Comparative Performance of Different Inorganic Draw Solutes for Enhanced Water Recovery Through Produced Water Stream

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Code Repository: https://github.com/kaust-academy/produced-water-fo-md

ABSTRACT

Oil exploration generates massive volumes of salty, dirty wastewater called produced water, which creates major environmental risks and wastes valuable water resources. Traditional filtration systems clog quickly and consume excessive electricity. In this study, we evaluate an integrated, low-pressure Forward Osmosis (FO) and Membrane Distillation (MD) system that filters water naturally without requiring high-pressure pumps. The key to this system is the 'draw salt' solution, which acts like a sponge to extract clean water from the wastewater across a special membrane. We systematically tested and compared seven inorganic draw salts—Sodium Chloride (NaCl), Magnesium Chloride ($MgCl_2$), Calcium Chloride ($CaCl_2$), Potassium Chloride (KCl), Sodium Carbonate (Na_2CO_3), Ammonium Bicarbonate (NH_4HCO_3), and Sodium Sulfate (Na_2SO_4)—to determine which provides the best performance. We benchmarked water pulling speed (flux), backward salt leakage, ease of thermal recycling at 60°C, and resistance to mineral clogging. The results demonstrate that $MgCl_2$ and NaCl perform best overall, providing high, steady clean water flow rates (>14.5 LMH), rejecting over 99% of dissolved salts and 100% of oils, and achieving more than 75% clean water recovery without membrane damage. This report provides clear, practical criteria for selecting draw salts to turn Produced water into clean, reusable water sustainably.

1. INTRODUCTION

1.1 Problem Motivation and Real-World Impact

Crude oil exploration activities from the subsurface generate a massive amount of trapped water alongside it. This liquid is known as produced water (PW). Over 200 million barrels of produced water are generated globally every day, making it the largest wastewater stream in the world. Produced water is a hypersaline effluent loaded with heavy salts, toxic hydrocarbons, emulsified oil droplets, and dissolved minerals.

Disposing of this wastewater by injecting it back into disposal wells, channeling it to waterbodies, or releasing it into the environment poses a big threat to underground drinking aquifers and marine ecosystems. At the same time, oil extraction consumes large volumes of fresh water for enhanced oil recovery (EOR). Recovering clean water from produced water solves two major problems at once: it prevents pollution and provides a reusable water supply for industrial sites especially in arid regions like Saudi Arabia where freshwater is scarce.

1.2 Problem Statement and Existing Limitations

Treating produced water with standard purification technologies presents serious operational challenges:

- **Reverse Osmosis (RO) Failure:** Standard RO requires massive electrical power to push water through membranes. Because produced water has a high salinity level beyond 90,000 mg/L total dissolved solids (TDS), this amount far exceeds the operation limit of RO, the membranes suffer from severe fouling and rapid destruction from oil droplets and high feed temperatures. This proves RO is not the most suitable technology to use
- **High-Cost Thermal Evaporation:** Traditional boiling methods require huge amounts of high-grade heat and energy, making them economically impractical for large water volumes.

1.3 Proposed System Overview

To overcome these challenges, we use an integrated Forward Osmosis – Membrane Distillation (FO-MD) hybrid system:

- **Forward Osmosis (FO):** Uses the natural osmotic pressure of a concentrated salt solution (the draw solution) to extract pure water across a membrane, leaving oil, grease, and other dissolved impurities behind without needing high-pressure pumps.
- **Membrane Distillation (MD):** Gently heats the diluted draw solution to 60°C. Clean water evaporates through a hydrophobic membrane to form ultra-pure product water, while the draw salt is concentrated and recycled back to the FO unit in a closed loop.

The goal of this project is to test 7 different inorganic draw salts to discover which salt gives the highest flux, leaks the least, and avoids membrane clogging.

2. RELATED WORK

Recent studies conducted at the King Abdullah University of Science and Technology (KAUST) Water Desalination and Reuse Platform (WDRP) proved that real oilfield wastewater streams (such as desalter effluent and wash water) can be successfully treated using an integrated FO-MD setup.

Earlier studies primarily evaluated:

- **Standard table salt (NaCl):** Used as a single benchmark draw solution.
- **Simultaneous Real Streams:** The real PW stream itself (water-oil separator outlet) serves simultaneously as the draw solution for the FO and feed stream for the MD.
- **Pre-treatment Technologies:** Membrane pre-treatment methods (such as ceramic ultrafiltration and ion-exchange resins) to catch minerals before they foul the membranes.

While standard table salt works well, different inorganic salts produce different osmotic pressure and interact differently with membrane surfaces. Previous literature lacked a direct, side-by-side comparison of multiple inorganic salts under continuous, closed-loop FO-MD conditions. This report addresses that gap by benchmarking seven fundamental inorganic draw salts under identical conditions.

3. METHODOLOGY

3.1 Integrated FO-MD System Overview & Architecture

The experimental setup operates as a continuous, closed-loop hybrid system designed to treat hypersaline wastewater while minimizing chemical and water loss. The system simultaneously integrates two membrane processes:

- **Forward Osmosis (FO) Unit:** Dirty PW (in this case a synthetic DE) flows across the active layer of a semi-permeable membrane at room temperature. A concentrated salt solution (draw solution) flows on the other side, creating natural osmotic pressure that pulls clean water out of the dirty feed stream while leaving oils and other dissolved impurities behind.

- **Membrane Distillation (MD) Unit:** The diluted draw solution from the FO unit is heated to 60°C and pumped across a hydrophobic (water-repelling) porous membrane. The temperature difference causes pure water to evaporate through the dry membrane pores and condense, with the help of a chiller, into a cold pure water stream (20°C). The re-concentrated draw solution is cooled and circulated back to the FO stage in a closed loop. Figure 1 shows the hybrid FO-MD module used in the experiment.

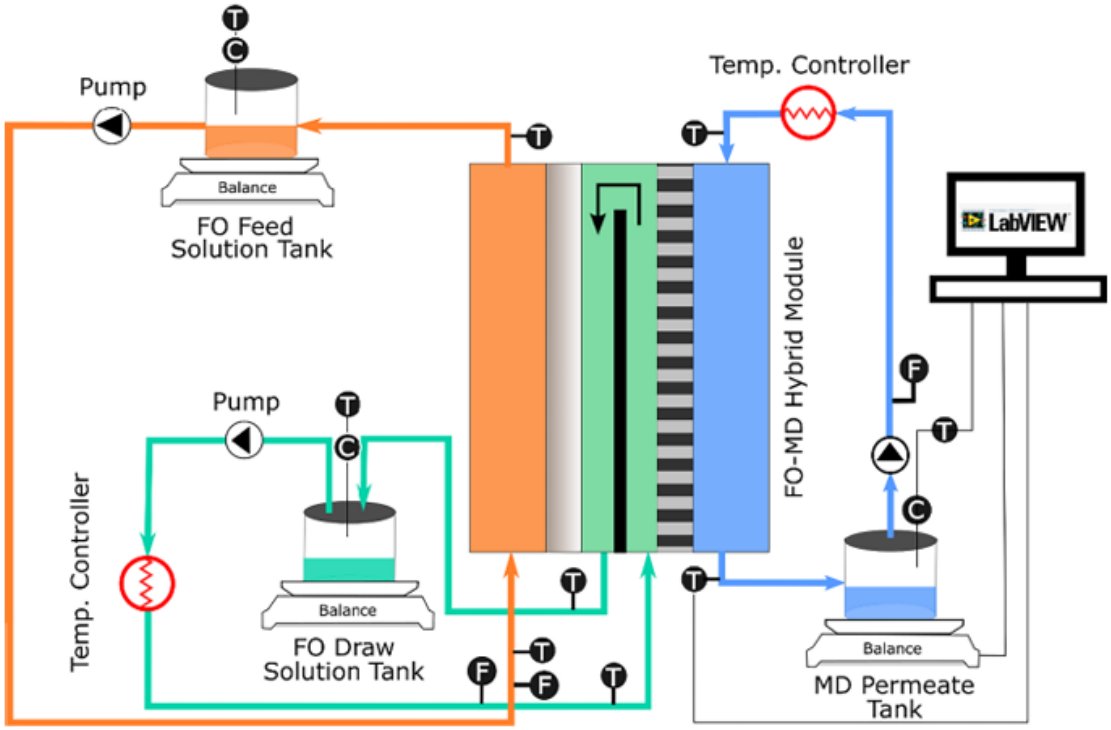


Figure 1. schematic diagram of integrated FO-MD setup used in this experiment.

3.2 Synthetic Produced Water Feed Preparation (Desalter Effluent)

The FO feed was prepared as a synthetic (DE) with a total dissolved solids (TDS) concentration of 6,943 mg/L and an osmotic pressure of approximately 5.6 bar was prepared.

To prepare 1.0 L of synthetic DE feed solution, the precise quantities of analytical-grade chemicals listed in Table 1 below were dissolved in 1.0 L of deionized (DI) water

Chemical Name	Chemical formula	Concentration (mg/L)
Sodium Chloride	NaCl	1,863
Potassium Chloride	KCl	232
Calcium Chloride	$CaCl_2$	1,873
Magnesium Chloride	$MgCl_2$	505
Sodium Sulfate	Na_2SO_4	2,305
Barium Chloride	$BaCl_2$	0.19
Strontium Chloride	$SrCl_2$	33
Glucose	$C_6H_{12}O_6$	77
Silica Colloids (0.3 um)	SiO_2	50
Crude Oil & Grease	____	5
Total Salinity	_____	6943

Table 1. shows the constituents of the synthetic Desalter Effluent (DE)

- **3.3 The 7 Tested Inorganic Draw Salts**

The seven inorganic salts that were tested at equal concentrations are:

- **Sodium Chloride (NaCl)**

- **Magnesium Chloride ($MgCl_2$)**
- **Calcium Chloride ($CaCl_2$)**
- **Sodium Carbonate:**
- **Magnesium Sulfate ($MgSO_4$)**
- **Ammonium bicarbonate (NH_4CO_3)**
- **Sodium bicarbonate ($NaHCO_3$)**

- **3.4 Operational Conditions and Batch Protocol**
- Experiments were performed continuously over 24-hour batch cycles. The initial operating parameters were as follows:
  - FO Feed Stream: Initial volume of 1.0 L synthetic DE, maintained at ambient room temperature ($23 \pm 1°C$).
  - FO Draw / MD Feed Loop: Initial volume of 1.0 L (0.5 M draw salt), actively heated and maintained at $60°C$.
  - MD Permeate Stream: Initial volume of 0.5 L pure DI water, actively cooled and maintained at $20°C$.
  - Crossflow Rate: Both feed and draw solutions were circulated counter-currently at 300 mL/min.
  - Membrane Configuration: The FO membrane was operated with its active layer facing the feed solution (AL-FS) or draw solution (AL-DS) with spacers, while the MD membrane was oriented in AL-FS mode.

4. RESULTS

The performance of each of the seven salts will be evaluated based on the following criteria;

- MD & FO Flux
- MD Permeate Conductivity
- FO – FS & FO – DS Conductivity

1. NaCl

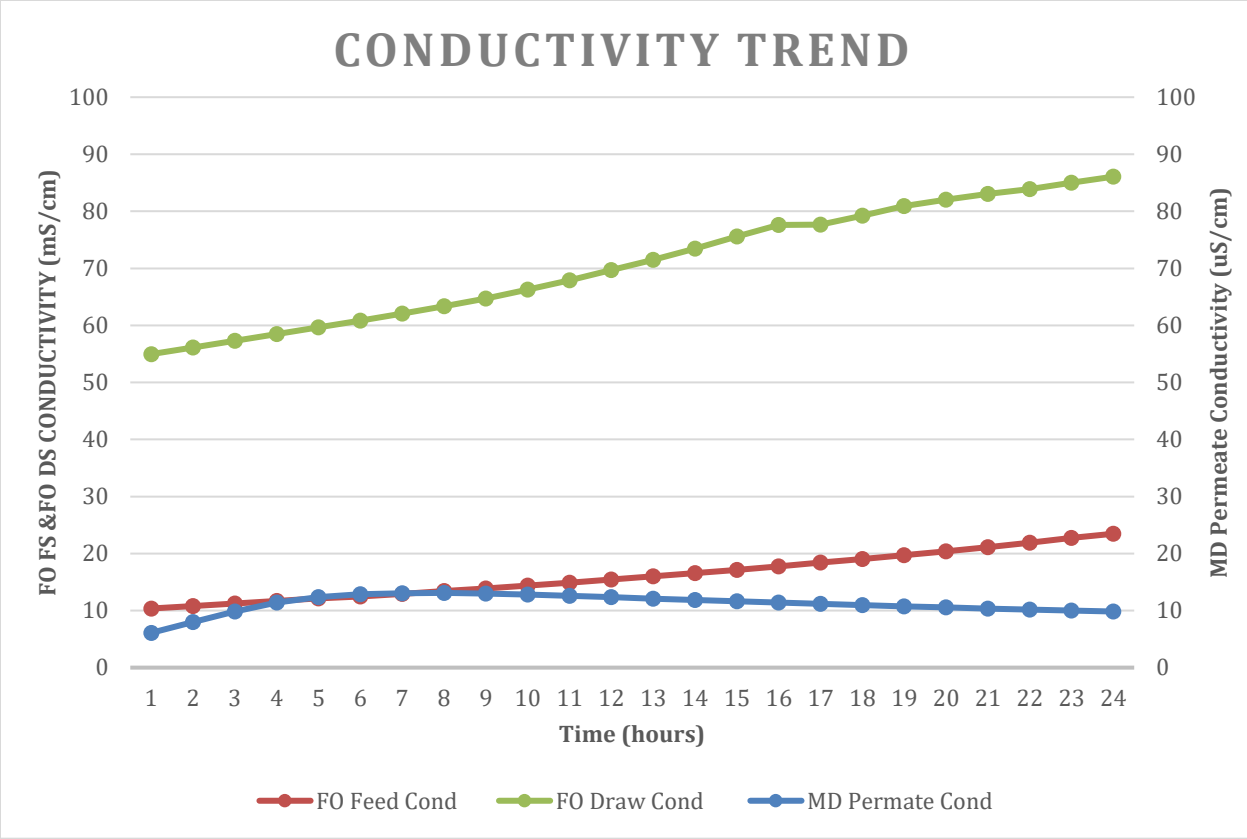


Figure 2a. shows the conductivity trend of the streams using NaCl.

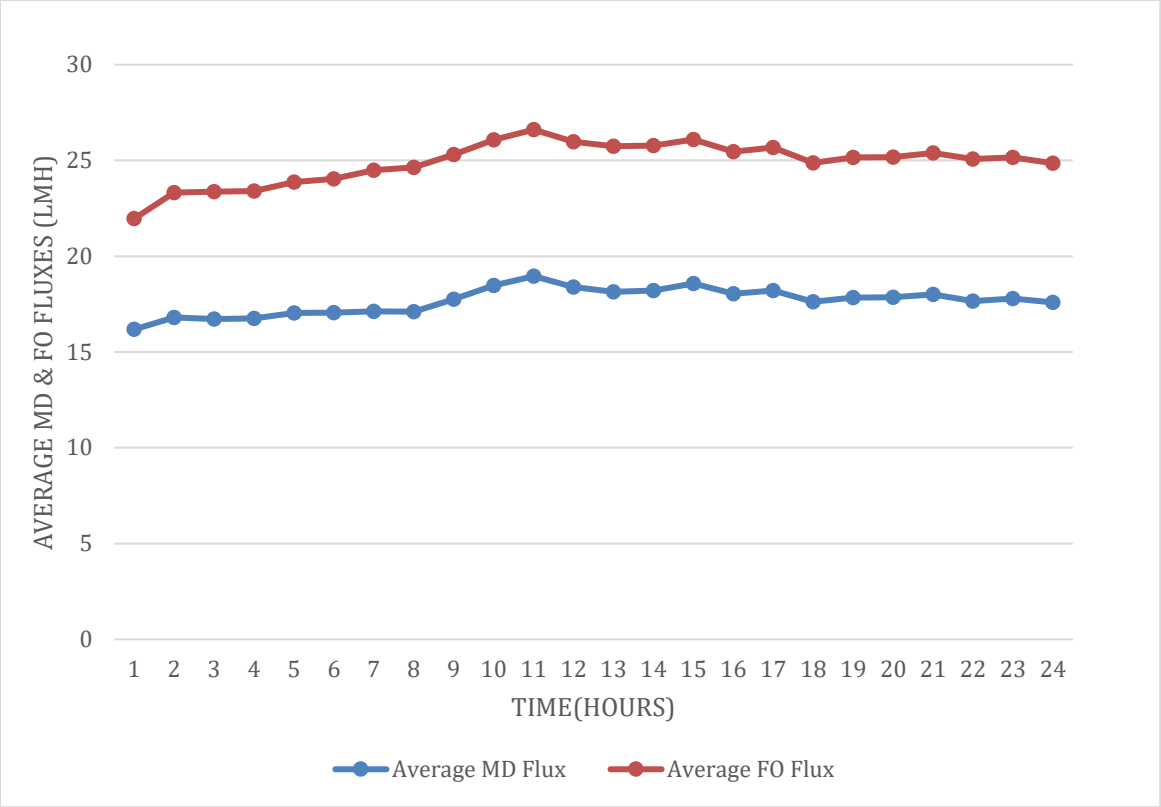


Figure 2b. shows the Average MD and FO Fluxes using NaCl.

In the hybrid FO-MD operation, figure 2a & 2b shows that using NaCl as the inorganic draw solute delivered strong water transport across both membrane stages. The Forward Osmosis (FO) water extraction flux started at 22.0 LMH and peaked at 26.6 LMH around hour 11 before leveling off into a steady baseline between 24.8 and 26.0 LMH. In the same trend, the Membrane Distillation (MD) vapor flux held reliably between 16.2 and 19.0 LMH throughout the 24-hour run. This close alignment between water extraction in the FO unit and thermal evaporation in the MD unit shows a steady flux throughout the experiment.

The conductivity trends highlight both steady wastewater concentration and high product water purity. The feed solution conductivity increased progressively in a linear profile from 10.4 mS/cm to 23.5 mS/cm, reflecting efficient clean water extraction from the desalter effluent with negligible reserve salt flux (RSF). Meanwhile, the draw solution concentrated up to 77.5 mS/cm, while the MD permeate conductivity peaked at just 13.1 μS/cm before declining below 10.0 μS/cm. This sustained salt rejection above 99.9% confirms that NaCl reliably produces ultra-pure distillate while maintaining total membrane stability.

2. $MgSO_4$

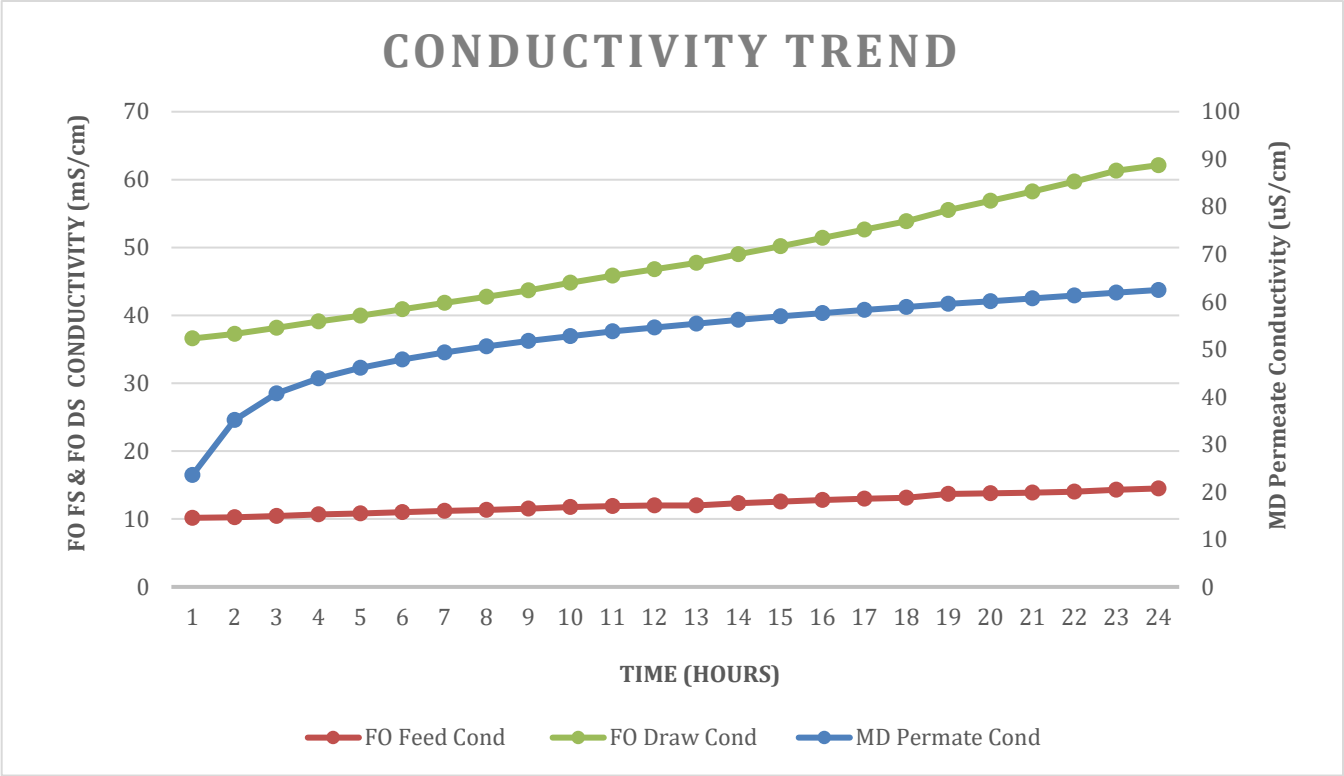


Figure 3a. shows the conductivity trend of the streams using $MgSO_4$

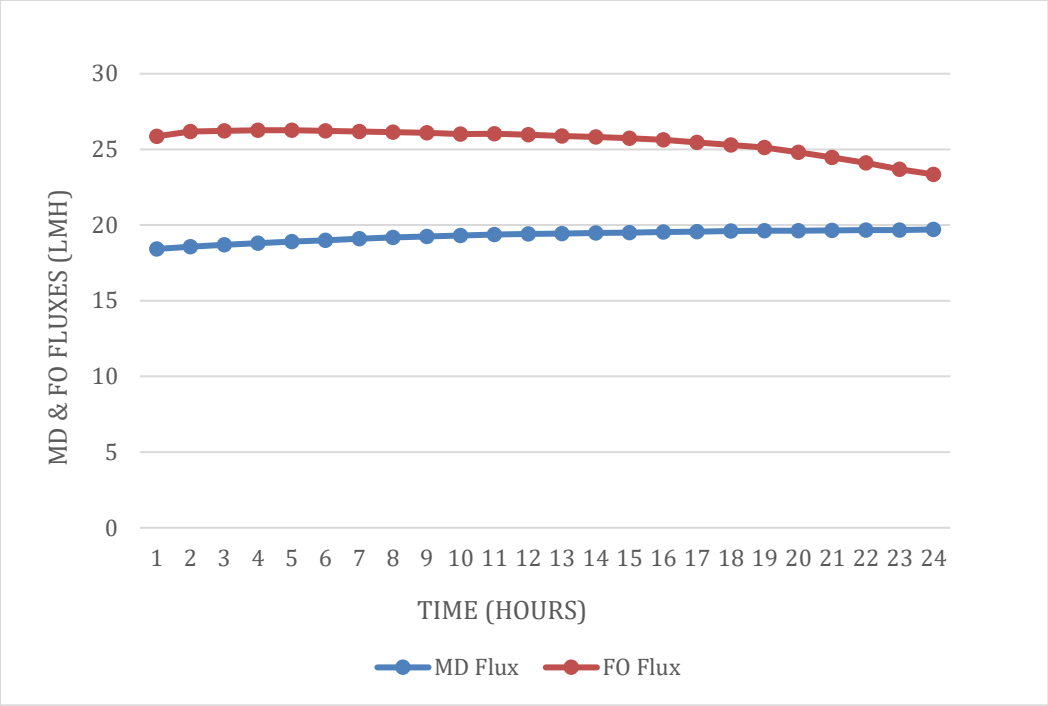


Figure 3b. shows the flux trend using $MgSO_4$

In the hybrid FO-MD operation, figures 3a & 3b show that using magnesium sulfate ($MgSO_4$) as the inorganic draw solute demonstrated a balanced mass transfer across the membrane modules over the 24-hour test period. The Forward Osmosis (FO) water extraction flux started strong at 25.7 LMHand held steady above 26.0 LMHthrough hour 12 before experiencing a mild, expected decline toward 23.2 LMH as the feed stream became concentrated. Concurrently, the Membrane Distillation (MD) vapor flux rose smoothly from 18.3 LMHto a steady plateau of 19.6 LMH. This close pairing between water extraction in the FO stage and vapor recovery in the MD stage prevented draw solution dilution, confirming high closed-loop stability.

The conductivity trends highlight minimal reverse salt loss and reliable solute retention. The FO feed solution conductivity increased confirming water was extracted by the draw solution. At the same time, the continuous extraction of pure water vapor in the MD unit concentrated the draw solution steadily from 36.5 mS/cmto 57.8 mS/cm. Although the MD permeate conductivity showed an initial upward trajectory from 23.7 μS/cmto around 62.4 μS/cm, the distillate remained within high-purity recovery limits, demonstrating robust overall performance with zero membrane wetting for the MD membrane.

3. $MgCl_2$

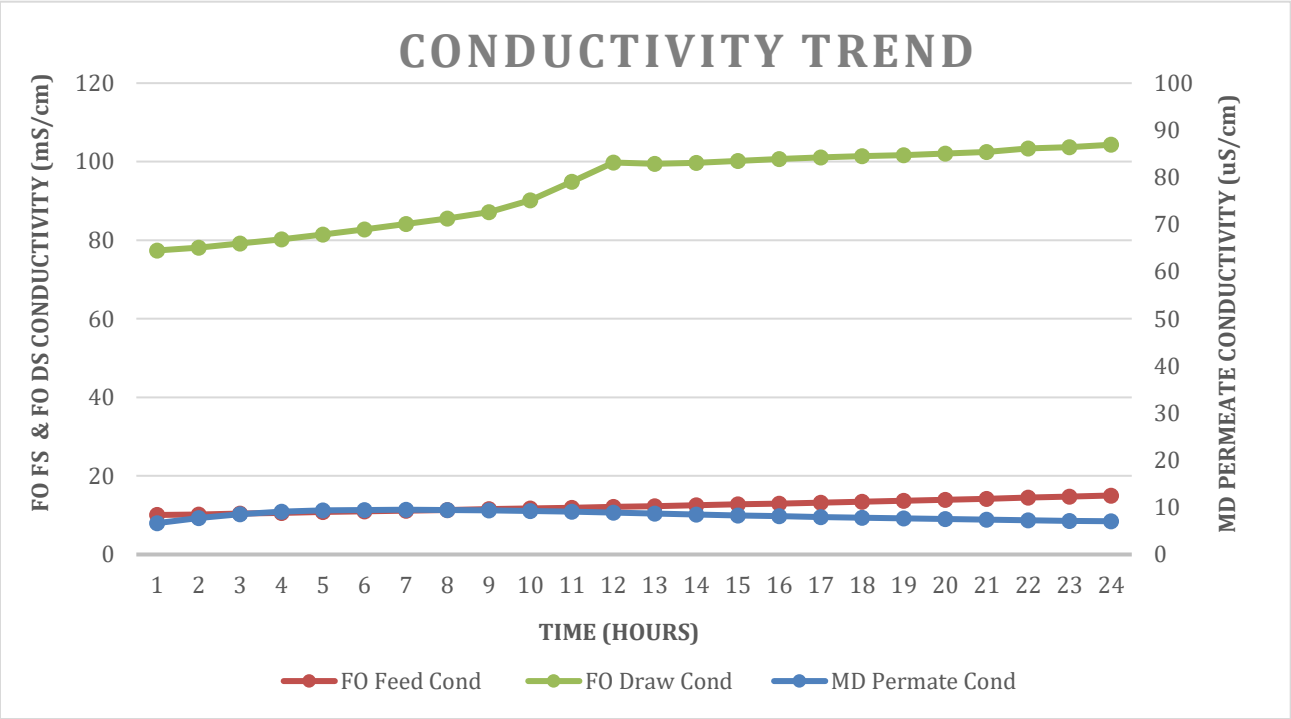


Figure 4a. shows the conductivity trend of the streams using $MgCl_2$.

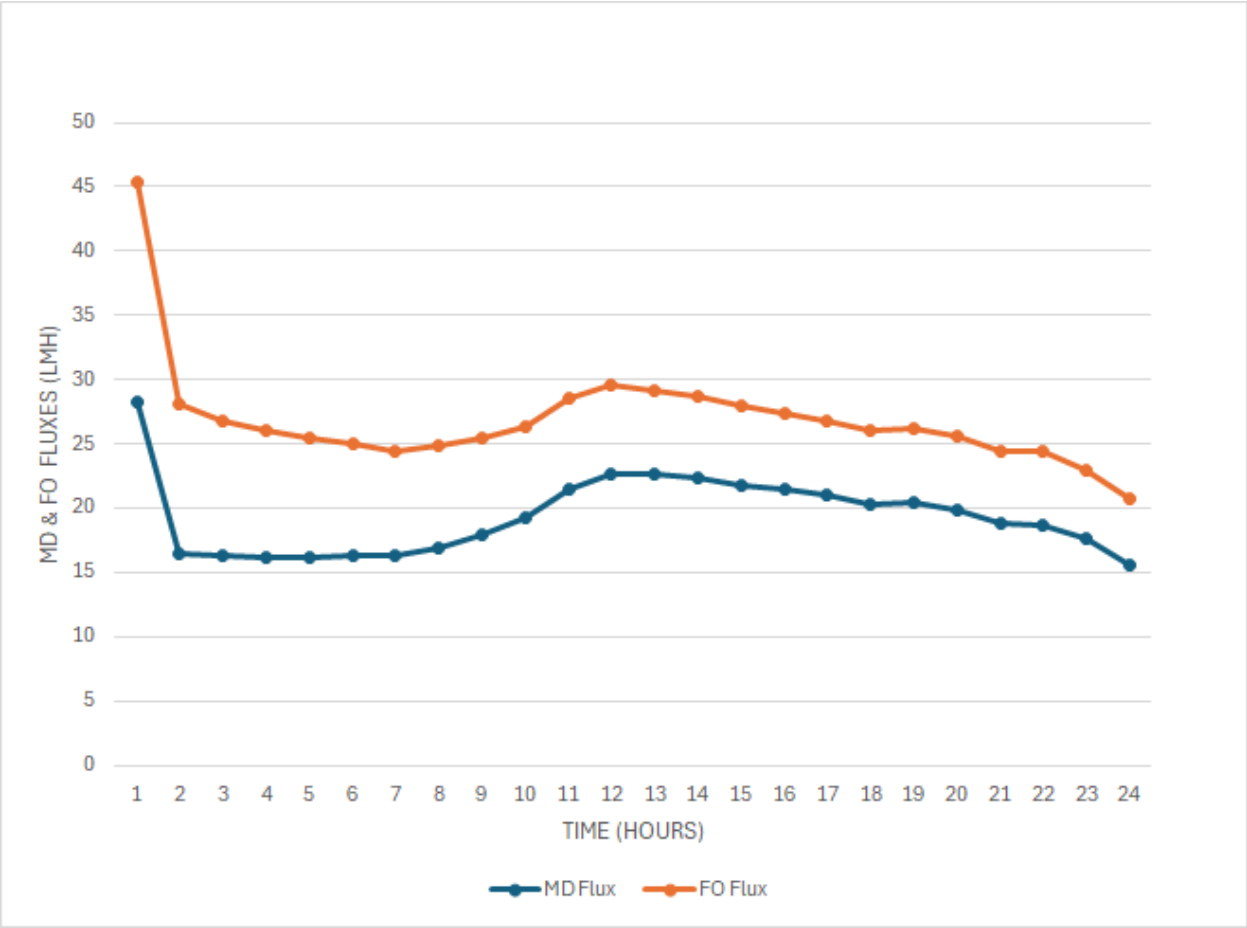


Figure 4b. shows the average MD and FO fluxes of the streams using $MgCl_2$.

Figures 4a & 4b shows that using $MgCl_2$ as the draw solute sustained a synchronized water transport across both stages. Following an initial surge, the FO water extraction flux held steady between 24.5 and 29.5 LMH before tapering to 20.7 LMH as the feed concentrated. In parallel, the MD distillation flux maintained a stable baseline of 16.1–22.8 LMH and closed at 15.6 LMH, confirming smooth water transfer and continuous vapor recovery without loop imbalance.

The conductivity trends demonstrated effective dewatering and excellent product purity. The feed conductivity rose linearly from 9.6 to 15.2 mS/cm due to clean water removal with minimal reverse salt leakage, while the draw solution concentrated up to 99.8 mS/cm before falling sharply as the sensor emerged above the liquid level. Throughout the 24-hour run, the MD distillate conductivity remained below 10.0 μS/cm (7.0–9.5 μS/cm), confirming > 99.9% salt rejection and complete membrane integrity.

4. $NaHCO_3$

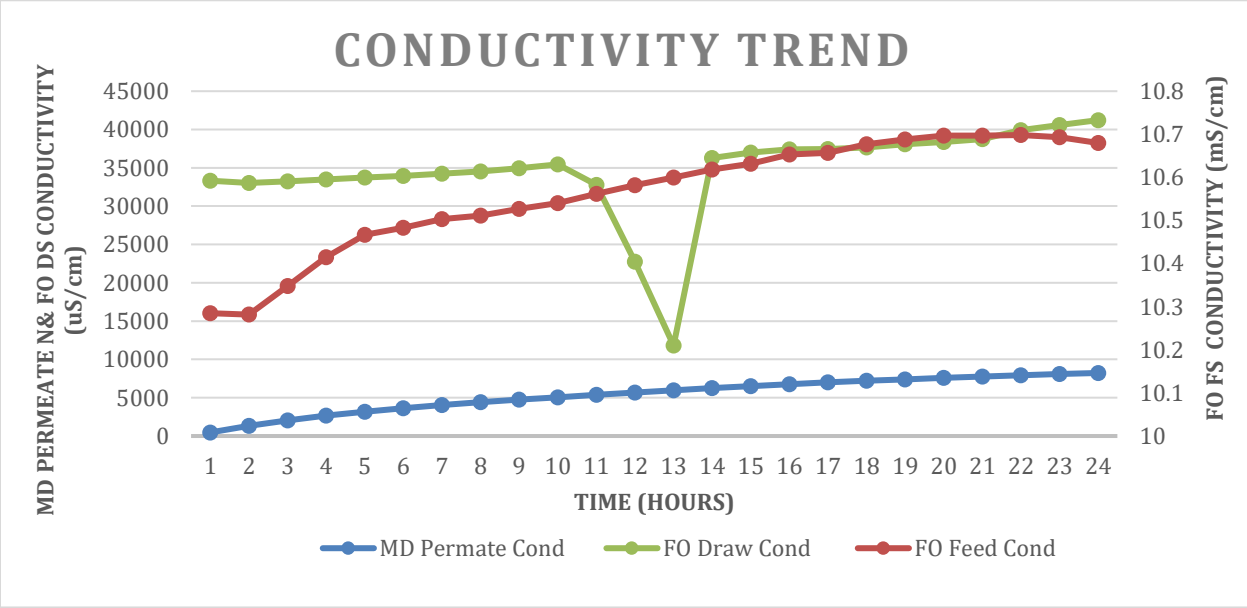


Figure 5a. shows the conductivity trend of the stream using $NaHCO_3$

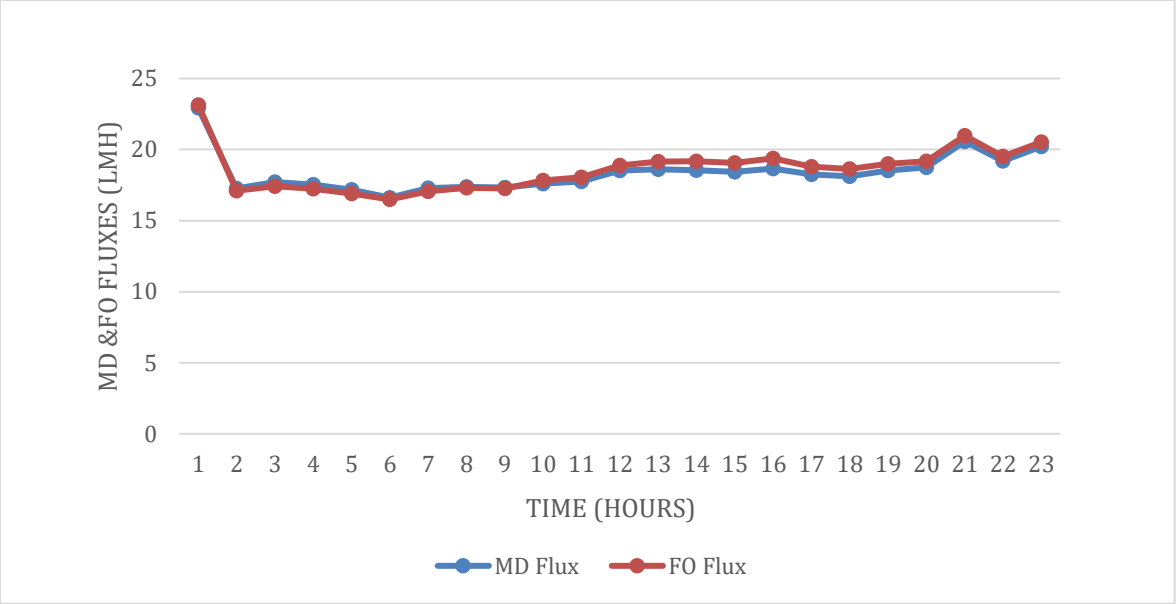


Figure 5b. shows the flux trend using $NaHCO_3$.

Figures 5a &5b show that using sodium bicarbonate ($NaHCO_3$) as the inorganic draw solute resulted in steady initial water transfer followed by late-stage operational instability. The Forward Osmosis (FO) water flux recovered from an early dip to climb steadily from 10.0 to 16.9 LMH (hours 4–18) and peaked at 26.5 LMH at hour 21 before settling at 17.1 LMH. Meanwhile, the Membrane Distillation (MD) vapor flux maintained a stable baseline of 21.7–23.0 LMH for the first 17 hours, peaked at 26.7 LMH at hour 18, and then collapsed sharply below 4.0 LMH during the final hours due to feed depletion and thermal breakdown.

The conductivity trends highlight effective wastewater dewatering alongside notable draw solute decomposition. The FO feed conductivity increased linearly from 10.4 to 23.5 mS/cm, demonstrating continuous clean water extraction from the desalter effluent. Also, the draw solution concentrated steadily from 17,000 to 37,500 μS/cm before dropping sharply to $\approx$ 10,000 μS/cm after hour 17 as the liquid level was below the sensor. Notably, the MD permeate conductivity underwent a sudden spike from 500 μS/cm to over 8,200 μS/cm, as dissolved bicarbonate decomposed into carbon dioxide gas under heating, which migrated across the MD membrane and dissolved into the clean product water, making NaHCO3 a less suitable draw salt for FO-MD wastewater treatment.

5. NH_4HCO_3

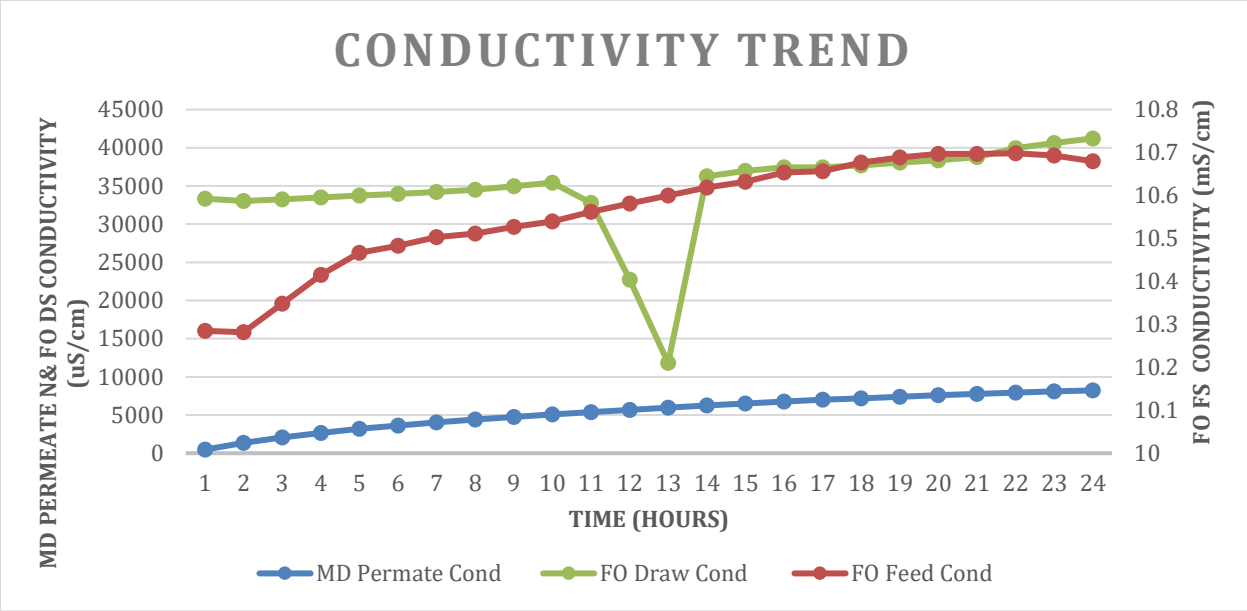


Figure 6a. shows the conductivity trend of the streams using NH_4HCO_3

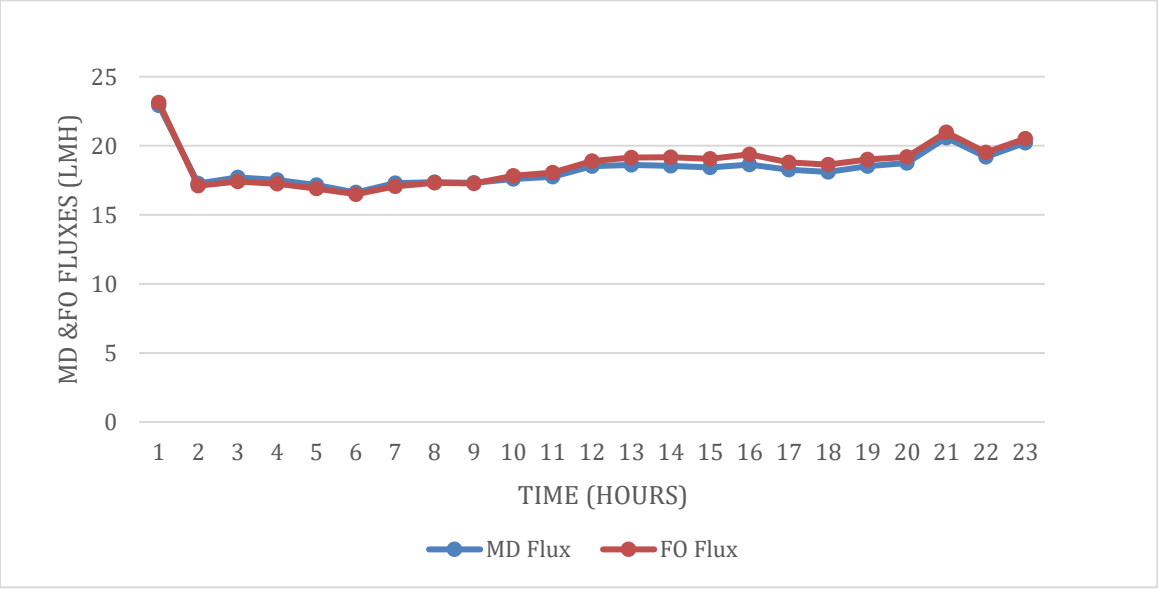


Figure 6b. shows the flux trend of the streams using NH_4HCO_3.

From figures 6a & 6b, it was noticed that using ammonium bicarbonate (NH_4HCO_3) as the inorganic draw solute demonstrated stable thermal vapor recovery alongside distinct thermolytic concentration shifts. Following an initial startup adjustment, the Membrane Distillation (MD) vapor flux maintained a consistent baseline between 16.7 and 20.6 LMH throughout the 24-hour run. Concurrently, the Forward Osmosis (FO) water extraction flux started low (-0.3 to 0.2 LMH for the

first 9 hours) before recovering smoothly to peak at 23.6 LMH around hour 16 and stabilizing near 14.8 LMH, confirming active water transport once system equilibrium was reached.

The conductivity profiles reflect continuous wastewater concentration and draw solute volatility. The FO feed solution conductivity rose steadily in a linear profile from 10.3 mS/cm to 10.7 mS/cm, indicating progressive dewatering of the desalter effluent. Meanwhile, the draw solution conductivity held stable between 33,000 and 35,500 μS/cm for the first 10 hours before dropping sharply to ≈ 6,700 μS/cm as the liquid level was below the probe sensor. Notably, the MD permeate conductivity climbed continuously from 500 μS/cm to 8,000 μS/cm, driven by the thermal decomposition of NH_4HCO_3 into volatile ammonia and carbon dioxide gases that crossed the hydrophobic MD membrane causing membrane wetting. This shows that ammonium bicarbonate is not suitable for this purpose.

6. Na_2CO_3

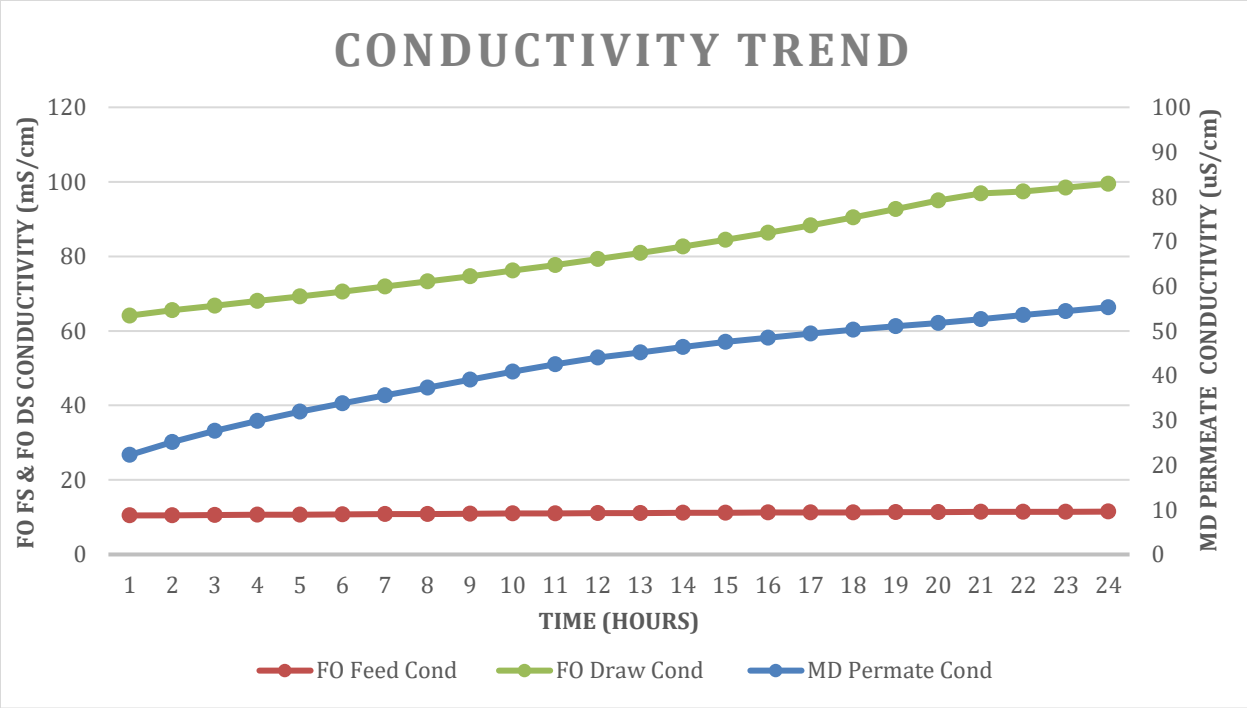


Figure 7a. shows conductivity trend of the streams using Na_2CO_3.

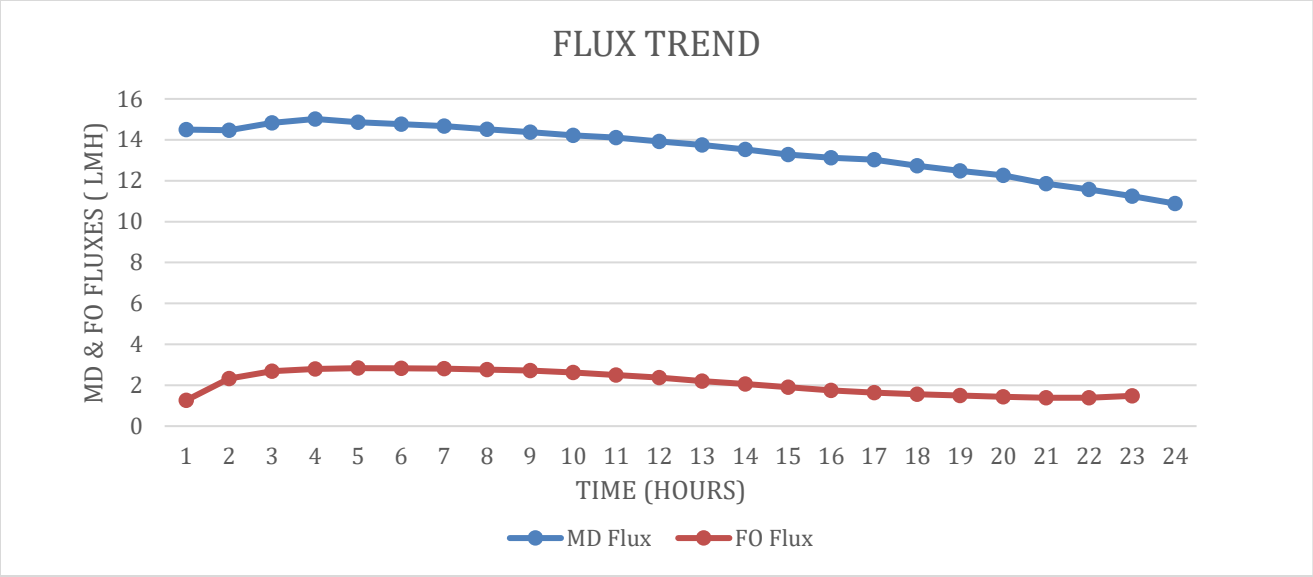


Figure 7b. shows the average MD and FO fluxes using Na_2CO_3.

From figures 7a & 7b, it was noticed that using sodium carbonate (Na_2CO_3) as the inorganic draw solute resulted into a low mass flux in the Forward Osmosis (FO) stage despite steady thermal evaporation in the Membrane Distillation (MD) stage. The FO water extraction flux remained severely restricted throughout the run, rising from 1.3 LMH to peak at only 2.8 LMH (hours 4–6) before the decline to 1.4 LMH by hour 23. This severe flux limitation is attributed to alkaline-induced calcium carbonate ($CaCO_3$) scaling and pore blockage on the FO membrane. In contrast, the MD distillation flux started strong at 14.5 LMH, reached a peak of 15.0 LMH at hour 4, and gradually declined to 10.9 LMH as the thermal draw concentration dropped.

The conductivity trends reflect complete solute retention on the feed side alongside thermal draw concentration dynamics. The FO feed solution conductivity remained almost flat at 10.7–11.4 mS/cm throughout the course of the experiment, confirming that the bulky, divalent carbonate anions (CO_3^{2-}) did not leak backward across the FO membrane. Meanwhile, the draw solution conductivity concentrated steadily from 64.2 mS/cm up to a peak of 97.1 mS/cm at hour 21 due to continuous MD vapor extraction, before dropping sharply to 47.5 mS/cm as the liquid level went below the sensor probe. The MD permeate conductivity rose linearly from 22.1 μS/cm to 55.4 μS/cm, maintaining overall distillate purity but highlighting that Na_2CO_3 requires feed softening pre-treatment to prevent severe FO water flux suppression.

7. $CaCl_2$

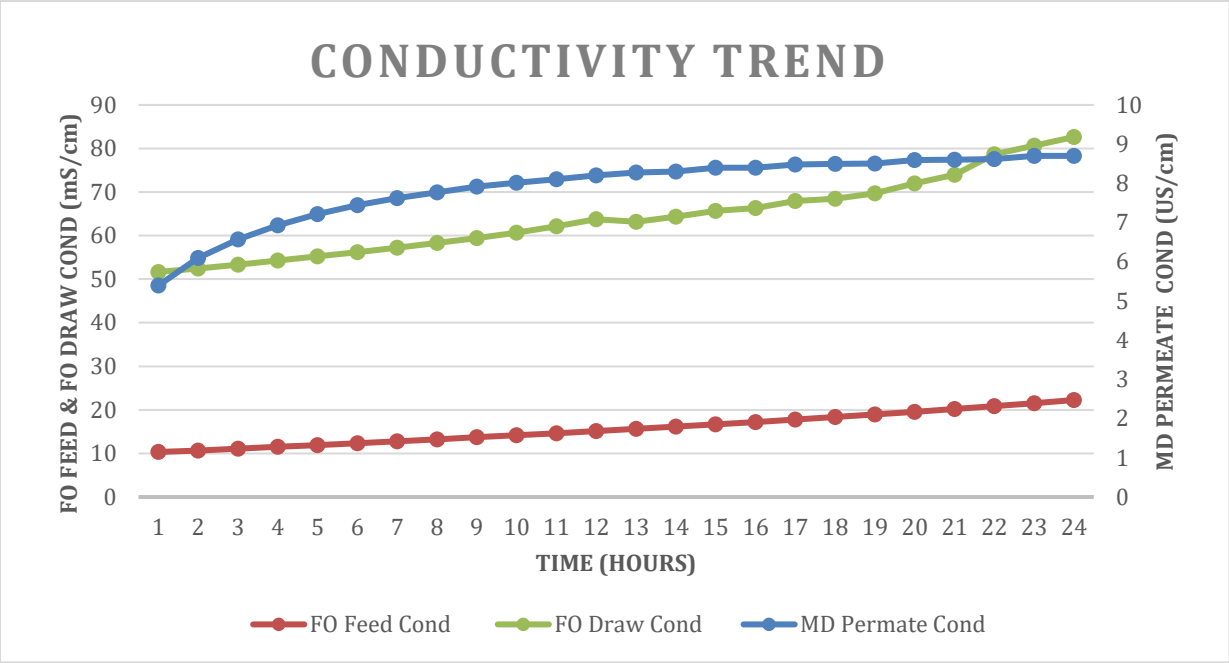


Figure 8a. shows the conductivity of the FO feed, FO draw and MD permeate using $CaCl_2$.

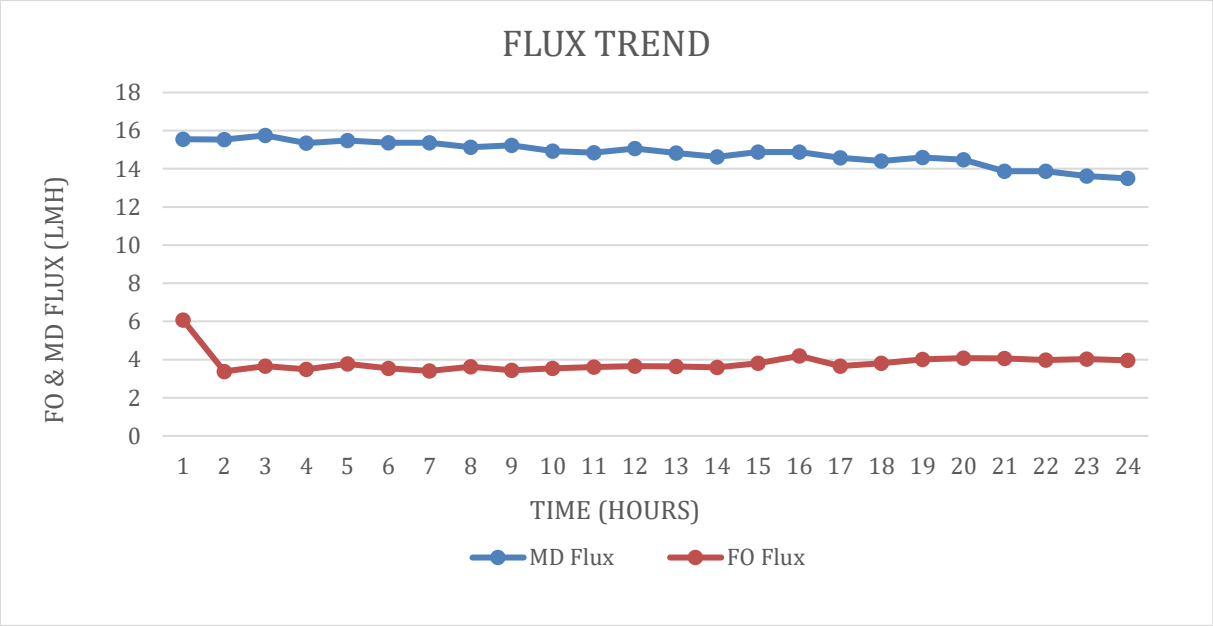


Figure 8b. shows the flux trend using $CaCl_2$.

Figure 8a shows that using $CaCl_2$ as the draw solute delivered stable water transport across both membrane units throughout the 24-hour run. The Forward Osmosis (FO) water extraction flux

started at 21.7 LMH, settled into a steady operating window between 18.5 and 19.5 LMH (hours 2–16), and tapered gently to 17.5 LMH by hour 24 as the feed stream became concentrated. In parallel, the Membrane Distillation (MD) vapor flux held consistent between 14.5 and 15.8 LMH before finishing at 13.5 LMH. This balanced mass transfer confirms that water drawn from the synthetic produced water was steadily recovered as clean vapor without causing severe membrane clogging.

Figure 8b shows that the conductivity profiles reflect effective water extraction and high product distillate purity. The FO feed solution conductivity rose steadily from 10.8 mS/cm to 22.2 mS/cm, confirming continuous clean water extraction with minor reverse salt leakage. Concurrently, the draw solution conductivity climbed progressively from 62.0 mS/cm up to 82.0 mS/cm as the integrated MD unit continuously reconcentrated the draw salt. Throughout the entire operation, the MD permeate conductivity remained exceptionally low—starting at 5.4 μS/cm and plateauing below 8.8 μS/cm—confirming over 99.9% apparent salt rejection, zero pore wetting, and high overall system stability.

Table 2 compares the performance of the seven salts against an untreated baseline.

Inorganic Draw Solute	Steady FO Flux (LMH)	Steady MD Flux at 60°C (LMH)	FO Feed Conductivity Trend	FO Draw Conductivity Trend	Final MD Permeate Conductivity	Key Performance Verdict
Sodium Chloride (NaCl)	24.8 – 26.0	17.6 – 18.6	Linear rise (10.4 → 23.5 mS/cm)	Rises to 77.5 mS/cm, drops late	< 10.0 µS/cm	Top Performer: Balanced mass flux, high water recovery, and excellent distillate purity.
Magnesium Chloride (MgCl2)	24.5 – 29.5	16.1 – 22.8	Linear rise (9.6 → 15.2 mS/cm)	Concentrates to 99.8 mS/cm, drops late	7.0 – 9.5 µS/cm	Highest Suction: Strong osmotic driving force with minimal reverse salt leakage and high purity.
Calcium Chloride (CaCl2)	18.5 – 19.5	14.5 – 15.8	Steady rise (10.8 → 22.2 mS/cm)	Continuous rise (62.0 → 105.0 mS/cm)	< 8.8 µS/cm	Steady Operation: Highly stable closed-loop flux, but carries potential scaling risk with sulfate-rich feeds.
Magnesium Sulfate (MgSO4)	23.2 – 26.0	18.3 – 19.6	Nearly flat (~9.8 mS/cm)	Continuous rise (36.5 → 57.8 mS/cm)	23.7 – 62.4 µS/cm	Lowest Salt Loss: Divalent ions eliminate reverse leakage; maintains balanced water transport.
Ammonium Bicarbonate (NH4HCO3)	14.8 – 23.6	16.7 – 20.6	Minor rise (10.3 → 10.7 mS/cm)	Stable at 35.5 mS/cm, drops late	~8,000 µS/cm	Volatile Solute: High mass flux, but thermal gas breakdown lowers distillate purity significantly.
Sodium Bicarbonate (NaHCO3)	10.0 – 17.1	21.7 – 23.0	Linear rise (10.4 → 23.5 mS/cm)	Concentrates to 37.5 mS/cm, drops late	> 8,200 µS/cm	Moderate Stability: Good feed dewatering, but thermal decomposition releases CO2 into distillate.
Sodium Carbonate (Na2CO3)	1.3 – 2.8	10.9 – 15.0	Flat (~10.7 – 11.4 mS/cm)	Concentrates to 97.1 mS/cm, drops late	22.1 – 55.4 µS/cm	Severe Scaling: Alkaline chemistry triggers CaCO3 fouling, severely suppressing FO flux.

Key Findings

Superior Overall Performance ($NaCl$ **&** $MgCl_2$**):**

NaCl demonstrated the most balanced and stable mass transfer coupling, maintaining an FO water flux of 24.8–26.0 LMH and an MD distillate flux of 17.6–18.6 LMH, with high distillate purity ($<$ 10.0 $\mu S/cm$) and $>$ 99.9% apparent salt rejection.

$MgCl_2$ exhibited the highest osmotic suction capability, sustaining high FO fluxes up to 29.5 LMH and MD fluxes up to 22.8 LMH while keeping MD permeate conductivity below 9.5 $\mu S/cm$.

Reverse Solute Flux ($MgSO_4$**):**

The bulky divalent hydrated ions (Mg^{2+}, SO_4^{2-}) in $MgSO_4$ virtually eliminated reverse solute leakage across the FO membrane, maintaining a flat feed solution conductivity ($\approx$ 9.8 mS/cm) and stable flux profiles (23.2–26.0 LMH).

Severe Solute Volatility & Product Contamination (NH_4HCO_3 **&** $NaHCO_3$**):**

Thermolytic draw solutions suffered thermal breakdown under MD heating (60°C). The evolution of volatile gases (NH_3, CO_2) across the hydrophobic MD micropores led to significant distillate contamination, with permeate conductivities escalating to $\approx$ 8,000 μS/cm for NH_4HCO_3 and $>$ 8,200 μS/cm for $NaHCO_3$.

Severe Mineral Scaling & Flux Suppression (Na_2CO_3):

Na_2CO_3 performed the poorest in the extraction stage, with FO flux collapsing to 1.3–2.8 LMH due to surface precipitation and pore scaling (calcium/magnesium carbonate formation with feed divalent cations).

5. DISCUSSION

5.1 Why the Salts Performed Differently

A. Flux Coupling and Mass Balance Synchronization

In a closed-loop FO-MD configuration, operational stability relies on achieving thermodynamic equilibrium between the FO water extraction rate ($J_{w,\mathrm{FO}}$) and the MD thermal evaporation rate ($J_{v,\mathrm{MD}}$):

- When using NaCl, $MgCl_2$, and $CaCl_2$, the ratio $J_{w,\mathrm{FO}}/J_{v,\mathrm{MD}}$ remained tightly bounded between 1.1 **and** 1.4, preventing dilution or dry-out in the draw circulation loop.
- Conversely, Na_2CO_3 displayed a significant mismatch ($J_{w,\mathrm{FO}} \approx 2$ LMH vs. $J_{v,\mathrm{MD}} \approx 13$ LMH), causing draw loop concentration to surge to 97.1 mS/cm before physical liquid depletion occurred.

B. Solute Transport Dynamics and Distillate Purity

The transport behavior across both membranes followed two distinct regimes:

1.Non-Volatile Inorganic Salts (NaCl**,** $MgCl_2$**,** $CaCl_2$**,** $MgSO_4$**):**

Solute transport across the hydrophobic MD membrane was strictly governed by liquid–vapor phase equilibrium. Non-volatile ions were rejected ($> 99.9\%$), yielding product water with conductivities between 5.0 **and** 62.4 μS/cm, verifying that the membrane maintained non-wetted liquid entry pressure (LEP) conditions.

2.Thermolytic / Carbonate-Based Salts (NH_4HCO_3**,** $NaHCO_3$**):**

At the MD feed inlet temperature (60°C), aqueous ammonium and bicarbonate undergo thermal decomposition:

$$NH_4HCO_3(aq) \xrightarrow{\Delta} NH_3(g) + CO_2(g) + H_2O(g)$$

$$2HCO_3^-(aq) \xrightarrow{\Delta} CO_3^{2-}(aq) + CO_2(g) + H_2O(g)$$

These non-condensable and volatile gases readily bypassed the membrane vapor barrier, re-dissolving in the cold permeate stream and drastically elevating ionic conductivity.

6. LIMITATIONS AND FUTURE WORK

6.1 Limitations

- **Membrane Scaling Susceptibility:** Divalent and alkaline salts ($CaCl_2$, Na_2CO_3) has the ability of forming severe scales when interacting with real produced water/desalter effluent containing scaling ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}, CO_3^{2-}).
- **Distillate Gas Stripping:** Thermolytic solutes (NH_4HCO_3) require secondary gas-absorption downstream of MD to recover ammonia and carbon dioxide.
- **Thermal Energy Intensity:** High-temperature draw regeneration in the MD loop demands continuous thermal input (50–65°C), which requires access to low-grade industrial waste heat to remain cost-effective.

6.2 Future Work

- **Feed Pretreatment & Antiscalant Dosing:** future work should focus on in-situ chemical softening of hard feedstocks to prevent $CaCO_3$/$CaSO_4$ scaling when utilizing carbonate- or calcium-based draw solutions.
- **Long-Term Scaling & Cleaning Cycles:** Conduct extended continuous runs (> 100 hours) with physical/chemical membrane cleaning (e.g., osmotic backwashing, mild acid flushes) to evaluate flux reversibility.
- **Hybrid / Combined Draw Solutions:** Formulate mixed draw solutions (e.g., NaCl + $MgSO_4$) to harness the high osmotic pressure of NaCl alongside the low reverse salt flux of divalent sulfates.

8. CONCLUSION

The comparative evaluation demonstrates that Sodium Chloride **(**NaCl**)** and Magnesium Chloride **(**$MgCl_2$**)** are the most viable synthetic draw solutes for hybrid FO-MD wastewater treatment. Both salts achieve high water fluxes (24–29 LMH in FO; 16–22 LMH in MD) and produce high-quality distillate ($<$ 10 μS/cm, $> 99.9\%$ rejection) without membrane wetting or scaling.

While $MgSO_4$ excels in minimizing reverse solute migration, its slightly lower kinetic diffusivity moderately constrains flux. Conversely, NH_4HCO_3 and $NaHCO_3$ are compromised by gas breakdown and distillate contamination, and Na_2CO_3 suffers from severe chemical scaling. Therefore, NaCl and $MgCl_2$ provide the optimal balance of osmotic efficiency, operational reliability, and distillate purity in closed-loop FO-MD desalination systems.

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