Experimental Study of a Brackish Water Desalination Plant

Estudio experimental de una planta de desalinización de agua salobre

Estudo experimental de uma planta de dessalinização de água salobra

Ifrah Asif [1], Mirza Hammad Baig [2,(*)], Sohail Hasnain [3], Sadia Ahmed [4]

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Summary. - Water desalination is crucial for addressing global water scarcity affecting over 2 billion people. By 2050, water demand could rise by 20-30% due to population growth and urbanization. Currently, over 40% of the global population lacks access to clean water due to overexploitation of conventional sources like rivers and groundwater. This report focuses on experimental analysis of brackish water desalination, primarily using reverse osmosis (RO). Desalination plays a vital role in converting seawater or brackish water into drinkable water, especially in coastal areas. The study explores various desalination methods such as ion exchange, membrane distillation, and vapor compression distillation. Technological advancements, particularly in RO distillation process has enhanced efficiency and sustainability. In this report, pre-treatment processes, including filtration, chemical dosing, antiscalant injection, water softening, are also employed to remove contaminants before desalination. The performance of RO is evaluated based on factors like pressure drop, feed flow rate, and recovery ratio, analyzing water flux, salt rejection rate, energy consumption, and system efficiency. The results provide insights into optimizing brackish water desalination and the discussions are carried out for improvement of the ways such as post treatment, membrane cleaning and advancement in membrane materials for sustainable freshwater production.
Keywords: Water desalination, brackish water, reverse osmosis, multistage, ion exchange, recovery ratio, flux, salt rejection rate.

(*) Corresponding Author
[1] Lecturer, Department of Mechanical Engineering, NED University of Engineering and Technology, Karachi, Pakistan, ifrahasif@neduet.edu.pk, ORCID iD: https://orcid.org/0000-0001-7551-2199
[2] Lecturer, Department of Mechanical Engineering, NED University of Engineering and Technology, Karachi, Pakistan hammadbaig@neduet.edu.pk, ORCID iD: https://orcid.org/0000-0001-7544-8297
[3] Lecturer, Department of Mechanical Engineering, NED University of Engineering and Technology, Karachi, Pakistan sohail@cloud.neduet.edu.pk, ORCID iD: https://orcid.org/0009-0005-2970-2908
[4] Undergraduate Student, Department of Mechanical Engineering, NED University of Engineering and Technology, Karachi, Pakistan ahmed4406016@cloud.neduet.edu.pk, ORCID iD: https://orcid.org/0009-0007-6072-3437

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Resumen. - *La desalinización del agua es crucial para abordar la escasez global del agua que afecta a más de 2 mil millones de personas. Para 2050, la demanda de agua podría aumentar en un 20-30% debido al crecimiento de la población y la urbanización. Actualmente, más del 40% de la población mundial carece de acceso al agua limpia debido a la sobreexplotación de fuentes convencionales como ríos y agua subterránea. Este informe se centra en el análisis experimental de la desalinización de agua salobre, utilizando principalmente la ósmosis inversa (RO). La desalinización juega un papel vital en la conversión de agua de mar o agua salobre en agua potable, especialmente en las zonas costeras. El estudio explora varios métodos de desalinización, como el intercambio de iones, la destilación de membrana y la destilación de compresión de vapor. Los avances tecnológicos, particularmente en el proceso de destilación de RO, han mejorado la eficiencia y la sostenibilidad. En este informe, también se emplean procesos de pretratamiento, incluida la filtración, la dosificación química, la inyección antiscal de inyección, el ablandamiento del agua, para eliminar los contaminantes antes de la desalinización. El rendimiento de RO se evalúa en función de factores como la caída de presión, la velocidad de flujo de alimentación y la relación de recuperación, el análisis del flujo de agua, la tasa de rechazo de la sal, el consumo de energía y la eficiencia del sistema. Los resultados proporcionan información sobre la optimización de la desalinización de agua salobre y las discusiones se llevan a cabo para mejorar las formas en que el tratamiento posterior, la limpieza de membranas y el avance en los materiales de membrana para la producción sostenible de agua dulce.*
Palabras clave: *Desalinización del agua, agua salobre, ósmosis inversa, etapas múltiples, intercambio de iones, relación de recuperación, flujo, tasa de rechazo de la sal.*

Resumo**. -** *A dessalinização da água é crucial para abordar a escassez global de água que afeta mais de 2 bilhões de pessoas. Até 2050, a demanda da água poderá aumentar de 20 a 30% devido ao crescimento e urbanização da população. Atualmente, mais de 40% da população global carece de acesso à água limpa devido à superexploração de fontes convencionais como rios e águas subterrâneas. Este relatório se concentra na análise experimental da dessalinização da água salobra, usando principalmente osmose reversa (RO). A dessalinização desempenha um papel vital na conversão de água do mar ou água salobra em água potável, especialmente em áreas costeiras. O estudo explora vários métodos de dessalinização, como troca de íons, destilação da membrana e destilação de compressão de vapor. Os avanços tecnológicos, particularmente no processo de destilação de RO, aumentaram a eficiência e a sustentabilidade. Neste relatório, os processos de pré-tratamento, incluindo filtração, dosagem química, injeção antiscalante, amolecimento da água, também são empregados para remover contaminantes antes da dessalinização. O desempenho do RO é avaliado com base em fatores como queda de pressão, taxa de fluxo de alimentação e taxa de recuperação, análise de fluxo de água, taxa de rejeição de sal, consumo de energia e eficiência do sistema. Os resultados fornecem informações sobre a otimização da dessalinização da água salobra e as discussões são realizadas para melhorar as maneiras como pós -tratamento, limpeza de membranas e avanço em materiais de membrana para produção sustentável de água doce.*
Palavras-chave: *Desalinização da água, água salobra, osmose reversa, vários estágios, troca de íons, taxa de recuperação, fluxo, taxa de rejeição de sal.*

1. Introduction. - In water-stressed nations where desalinated water greatly outweighs freshwater source supplies, desalination has come up as a critical component in helping to fulfill rising water demands.(Darre & Toor, 2018). In the commercial distillation process, fresh water that is almost completely devoid of salt is separated from salt water, with the salts concentrated in the rejected brine stream.(El-Dessouky & Ettouney, 2002). About 71% of the surface of the Earth is made up of primarily saline water. According to estimates from the World Health Organization (WHO), 159 million people who depend on the oceans are among the 844 million individuals who lack access to safe potable water globally.(Hoslett et al., 2018). Almost 99 % is seawater, which can be purified through desalination processes for various potable and drinking usage purposes.(Kabir et al., 2024).

Salinity levels in brackish water are lower than in seawater due to a decrease in total dissolved solids (TDS). The low salinity of brackish water (between 1000 and 10,000 mg/L TDS) makes it a good substitute. (Honarparvar et al., 2019). Various techniques have been used to make saline/brackish water potable. Filtration, precipitation, sterilization, chemical treatment, etc. are some processes that remove macro impurities from impure water.(Thimmaraju et al., 2018).

There are two variety of desalination systems: thermal systems, which are powered by heat, and membrane-based systems, which are powered by electricity. There are two primary varieties of the former: pressure-driven reverse osmosis facilities and direct current electrical dialysis units that function under an electrical potential difference.(Elbassoussi et al., 2024)

Membrane processes like RO have been widely adopted for water treatment and reuse. The global market for RO continues to grow and is predicted to reach $8.1 billion by 2018.(Joo & Tansel, 2015). Over the last forty years, reverse osmosis membrane technology has advanced to account for 44% of global desalting output capacity and 80% of all desalination plants deployed globally.(Greenlee et al., 2009). Finding the ideal polymeric membrane materials was the main focus of research from the late 1950s to the 1980s (Lee et al., 2011). However, membrane fouling is an inevitable issue. Membrane fouling leads to higher operating pressure, flux decline, frequent chemical cleaning and shorter membrane life. (Jiang et al., 2017). Based on the weight, substance, and energy balances and considering concentration polarization a mathematical simulation model was created. The simulation results are over 96% near ROSA and over 80% close to the experimental data, according to comparison of this model and ROSA. (Hadadian et al., 2021)

Owing to its drawbacks, including the requirement for chemical input online, the conventional coagulation, flocculation, and sedimentation chains are not seen to be an option in small water treatment systems. Many studies have proposed membrane filtration (MF/UF) procedures in gravity-driven mode (GDM) that do not require pre-treatment.(Rasouli et al., 2024). Gravity-driven membrane (GDM) filtration is a popular choice for long-term passive filtration due to its high particle removal efficiency, low energy consumption and capacity to obtain a stabilized flux.(Rasouli et al., 2024)

In many situations, tunable methods like membrane capacitive deionization (MCDI), capacitive deionization (CDI), and electrodialysis (ED) are superior to traditional reverse osmosis (RO) because of their lower energy requirements and operating costs.(Honarparvar et al., 2019). Distillation is a thermal energy-based method that efficiently rids polluted water of impurities. The basic idea behind this method is to boil the salt water, let it evaporate, and then collect the condensed vapour to create pure water.(Thimmaraju et al., 2018)

Electrodialysis is a voltage driven process. This process uses electrical potential to remove salt using a membrane leaving fresh water behind.(Thimmaraju et al., 2018). Because electrodialysis (ED) uses less energy than other methods for treating industrial water, it is more practical. Anion exchange membranes (AEM) and cation exchange membranes (CEM) are the two types of membranes utilized in electrodialysis.(Rathod et al., 2024). Seawater/brackish desalination of water is a popular application for Multi Effect Desalination Systems (MED) driven by Mechanical Vapour Compression (MVC). The energy utilized to power these devices can come from renewable sources, such as solar, wind, or a mix of the two.(Shamet & Antar, 2023)

Membrane distillation (MD) presents a viable substitute for traditional saltwater desalination methods. Regrettably, the membrane production techniques often involve the use of hazardous solvents and non-biodegradable polymers.(Gontarek-Castro & Castro-Muñoz, 2024). Membrane distillation (MD) is a crucial technique for achieving nearly 0% discharge of hyper saline wastewater. However, it frequently faces problems due to the accumulation of mineral scale on the membrane surface.(Zhu et al., 2024). Solar distillation is one of the solutions of getting potable water using solar energy. Solar distillation unit coupled with thermal collectors, photovoltaic panels, and concentrators.(Manchanda & Kumar, 2018)

2. Methodology. - Following are the foremost common methods that are utilized in the treatment and purification of the water:

- Boiling
- Distillation
- Water filters
- Ultra violet light
- Ion exchange
- Microfiltration (MF)
- Ultra-filtration (UF)
- Nanofiltration (NF)
- Reverse Osmosis (RO)
- Vapor compression
- Multistage flash
- Electrodialysis

Boiling: Employed as a primary method during emergencies, boiling water effectively eliminates waterborne pathogens, particularly when turbidity is present. It is recommended to maintain a vigorous boil for a minimum of 3 minutes (increasing to 5 minutes at higher elevations) to ensure thorough disinfection.

Distillation: This method involves heating water to produce steam, which is then condensed to remove impurities, including volatile organic compounds (VOCs). Employing additional filtration mechanisms can augment the purification process, ensuring a comprehensive removal of contaminants.

Water Filtration: Utilizing a variety of physical and adsorptive mechanisms, water filtration systems effectively remove contaminants from water sources. Common types include sediment, ceramic, and activated carbon filters, each offering unique advantages in purifying water.

UV Light: UV disinfection systems utilize ultraviolet light to eradicate bacteria and viruses by disrupting their genetic material. This method provides a highly efficient and environmentally friendly approach to water treatment.

Ion Exchange: Ion exchange technology facilitates the removal of ions from water, resulting in demineralization. While effective in purifying water, it is imperative to adhere to regular maintenance protocols to prevent microbial contamination.

Microfiltration: Employing membranes with fine pores, microfiltration effectively removes particles, bacteria, and other contaminants from water. This method finds extensive applications in various industries, including pharmaceuticals and food processing.

Ultrafiltration: With smaller pore sizes compared to microfiltration, ultrafiltration systems can effectively concentrate proteins and enzymes while removing larger molecules and particles. This process is integral in achieving high-purity water for specialized applications.

Nanofiltration: Nanofiltration systems utilize advanced membrane technology to selectively remove small molecules and ions from water sources. This process is particularly useful in concentrating and purifying substances such as sugars and dyes.

Reverse osmosis: Reverse Osmosis is a process that uses the membrane. It is abbreviated as RO. It has the smallest pores size range from 0.0001-0.001 microns. The pressure requirement is 25-100 Bar which is the largest among all. The RO process is used to remove water and concentrate very small molecular weight substances. Typical applications include concentrating dairy or food products (lactose) , recovery/polishing of water from permeate , recovery/polishing of evaporator condensate.

RO systems can be efficaciously pragmatic to saline groundwater, seawater and brackish water. It may also account for confiscation of inorganic contaminants like, arsenic, nitrates, radio nuclides and other toxins such as pesticides. The mechanism of RO systems works on such track where the pressure is applied to a greater concentration solution to go through semipermeable plastic membrane and producing a more strenuous solution. Pressurization of the feed water is the basic energy need for RO. Within the membrane module containing compactly arranged passages, the feed water must be acquiesced and other pollutants causing the turbidity must be eradicated.

In RO systems, membrane washing via backwashing is crucial to maintain performance and extend membrane life. However, particles that accumulate cannot be completely removed, leading to reduced efficiency. Scaling, primarily due to calcium carbonate, decreases membrane permeability and irreversibly damages membranes. Fouling, the accumulation of solids on membrane surfaces, further diminishes system performance, causing pressure and flux losses. Proper waste disposal is essential due to the high concentration of brine produced, typically exceeding that of seawater. Discharging brine into sewerage lines can impact underground water levels and ecological balance over time. Throughout the world there are many of the municipal water treatment facilities that utilizes RO membrane. Although it looks similar and is fabricated in a different way to RO membranes for dairy and other highly specific sanitary applications.

3. Experimental analysis of reverse osmosis. - For the experimental analysis of reverse osmosis, the brackish water was first pre-treated to remove any large particles or organic matter that could damage the semipermeable membrane.

3.1. Pre-treatment. - The pre-treatment processes involved were sediment filtration, carbon filtration, water softening, antiscalant injection and micro filtration.

- Sediment filtration: Firstly, water passes through sediment filters to remove larger particles like sand or dirt.
- Carbon filtration: Then, the carbon filtration was done to remove chlorine and organic compounds present in water.
- Water softening: Then, water softening was done to remove the calcium and magnesium ions.
- Antiscalant solution: Then, antiscalant solution was injected to prevent the scale formation in the RO membrane.
- Micro-filtration: Then, the micro-filtration was done to remove the micro-organisms and bacteria that could foul the RO membrane.

Figure I. Pre-treatment of brackish water.

3.2. Methodology for Experimental analysis of reverse osmosis. - In the experimental analysis of reverse osmosis (RO), meticulous pre-treatment of brackish water was paramount to safeguard the integrity of the semipermeable membrane. This pre-treatment regimen encompassed a series of sophisticated processes tailored to remove various contaminants that could compromise membrane performance.

Initially, the brackish water underwent sediment filtration, a crucial step aimed at eliminating larger particles such as sand and dirt. Subsequently, carbon filtration was employed to effectively remove chlorine and organic compounds present in the water, ensuring optimal membrane function. Following carbon filtration, water softening procedures were implemented to tackle the removal of calcium and magnesium ions, which are notorious for causing scale formation on the RO membrane. To further fortify membrane protection, an antiscalant solution was judiciously injected to mitigate the risk of scale deposition, thereby prolonging membrane longevity and efficacy. Moreover, microfiltration was meticulously conducted to target the removal of microorganisms and bacteria that could potentially foul the RO membrane, ensuring the highest standards of water purity and safety.
The equations involved to calculate these factors are as,

$$Flux:\ J = \frac{Q}{A}$$

(Halliday et al., 2013)

$$Recovery:\ R = \frac{Q_p}{Q_f}$$

(Wang & Zhou, 2013)

$$Permeability:\ K = \frac{J}{TMP}$$

(Baker, 2023)

$$Rejection:\ r = \frac{C_p}{C_f}$$

(Davis, 2010)

$$Energy\ consumption:\ E = \frac{P}{t}$$

(Moran et al., 2010)

In the given context: Q represents flow rate, A represents area, Qp represents permeate flow rate, Qf represents feed flow rate, TMP represents trans-membrane pressure, Cp represents concentration of solute in permeate, Cf represents concentration of solute in the feed, P represents power consumption and t represents time.

Figure II. Reverse Osmosis process.

4. Experimental analysis of ion exchange distillation. - In the ion exchange process for treating brackish water, the resin bed undergoes meticulous preparation through regeneration with a brine solution to enhance its exchange capacity. Once ready, the brackish water is introduced into the system, initiating the ion exchange phenomenon. As water flows through the resin bed, unwanted ions are removed, and desirable ions are released, facilitating purification. Throughout the process, careful monitoring of parameters such as water flow rate, resin exchange capacity, and contact time ensures optimal performance. After treatment, the exhausted resin is regenerated using a brine solution, maintaining the system's effectiveness in producing high-quality water.

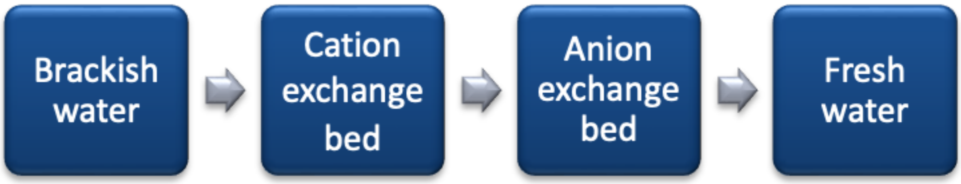

Figure III. Ion exchange process

4.1. Experimental analysis of vapor compression distillation. - For the experimental analysis of vapor compression distillation, the equipment and setup were prepared, including the vapor compression distillation unit, heat source, condenser, and collection vessels. Then, a specific brackish water sample was selected for testing. The distillation process was initiated by applying heat to the brackish water, causing evaporation. The vapor was then compressed using a compressor, increasing its temperature and pressure. Next, the compressed vapor was cooled in the condenser, causing it to condense back into liquid form. The resulting distilled water was collected in the vessels, while the remaining concentrated brine was disposed of. Throughout the experiment, various parameters such as temperature, pressure, and flow rate were measured and recorded. The collected data was then analyzed to evaluate the performance of the vapor compression distillation process and determine its efficiency in producing fresh water from brackish water.

4.2. Experimental analysis of electrodialysis distillation. - For the experimental analysis of electrodialysis distillation, firstly, the experimental setup was prepared, including the electrodialysis cell, electrodes, and brackish water feed solution. The cell was filled with the feed solution, and the electrodes were positioned accordingly. Then, an electric field was applied across the cell, causing the migration of ions through ion-exchange membranes. This process helped separate the ions and remove impurities from the brackish water. The purified water and concentrated brine were collected separately. Throughout the experiment, parameters such as voltage, current, and conductivity were measured and recorded. The collected data was then analyzed to evaluate the performance of the electrodialysis distillation process and assess its efficiency in desalinating brackish water.

4.3. Experimental analysis of multi-stage flash distillation. - For the experimental analysis of multi-stage flash distillation, firstly, the experimental setup was prepared, including the flash chamber, heat source, and brackish water feed. The brackish water was heated using the heat source, causing it to evaporate. The resulting vapor was then condensed in a series of flash chambers, each operating at a lower pressure than the previous one. This process allowed for the separation of fresh water vapor from the concentrated brine. The fresh water vapor was collected and condensed into liquid form, while the concentrated brine was removed. Throughout the experiment, parameters such as temperature, pressure, and flow rate were carefully monitored and recorded. The collected data was then analyzed to evaluate the efficiency and performance of the multi-stage flash distillation process.

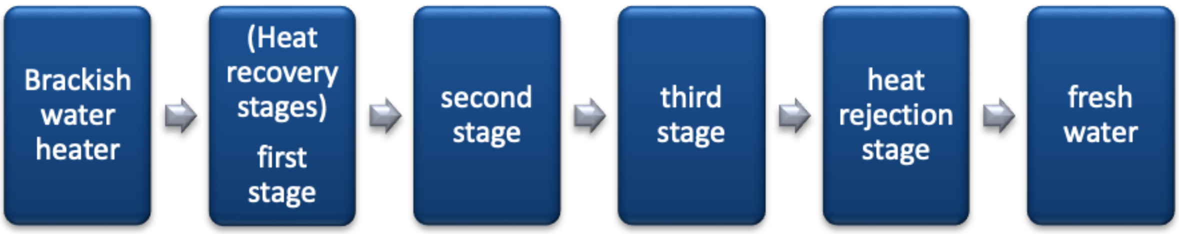

Figure IV. Multi-stage flash distillation.

5. Results and Discussions. - The specifications of the membrane used in reverse osmosis are shown in Table I. In Table II, the dimensions of the membrane are shown and the operating limits and maximum pressure, temperature conditions and the pH range for both short term and continuous cleaning are listed in Table III. In Table IV, the system details of the ROSA software are shown including the feed pressure, temperature, TDS, flow factor, avg NDP. Number of elements is taken to be 1 and in Table V, for 1 element the stage details are shown. The re-circulation flow, permeate pressure and boost pressure are found to be zero in this case. The raw water test report before the reverse osmosis is shown in Table VI and the results of the reverse osmosis are shown in the final test report after the process of reverse osmosis in Table VII. The total dissolved solids (TDS) was 3230 ppm initially but after the RO process it became 15 ppm. The total hardness initially was 710 ppm and after the RO process it became 150 ppm and the total suspended solids were found to be nil. From all of these results, it is clearly shown that the brackish water is converted into pure and drinkable water and all the impurities including the dissolved and suspended solids, organic compounds, bacteria, chlorine, micro-organisms, chloramines are removed by virtue of reverse osmosis. For further purification and advanced cleaning and to make the process more, there are various ways including the advancement in membrane cleaning, membrane technology, more effective monitoring and post-treatment. Advancement in membrane materials and design can enhance permeability, selectivity, and durability, improving overall efficiency. Implementing regular membrane cleaning protocols using appropriate chemicals and techniques to remove fouling and maintain performance. All of these factors and other factors as effective pump designs, pressure recovery devices, and optimization of operating conditions such as accurate pressure drop and flow rate through the membrane can improve RO plant's efficiency.

Product	**Part number**	**Active area ft²(m²)**	**Applied pressure psig(bar)**	**Permeate flow rate gpd(m³/d)**	**Stabilized salt rejection %**
BW30-4040	80783	82(7.6)	225(15.5)	2400(9.1)	99.5

Table I. Membrane specifications.

Product	**A**	**B**	**C**	**D**
BW30-4040	40.0(1,016)	1.05(26.7)	0.75(19)	3.9(99)

Table II. Membrane dimensions.

Maximum operating temperature °F(°C)	**Maximum operating pressure psi(bar)**	**Maximum feed flow rate Gpm(m³/h)**	**Maximum pressure drop Psig(bar)**	**pH range (continuous operation)**	**pH range (short term cleaning)**	**Maximum feed silt density index**	**Free chlorine tolerance**
113°F(45°C)	600 psi(41 bar)	4040 elements 16gpm(3.6 m³/h)	15 psig(1 bar)	2-11	1-12	SDI 5	<0.1 ppm

Table III. Operating limits.

Feed flow to stage 1	6.93 gpm
Feed pressure	200.6 psig
Flow factor	0.85
Total active area	78.00 ft²
Pass 1 permeate flow	1.04 gpm
Pass 1 recovery	15.00 %
Feed temperature	25°C
Feed TDS	3250.01mg/l
Average pass 1 flux	19.2 gfd
Number of elements	1
Average NDP	154.2 psig
Concentration	44.14 psig
Power	0.76 kW
Specific energy	12.13 kWh/kg

Table IV: System details.

Stage	1
Element	BW30-4040
#PV	1
#Ele	1
Feed flow	6.93 gpm
Feed pressure	195.68 psig
Rrcirc flow	0.00 gpm
Conc flow	5.89 gpm
Conc pressure	194.01 psig
Permeate flow	1.04 gpm
Avg flux	19.2 gfd
Permeate press	0 psig
Boost press	0 psig
Perm TDS	29.12 mg/l

Table V. Stage details.

Parameters	Analysis Results	Units
Total dissolved solids	3230	ppm
Total suspended solids	2	ppm
Total hardness	710	ppm as CaCO3
pH	7.5	-
Calcium hardness	256	ppm as CaCO3
Magnesium hardness	454	ppm as CaCO3
Iron total	0.2	ppm as Fe2+

Table VI. Raw (brackish) water test report.

Parameters	Analysis results	Units
Total dissolved solids	15	ppm
Total suspended solids	Nil	ppm
Total hardness	150	ppm as CaCO3
pH	7.5	-
Calcium hardness	40	ppm as CaCO3
Magnesium hardness	53	ppm as CaCO3
Iron total	Nil	ppm as Fe2+

Table VII. Final report of water after RO process.

5. Comparative Analysis of Desalination Methods and Advantages of Reverse Osmosis (RO). -

5.1. Reverse Osmosis (RO). - RO is a membrane-based technology that forces saline water through a semipermeable membrane under high pressure, selectively rejecting salts and other dissolved impurities. This process has gained prominence as the leading desalination method globally.

Advantages: RO systems demonstrate high salt rejection rates (up to 99%) and are highly effective across a range of salinity levels, from seawater to brackish sources. They also tend to consume less energy than thermal desalination methods due to their non-reliance on heat, making RO more economically viable, particularly for high-volume applications. Moreover, advancements in membrane materials and configurations have increased permeability and selectivity while mitigating fouling, thus improving RO's operational efficiency and lifespan.

Disadvantages: Despite its efficacy, RO membranes are susceptible to fouling from organic matter, scale, and biofouling, necessitating regular maintenance and chemical cleaning protocols. High-pressure requirements for seawater desalination also elevate energy costs and can increase system wear.

5.2. Multi-Effect Distillation (MED). - MED is a thermal process that involves a series of evaporators ("effects") where steam from one effect heats the next stage at progressively lower temperatures.

Advantages: MED is robust and ideal for large-scale desalination applications, especially when renewable heat sources are available. Its multi-stage design allows for efficient energy recycling, and it is less prone to biological fouling, making it suitable for regions with high salinity or limited maintenance resources.

Disadvantages: The high capital costs and spatial requirements make MED less feasible for smaller facilities. Additionally, MED's reliance on thermal energy results in elevated operational costs and makes it susceptible to fluctuations in energy prices.

5.3. Multi-Stage Flash (MSF). - MSF desalination rapidly heats seawater, which is then "flashed" to steam in multiple stages under decreasing pressure levels.

Advantages: MSF systems are highly reliable and capable of long operational lifespans, making them suitable for continuous, large-scale desalination. They are also effective for high-salinity seawater and can leverage waste heat, contributing to energy efficiency in combined power and water production settings.

Disadvantages: MSF is one of the most energy-intensive desalination technologies, given its heavy reliance on thermal energy. The high operational and maintenance costs, coupled with significant environmental concerns related to brine discharge, restrict its widespread use.

5.4. Electrodialysis (ED). - ED utilizes an electric field to drive ions through selective membranes, effectively separating salts from water.

Advantages: ED is particularly efficient for low-salinity water sources, such as brackish water, due to its low energy consumption relative to salinity. It also has minimal chemical requirements for maintenance and can be more cost-effective at smaller scales.

Disadvantages: ED's limited desalination capability for seawater restricts its applicability in high-salinity contexts. Additionally, membrane fouling can still be an issue, especially in water sources with high organic content.

5.4. Membrane Distillation (MD). - MD is a thermally driven membrane process that utilizes a temperature gradient to drive water vapor through a hydrophobic membrane, leaving salts behind.

Advantages: MD achieves high salt rejection and can utilize waste heat, making it suitable for niche applications, including zero-liquid discharge systems. MD systems can operate at relatively low temperatures, which reduces thermal energy demands.

Disadvantages: Scaling and fouling issues can impact membrane performance, and the technology remains cost-intensive due to complex membrane requirements. Additionally, the reliance on non-biodegradable materials raises environmental concerns, limiting MD's sustainability profile.

RO's superiority lies in its combination of high efficiency, flexibility, and scalability across various salinity levels and operational scales. Unlike thermal processes, which require significant energy input and large physical footprints, RO is compact and energy-efficient, especially when treating brackish or moderately saline water. Its adaptability to different water sources and the continuous innovation in membrane technology make RO an optimal solution for desalination. While fouling remains a challenge, advancements in fouling-resistant membranes and cleaning protocols have made RO systems increasingly resilient, reducing maintenance frequency and prolonging membrane life. These qualities position RO as the preferred choice for sustainable desalination, especially where operational flexibility and cost-effectiveness are critical considerations.

6. Factors Influencing the Performance of the Reverse Osmosis (RO) Process

6.1. Membrane Characteristics. - The efficiency of the RO process is closely linked to the properties of the membrane used:

6.2. Material Composition. - Polyamide membranes are widely chosen for brackish water desalination due to their high salt rejection capabilities and durability. In contrast, cellulose acetate membranes are less commonly used due to their lower resistance to pH variations.

6.3. Pore Structure. - The size and structure of the membrane's pores directly influence salt rejection. Smaller pores typically enhance salt rejection but may reduce the flow rate. For brackish water, membranes are designed to balance pore size, achieving effective salt removal while maintaining adequate water permeability.

6.4. Fouling Resistance. - RO membranes are prone to fouling from organic matter, salts, and biological growth, which can reduce efficiency. To combat this, anti-fouling coatings are often applied, enhancing the membrane's operational life and sustaining process performance.

7. Operating Conditions. - The conditions under which RO operates significantly impact its effectiveness:

7.1. Pressure. - Brackish water desalination operates at a lower pressure range (10-20 bar) than seawater desalination, due to its reduced salinity. The pressure must be sufficient to overcome the osmotic pressure, enabling permeate flow while optimizing energy use.

7.2. Temperature. - Elevated temperatures generally increase water permeability but may compromise salt rejection. As a result, RO systems for brackish water typically operate at moderate temperatures to balance water flux and salt removal.

7.3. Recovery Rate. - The recovery rate, or the percentage of feed water converted into permeate, is optimized to prevent excessive concentration of salts at the membrane surface. This concentration polarization can lead to fouling, so maintaining an appropriate recovery rate is essential for system efficiency and durability.

8. Water Quality. - The initial quality of the feed water, including salinity and the presence of contaminants, also affects RO performance.

8.1. Salinity. - Although brackish water is less saline than seawater, it still requires effective salt removal to achieve the desired level of purification. Lower salinity allows for energy-efficient operation at reduced pressures.

8.2. Contaminants. - Brackish water may contain organic materials, suspended particles, and microorganisms that can lead to membrane fouling. Pre-treatment, such as sedimentation or filtration, is typically applied to improve RO performance by minimizing the risk of fouling.

9. Conclusion. - After undergoing reverse osmosis (RO), the water undergoes a significant transformation in its composition. The total dissolved solids (TDS) decrease significantly from an initial 3230 ppm to just 15 ppm. Similarly, the total hardness decreases from 710 ppm to 150 ppm after treatment, and there are no total suspended solids present. These results demonstrate the effectiveness of reverse osmosis in removing various pollutants, such as dissolved and suspended particles, organic compounds, bacteria, chlorine, microorganisms, and chloramines. As a result, the treated water becomes pure and safe for consumption. The substantial reduction in TDS and hardness levels, along with the absence of suspended solids, underscores the efficiency of the RO process in water purification.

10. Future recommendations. - There are various ways to enhance the purification process and achieve advanced cleaning. This includes advancements in membrane technology, improved monitoring, and post-treatment. By improving the permeability, selectivity, and durability of membranes through material and design enhancements, overall efficiency can be increased. Implementing regular membrane cleaning procedures to prevent fouling and maintain performance using appropriate chemicals and methods is crucial. Efficiency can also be boosted by efficient pump designs, pressure recovery equipment, and optimizing operating conditions like precise pressure drop and membrane flow rate.

10.1. Membrane Cleaning Improvements. –

Tailored Chemical Cleaners: Use specific cleaning agents tailored to different types of fouling (e.g., acid cleaners for scaling, alkaline cleaners for organic fouling). Customized chemical blends can target fouling more effectively and minimize membrane damage.

Enzymatic Cleaning: For organic fouling, enzymatic cleaners can be employed to break down biofilm layers without damaging the membrane material. This is especially useful in systems prone to biofouling.

Periodic Backwashing and Forward Osmosis: Integrate regular backwashing with air scouring to remove particles from the membrane surface. In forward osmosis, alternating directions in flow help release deposited particles, maintaining membrane permeability.

Electrically Enhanced Cleaning: Introducing an electric field across the membrane surface can help repel charged foulants, reducing biofouling and scaling. This approach, called electrochemical cleaning, has shown potential in maintaining flux and extending membrane lifespan.

10.2. Enhanced Monitoring Techniques. -

Real-time Fouling Detection Sensors: Install sensors that monitor pressure drop, permeate quality, and flow rates to detect fouling or scaling as it develops. Optical or ultrasonic sensors can identify fouling layers in real time, enabling proactive cleaning before significant flux reduction.

Automated Data Analytics: Use machine learning algorithms to analyze operational data (e.g., temperature, pressure, and flux) and predict potential fouling events. This preemptive approach allows operators to adjust cleaning schedules based on real-time data rather than fixed intervals.

pH and Conductivity Monitoring: Regularly monitor pH and conductivity levels, especially in feed and brine streams, to detect changes indicating scaling or chemical imbalance. Conductivity monitoring, in particular, is useful for tracking salinity changes that may require operational adjustments.

10.3. Post-Treatment Optimization. -

Advanced Oxidation Processes (AOPs): Implement AOPs, such as ozone or UV treatments, to degrade any remaining organic contaminants and improve water quality. AOPs are highly effective in eliminating residual micropollutants that may not be removed by membranes alone.

Activated Carbon Filtration: Use granular activated carbon (GAC) as a post-treatment step to adsorb dissolved organic compounds (DOCs) and trace contaminants, improving taste and safety. GAC is effective for removing substances that might otherwise compromise water quality.

Ion Exchange for Heavy Metals: In areas with potential heavy metal contamination, an ion exchange unit can selectively remove ions like lead, copper, and mercury. This process is particularly beneficial when dealing with brackish water sources with variable metal content.

Antiscalant Dosing in Post-Treatment: Apply controlled antiscalant dosing in the final stages to mitigate the potential of scaling in downstream equipment, ensuring consistent quality and flow in distributed water.

10.4. Operational Efficiency Enhancements. -

Energy Recovery Devices (ERDs): Incorporate ERDs, such as pressure exchangers or isobaric chambers, to capture and reuse energy from the brine stream. This reduces overall energy costs and improves system efficiency.

Optimized Pressure and Flow Controls: Use variable-frequency drives (VFDs) on pumps to dynamically adjust pressure and flow rates based on real-time demands and membrane conditions. Lower pressure settings during low fouling can prolong membrane life.

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Author contribution:

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4. Discussion of the results
5. Writing of the manuscript
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