 500 ppm. This is in a comparison against livestock water production of the highest product water level of 1000 ppm.
- Lower pump pressure and flow rate can introduce the most energy-efficient RO system of TRPRLB, which can elucidate the lowest fresh water production cost. This is specifically for producing livestock water with a higher salinity level of 1000 ppm.
- The TRPRLB layout is likely optimised for various water qualities. As the target salinity level increases, the design may inherently limit the upper bounds of productivity to guarantee adequate elimination of solutes without compromising system integrity.

Table 7. Optimisation results of TRPRLB at $C_{f(plant)}$ = 20000 ppm and T = 20 ºC for producing livestock water

Layout	Optimal values		Water productivity (m³/day)	Product water salinity (ppm)	Solute rejection% (-)	Water recovery% (-)	Specific energy consumption (kWh/m³)
	Pump pressure (atm)	Feed flowrate (m³/day)					
Tapered retentate permeate reprocessing layout B (TRPRLB)	25.54	6469.668	3071.415	1000	94.998	47.474	1.238

5. Conclusions

Worldwide, the need for freshwater resources is increasing due to factors such as urbanization, population increase, and industrialization. Desalination becomes a vital way to supplement the water supply in areas where conventional water sources are scarce. Reverse osmosis (RO) is a desalination technology that is notable for its effectiveness and adaptability. The idea is to develop several RO process designs for desalinating high-salinity brackish water to meet the different needs for water quality in different industries. This initiative aims to customize the RO system to produce various grades of water, such as industrial water with less than 50 ppm, bottled water at 200 ppm, tap water with 500 ppm, irrigation water reaching 800 ppm, and livestock water, through rigorous process simulation and optimization-based modeling. This flexible approach highlights the importance of creating a dependable and effective desalination process in addition to promising to satisfy the unique requirements of various water end consumers. This effort aims to combine water quality, operational effectiveness, and environmental sustainability by optimising RO designs. It provides a strong answer to the increasing problems associated with water scarcity and quality in a variety of applications.

By conducting this study, the goal was to determine the most efficient and effective design for high-salinity brackish water RO desalination system, considering various performance indicators and the specific requirements of different water types. Specifically, five layouts of large-scale RO systems specially to desalinate high salinity of brackish water were designed. To determine the performance of the developed layouts, an extensive model of a single RO unit was upgraded to simulate the designed layouts using fixed feed water salinity and temperature. The sensitivity analysis was conducted to signify the best RO layouts for desalinating high-salinity brackish water based on the comparison of the product water salinity, water productivity and the specific energy consumption. Accordingly, it was noticed that the tapered retentate permeate reprocessing layout was established as the paramount one that accomplish the best performance of water productivity, product salinity and specific energy consumption. Afterwards, the process optimisation was carried out to signify the optimal pump pressure and feed flowrate for the tapered retentate permeate reprocessing layout to guarantee the production of different grades of water including industrial water, bottled water, drinking water, irrigation, and livestock water. This in turn has enabled to select the highest water productivity for the used layout with acquiring the favourable requirements. The analysis of the optimised tapered retentate permeate reprocessing layout showed a production of industrial water with a recovery rate of 35.2% at a specific energy consumption of 1.973 kWh/m³. For bottled water, this layout attains optimised 72.32% at 1.623 kWh/m³. Also, the tapered retentate permeate reprocessing layout exhibited optimal performance for tap and drinking water with 64.98% at 1.688 kWh/m³. It also generated 58.128% at 1.353 kWh/m³ for irrigation water, and 47.474% at 1.238 kWh/m³ for livestock water.

CRediT Author Contribution Statement

Alanood A. Alsarayreh: Conceptualization, Supervision, Writing – Review & Editing, Investigation, Data Curation, Writing – Original Draft, Methodology, Validation, Funding Acquisition, Project Administration

Declaration Statements

Funding

"This research received no external funding."

Conflicts of Interest

"The authors declare no conflict of interest."

Use of AI Tools (if applicable)

"During the preparation of this work the author didn't use AI tools.

References

Ahdab, Y.D. and Lienhard, J.H. "Desalination of brackish groundwater to improve water quality and water supply", in Global Groundwater. Elsevier, pp. 559-575, (2021).

Albert, J.S., Destouni, G., Duke-Sylvester, S.M., Magurran, A.E., Oberdorff, T., Reis, R.E., Winemiller, K.O. and Ripple, W.J.,. "Scientists' warning to humanity on the freshwater biodiversity crisis". Ambio, 50(1), pp.85-94, (2021).

Al-hotmani, O., Al-Obaidi, M., John, Y., Patel, R., Manenti, F. and Mujtaba, I. "Minimisation of energy consumption via optimisation of a simple hybrid system of multi-effect distillation and permeate reprocessing reverse osmosis processes for seawater desalination", *in Computer Aided Chemical Engineering*, 48. Elsevier, pp. 379-384, (2020).

Al-Hotmani, O.M.A., Al-Obaidi, M.A., Li, J.P., John, Y.M., Patel, R. and Mujtaba, I.M. "A multi-objective optimisation frameworkfor MED-TVC seawater desalination process based on particle swarm optimisation", *Desalination*, 525, p. 115504, (2022).

Al-Obaidi, M.A., Alsarayreh, A.A., Al-Hroub, A. and Mujtaba, I.M. "Performance analysis of a medium-sized industrial reverse osmosis brackish water desalination plant", *Desalination*, 443, pp. 272-284, (2018).

Al-Obaidi, M.A., Alsarayreh, A.A., Al-Hroub, A., Alsadaie, S. and Mujtaba, I.M. "Performance analysis of a medium-sized industrial reverse osmosis brackish water desalination plant", Desalination, 443, pp. 272-284, (2018).

Al-Obaidi, M.A., Rasn, K.H., Aladwani, S., Kadhom, M. and Mujtaba, I. "Flexible design and operation of multi-stage reverse osmosis desalination process for producing different grades of water with maintenance and cleaning opportunity", Chemical Engineering Research *and Design*, 182, pp. 525-543, (2022).

Al-Obaidi, M.A., Alsarayreh, A.A., Bdour, A., Jassam, S.H. and Mujtaba, I.M. "Simulation and optimisation of a medium scale reverse osmosis brackish water desalination system under variable feed quality: Energy saving and maintenance opportunity", *Desalination*, 565, p. 116831, (2023).

Alsarayreh, A.A., Al-Obaidi, M.A., Patel, R. and Mujtaba, I.M. "Scope and limitations of modelling, simulation, and optimisation of a spiral wound reverse osmosis process-based water desalination', *Processes*, 8(5), p. 573, (2020).

Alsarayreh, A.A., Al-Obaidi, M.A., Al-Hroub, A., Patel, R. and Mujtaba, I.M. "Evaluation and minimisation of energy consumption in a medium-scale reverse osmosis brackish water desalination plant", *Journal of Cleaner Production*, 248, p. 119220, (2020).

Alsarayreh, A.A., Al-Obaidi, M.A., Al-Hroub, A.M., Patel, R. and Mujtaba, I.M. "Performance evaluation of reverse osmosis brackish water desalination plant with different recycled ratios of retentate", *Computers and Chemical Engineering*, 135, p. 106729, (2020).

Alsarayreh, A.A., Al-Obaidi, M.A., Farag, S.K., Patel, R. and Mujtaba, I.M. "Performance evaluation of a medium-scale industrial reverse osmosis brackish water desalination plant with different brands of membranes: A simulation study", *Desalination*, 503, p. 114927, (2021).

Ansari, M., Al-Obaidi, M.A., Hadadian, Z., Moradi, M., Haghighi, A. and Mujtaba, I.M. "Performance evaluation of a brackish water reverse osmosis pilot-plant desalination process under different operating conditions: Experimental study", *Cleaner Engineering*, 4, p. 100134, (2021).

Gondal, A. "Nanotechnology advancement in the elimination of chemical toxins from air spectrums", International Journal of Environmental Science and Technology, 20(11), pp. 12775-12792, (2023).

Mahmoudi, A., Bostani, M., Rashidi, S. and Valipour, M.S. "Challenges and opportunities of desalination with renewable energy resources in Middle East countries", Renewable and Sustainable Energy Reviews, 184, p. 113543, (2023).

Jalihal, P. and Venkatesan, R. "Advanced desalination technologies", *in Sustainable Water and Wastewater Processing.* Elsevier, pp. 93-131, (2019).

Reiss, C., Robert, C., Dietrich, J. and Mody, A. (2008) 'Pretreatment and design considerations for large-scale seawater facilities', Desalination Water Purification Research Development Program Report, 137.

Sadek, N., Attia, M. and El-Gafy, I. "Experimental performance analysis for reverse osmosis pilot plant subjected to different brackish salinity spectrum", Journal of King Saud University - Engineering Sciences, 36(7), pp. 438-445, (2024).

World Health Organization "Guidelines for drinking-water quality", *WHO Chronicle*, 38(4), pp. 104-108, (2011).