

THE EVALUATION OF POTENTIAL FORWARD OSMOSIS DRAW SOLUTES FOR
SEAWATER DESALINATION IN HAWAII

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I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

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For my family, friends, and those who have supported me through my growth and interests in the natural world.

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ABSTRACT

In response to the increasing scarcity of freshwater globally due to overconsumption and shifting precipitation patterns in response to climate change, this thesis focuses on testing a potentially energy efficient method of seawater desalination called forward osmosis. The focus of the thesis is to assist in determining some of the best draw solutions for seawater desalination in the Forward Osmosis process. The research began by literature review of water purification methods mostly focused on forward osmosis. A forward osmosis water purification system was assembled, and three different inorganic draw solutes selected. Three different concentrations (0.6M, 1M, 2M) of the draw solutions were tested for their effectiveness against deionized water as feed solution. The performance of the best draw solution concentrations; NaCl (2M), NH₄Cl (2M), KCl (2M) were tested against Seawater feed solution obtained from Ala Moana Beach Park. The 2M KCl draw solution had the best performance against both 2M NaCl and 2M NH₄Cl draw solutions as determined by water flux analyses and change in draw solution mass during FO process. The diluted draw solution products (NH₄Cl and KCl) of FO process have potential for minimizing the amount of freshwater used in fertigation (N and K sources).

TABLE OF CONTENTS

Acknowledgements	iv
Abstract	v
List of Tables	vii
List of Figures	viii
1.0 Introduction.....	9
1.1 Freshwater Scarcity	9
1.2 Forward Osmosis	11
1.2.1 Draw Solutes	13
1.3 Other Purification Techniques	15
1.4 Research objective	17
2.0 Methods.....	18
2.1 Materials: Chemical Draw Solutes, Membrane, and Seawater.....	18
2.2 Draw Solution Preparation.....	18
2.3 Fabrication of Forward Osmosis System.....	20
2.3.1 Determining Liquid Volume of the FO System.....	21
2.3.2 Marking/Graduating the Feed Solution and Draw Solution Flasks	22
2.4 The Forward Osmosis Experiment	23
3.0 Results and Discussion	26
3.1 Draw Solution Selection Process	26
3.2 Screening of Performance of Selected Draw Solutions	27
3.2.1 Water Flux Estimation of DI Water Feed Solution Experiments	31
3.3 Testing of Performance of Best Draw Solutions: Seawater Feed.....	35
3.3.1 Water Flux Estimation of Seawater Feed Solution Experiments.....	37
4.0 Conclusion	38
Appendices.....	40
Literature cited.....	41

LIST OF TABLES

Table 1. Draw solutions for Forward Osmosis and their recovery process	14
Table 2. The pH values of draw solutions before and after FO experiments	20

LIST OF FIGURES

Figure 1. Global locations of desalination plants	10
Figure 2. Bar graph demonstrating the rapid growth of desalination plants globally	11
Figure 3. Diagram of general Forward Osmosis system.....	12
Figure 4. Diagram of reverse osmosis from the RO Guide website	16
Figure 5. Bottles of draw solutions.	19
Figure 6. Thermo Scientific Orion Versa Star Pro pH meter	20
Figure 7. The components of the fabricated forward osmosis system used in experiments	21
Figure 8. The feed flask with labeled volume lines for visual observation	23
Figure 9. The use of forward osmosis desalination process in fertigation	26
Figure 10. Comparison of weight increase of draw solution with DI water as feed solution.....	28
Figure 11. Comparison of mass increase of KCl draw solutions with DI water feed	29
Figure 12. Comparison of mass increase of NH ₄ Cl draw solutions with DI water feed ..	30
Figure 13. Comparison of mass increase of all draw solutes with DI water feed	31
Figure 14. Illustration of water flux profiles of different membrane types and configurations	32
Figure 15. Comparison of the water flux trends of NaCl draw solutions with DI water feed solution	34
Figure 16. Comparison of the water flux trends KCl draw solution with DI water feed solution	34
Figure 17. Comparison of the water flux trends NH ₄ Cl draw solution with DI water feed solution	35
Figure 18. Comparison of weight increase of all tested draw solutes with Seawater feed	36
Figure 19. Comparison of the water flux trends 1M NaCl, 2M of NaCl, 2M of KCl, and 2M of NH ₄ Cl draw solutions with DI seawater feed solution	37

1.0 INTRODUCTION

1.1 Freshwater Scarcity

Water is vital for life on Earth as nature and industry require water for sustenance. (McKinney, 1963). Water comprises 71% of the earth's surface and of all the water, only 3% is freshwater (Bureau of Reclamation, 2019). Of all the freshwater, 2.5% of it is unavailable due to being heavily polluted or locked into polar ice caps, glaciers, soil, and atmosphere (Bureau of Reclamation, 2019). The remaining accessible freshwater accounts for 0.5% of earth's water leading to high freshwater demand, especially as rivers are drying out and precipitation patterns shift. Water is essential for the production and shipping of technology and goods (McKinney, 1963). The high population growth is increasing demand for freshwater due to high consumption of water; hence freshwater scarcity is a pressing matter (McKinney, 1963). Modern life depends greatly on freshwater for the manufacturing and transporting of goods, agricultural production, and consumption for survival. Efforts using thermal separation and reverse osmosis to desalinate water are successful for providing usable and potable water (Cath et al., 2006). Figure 1 shows the global locations of desalination facilities with the correlated size and business sector.

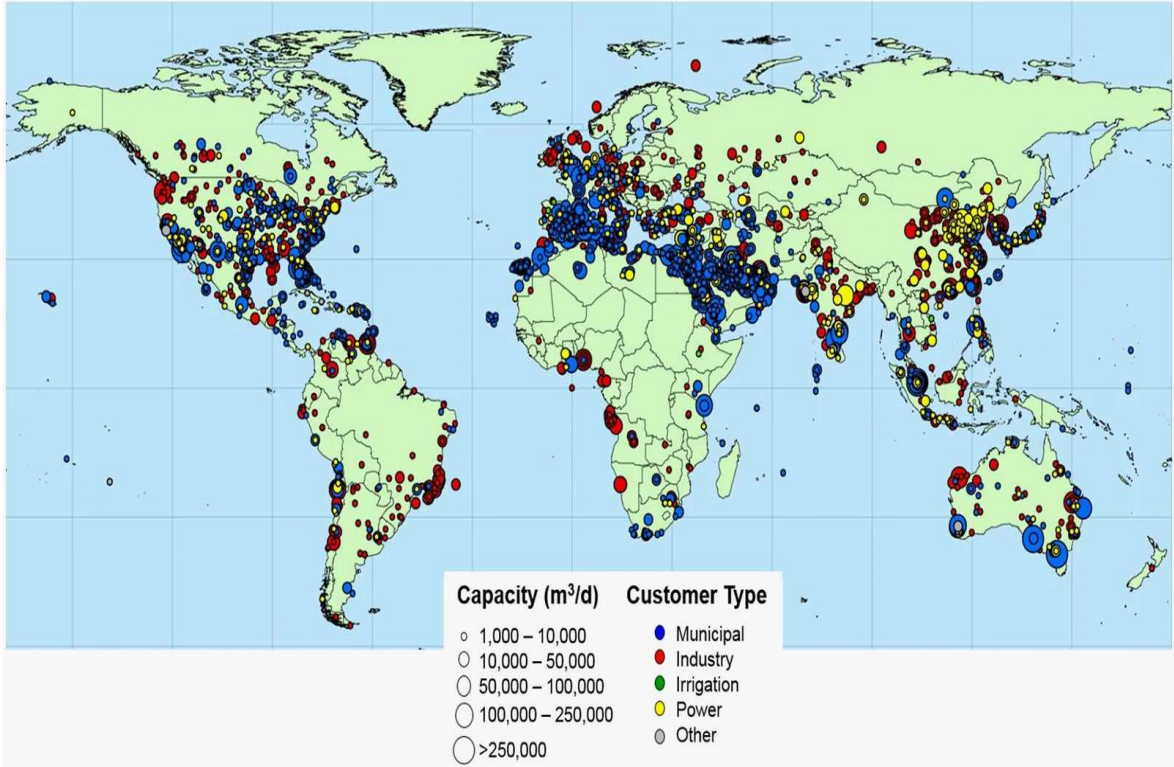


Figure 1 Global locations of desalination plants.

<https://www.wired.com/story/desalination-is-booming-but-what-about-all-that-toxic-brine/>

High energy, high cost, and the detrimental impacts to the local environment caused from the disposal of the brine by-product into the ocean are some of the factors limiting the scale at which seawater is purified (Simon, 2019) for commercial use. However, there has been an increasing demand for desalinated water especially for nations with seemingly few options and the adequate capital to utilize desalination options due to their success in producing a viable freshwater supply as presented in Figure 2.

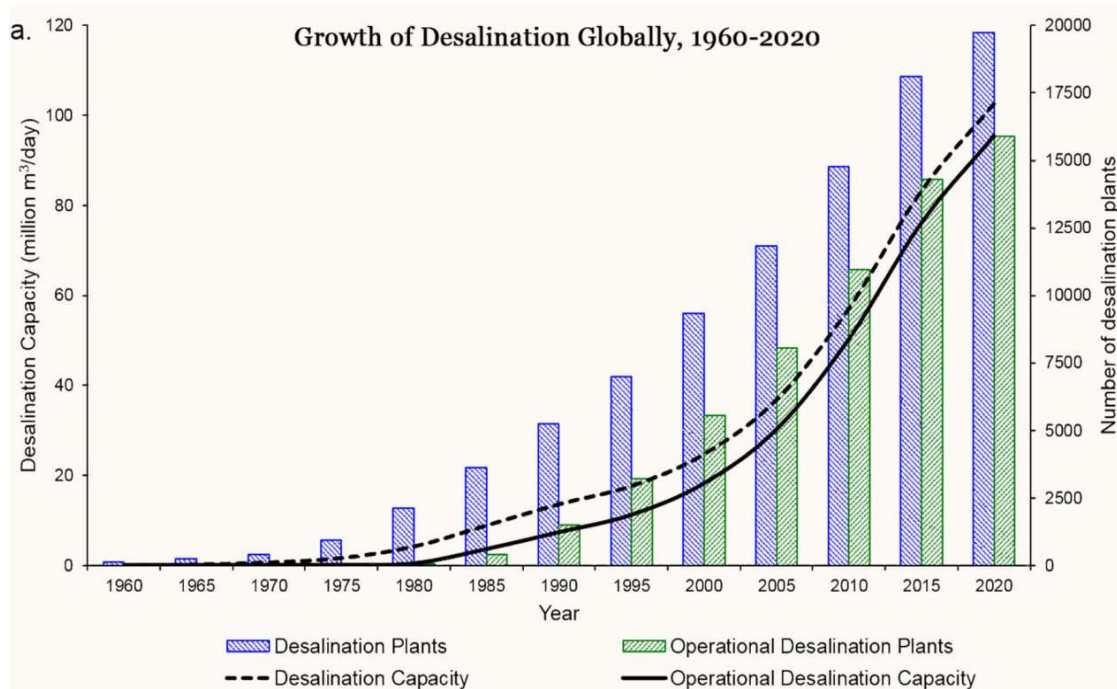


Figure 2. Bar graph demonstrating the rapid growth of desalination plants globally. Source “As Water Scarcity Increases, Desalination Plants Are on the Rise” J. Robbins, 2019, <https://e360.yale.edu/features/as-water-scarcity-increases-desalination-plants-are-on-the-rise>.

Desalination technologies are generally based on either thermal or membrane technological processes. Both methods pump the remaining brine out to sea, and which sinks to the seafloor, harming the ecosystem. Global desalination brine production is an abundant waste element (Simon, 2019). Advances in membrane technology harbor the potential for facilities with reverse osmosis to require less pressure, and less energy, to filter seawater and therefore, less brine (Simon, 2019).

1.2 Forward Osmosis

Forward osmosis (FO) is a membrane utilizing water purification technology driven by osmotic pressure variances across a semipermeable membrane (Korak, 2015). Forward Osmosis works by placing a semipermeable membrane in between a feed solution and a

draw solution (Shaffer, 2014). Water molecules are ‘pulled’ through the membrane due to the osmotic properties of the draw solution. The water permeates through the semipermeable membrane from the feed solution, seawater with low osmotic pressure to a draw solution of high osmotic pressure as demonstrated in Figure 3 (Korak, 2015, Shaffer, 2014).

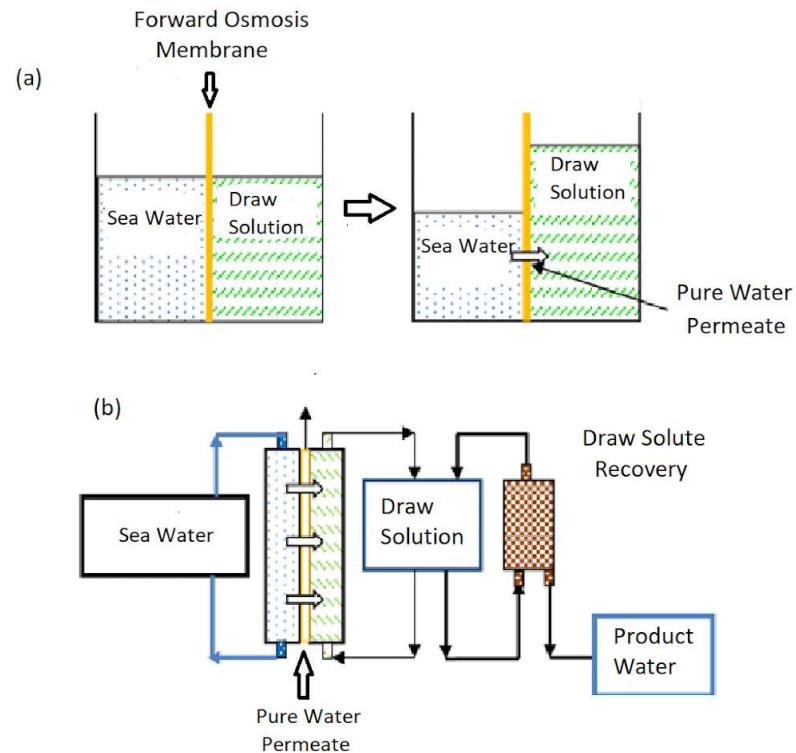


Figure 3. Diagram of general Forward Osmosis system.
https://www.researchgate.net/figure/Schematic-diagram-of-a-the-concept-of-forward-osmosis-FO-and-b-FO-setup-for_fig1_274255821

FO has been referred to as a low energy method of water filtration with a multitude of potential applications including the treatment of high salinity water, fertigation, osmotic dilution of RO feed source, and RO pre-treatment (Korak, 2015). Additionally, the utilization of FO has been suggested for applications including power generation, the

filtration of seawater and brackish water desalination, wastewater treatment, and food processing (Zhao, 2012).

The FO process demonstrates challenges of concentration polarization across the semipermeable membrane, reverse solute diffusion of draw solution into the feed solution, and slight membrane fouling of particulates (Zhao, 2012). Comparatively to Reverse Osmosis, FO does not require high pressure pumping to push water through the membrane and FO also has the potential to aid in achieving high water flux and high-water recovery due to the high osmotic pressure gradient across the membrane (Zhao, 2012). To reduce the amount of potent desalination waste brine, High water recoveries are important. (Zhao, 2012). The FO process with the right draw solutions, lends to the potential to achieve low energy consumption, resulting in the diminishing of costs (Zhao, 2012).

1.2.1 Draw solutes

Draw solutions contain draw solutes and these solutes work by affecting the osmotic pressure gradient that is needed to drive the separation in Forward Osmosis. This is done when a "draw" solution of higher concentration than the feed solution is used to stimulate a net flow of fresh water permeate through the semipermeable membrane into the draw solution thereby separating the feed water from its contaminants (McCutcheon, 2005). Selecting the best draw solution to use is the hurdle of this process as ideal draw solutions are solutions that are low cost, require low energy, possess a favorable recovery method, non-toxic, possess favorable osmotic capability, stable, highly soluble, and result in a quality end product (Shaffer, 2014). Most of the existing draw solutes require a regeneration step to return the draw solute compound to its initial state following the

Forward Osmosis process. A table of categorized draw solute chemicals with the respective recovery method is shown in Table 1. As a result, it is critical to consider the selection of draw solutions with a low reverse solute and easy regeneration for the efficiency of the Forward Osmosis process at a large scale (Long et al., 2018). The energy intensity of the recovery process is a vital difference in forward osmosis compared to the other membrane processes. It can be counter intuitive for the the energy intensity of the recovery process in Forward osmosis to be energy intensive, as the FO process cannot be comparable in efficiency with other pressure-driven processes if energy conservation is not the overall goal (Chekli et al., 2012).

Categories	Draw Solutes	Recovery Methods
Inorganic Compounds	NaCl	Reverse Osmosis
Inorganic Compounds	Inorganic fertilizer	Direct Use
Inorganic Compounds	Potassium sulfate (K ₂ SO ₄)	Reverse Osmosis
Inorganic Compounds	Sodium nitrate (NaNO ₃)	Direct Use
Inorganic Compounds	Aluminum sulfate (Al ₂ (SO ₄) ₃)	Precipitation
Inorganic Compounds	Magnesium Sulfate (Mg ₄ SO ₄)	Precipitation
Organic Compounds	Switchable polarity solvent (SPS)	Reverse Osmosis
Organic Compounds	Sodium Polyacrylate Solvent (PA A-Na)	Ultrafiltration, Membrane Distillation
Organic Compounds	CO ₂ Responsive Polymers (PNMAEMA)	Ultrafiltration
Organic Compounds	Poly (aspartic acid sodium salt)	Membrane Distillation
Organic Compounds	1-Cyclohexylpiperidine (CHP)	Heating

Organic Compounds	Oxalic Acid Complexes with Fe/Cr/Na	Nanofiltration
Organic Compounds	2-Methylimidazole Compounds	Membrane Distillation
Organic Compounds	Trimethylamine-carbon dioxide	Heating
Organic Compounds	Glucose, Fructose	Reverse Osmosis
Organic Compounds	Polyelectrolyte Incorporated with Triton-x114	Membrane Distillation
Organic Compounds	Poly (4-styrenesulfonic acid-co-maleic acid)	Nanofiltration
Functional Nanoparticles	Super Hydrophilic Nanoparticles	Ultrafiltration
Functional Nanoparticles	Hydrophilic Superparamagnetic Nanoparticles	Magnetic Separation
Functional Nanoparticles	Magnetic core-hydrophilic nanoparticles	Magnetic Separation
Functional Nanoparticles	Thermoresponsive Magnetic Nanoparticle	Magnetic Separation
Functional Nanoparticles	Dextran-coated MNPs	Magnetic Separation
Functional Nanoparticles	Hyperbranched Polyglycerol coated MNPs	Magnetic Separation

Table 1. Draw solutions for Forward Osmosis and their recovery process.
Source: <https://doi.org/10.3390/pr6090165>

1.3 Other Purification Technologies

One of the most widely utilized membrane techniques for water purification is Reverse Osmosis. Reverse osmosis (RO) is a pressure-driven membrane filtration process utilized to separate dissolved solutes from pure water permeate by diffusion (Crittenden,

2012), Figure 4. Water is pumped by electric power at high pressure across the surface of a semipermeable membrane, causing a portion of the water to pass through the membrane. Water passing through the membrane is referred to as permeate and is relatively free of targeted dissolved solutes, while the remaining water is referred to as the rejected water or brine (Crittenden, 2012).

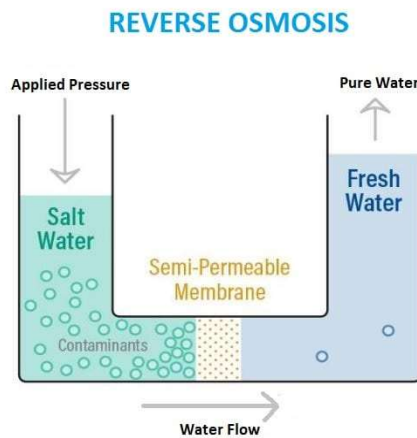


Figure 4. Diagram demonstrating the process of reverse osmosis from the RO Guide website. <https://ro-guide.com/how-reverse-osmosis-systems-work/>

The reverse osmosis process is a popular method for the desalination of seawater and brackish water. Uses of water filtered by Reverse Osmosis include the pharmaceutical industry, irrigation for the agriculture industry, industrial rinsing applications, and processing water for drinking (Rao, 2011). In Los Angeles and other cities, rainwater from sewer drains is filtered with the process of reverse osmosis and to be used as tap water in the possible occurrence of water shortages (Rao, 2011). Utilizing membranes in reverse osmosis, seawater is pumped at high pressures through a series of membrane filters to separate salt and other contaminants and currently produce 69 percent of desalinated water globally due to being less expensive and more efficient compared to the thermal separation methods (Simon, 2019).

Thermal desalination facilities heat the seawater to get pure vapor (Simon, 2019). The thermal desalination process involves the introduction of a feed solution into a thermal separation unit with the distilling of the feed solution in the thermal separation unit to result in the product of a distillate and a residual stream with a higher solute concentration than the feed solution. The most utilized thermal separation techniques are multi-stage flash distillation (MSF), and multi-effect distillation (MED) (Adham et al., 2013). This method currently produces the purest water of all the techniques. However, a major drawback is the high energy requirement for water to reach its boiling point.

Membrane Distillation (MD) is a hybrid of thermal-membrane process involving low-grade waste heat to generate high-quality distillates by producing a vapor pressure difference from brine concentrate across a hydrophobic membrane to generate high-quality distillates (Samer, 2015). The membrane Distillation process, when compared to Reverse Osmosis, presents advantages including higher product water quality and the capability to treat brines of high salinity. MD processes do tend to face issues of performance due to temperature and concentration polarization, in addition to the buildup of contaminants on the surface of the membrane (Kebria et al, 2020).

1.4 Research objective

The focus of this research in response to the issue of water scarcity and given the background of the potential in water filtration methods is to assist in determining some of the best draw solutions for seawater desalination with the Forward Osmosis process.

2.0 METHODS

2.1 Materials: Chemical Draw Solutes, Membrane, and Seawater

Three inorganic salts were chosen for this research for their potentially high osmotic pressure qualities. The draw solute salts that were purchased from Sigma Aldrich were Sodium Chloride (NaCl), Ammonium Chloride (NH₄Cl) and Potassium Chloride (KCl). FO Semipermeable membranes (FTSH2O flat sheets) were purchased from Sterlitech. The membrane is made of the polymer cellulose triacetate with a surface area of 20.6 cm² and precut for the specific Sterlitech acrylic membrane holder (CFO16) used on the FO system. The seawater feed was collected at Ala Moana Beach Park on April 30th and filtered using a 0.22µm filter. Deionized water (DI) was obtained from the UH Manoa chemistry stockroom.

2.2 Draw Solution Preparation

Draw solutions were made using the selected inorganic salt compounds (NaCl, KCl, and NH₄Cl) to be performance tested through the fabricated FO system. The draw solutions were composed of draw solutes, inorganic salts, and DI water. Various draw solution concentrations (0.6M, 1M, and 2M) were prepared (Figure 5) and tested for their draw solution performance. The best concentration of each draw solution category was utilized for the desalinization of seawater feed solution experiments.

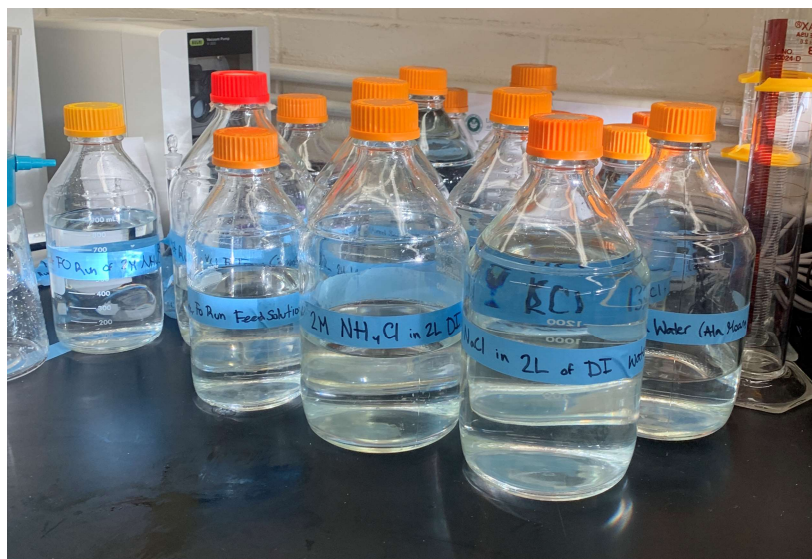


Figure 5. Bottles of draw solutions of varying concentrations premixed for the FO system.

To mimic the salt concentrations in seawater, 0.6M solutions of the inorganic salts (NaCl, KCl, and NH_4Cl) were prepared. The process of making the draw solutions began with calculating the grams of inorganic salts needed for the desired concentration with the volume solution made following equation 1, where n is the number of moles and V is the volume of the solvent.

$$M = \frac{n}{V}, \quad (1)$$

Once the grams of the salts were determined, solutions were made one at a time by measuring 2 liters of DI water using graduated cylinders and capping the bottles to prevent evaporation. The mass of the desired inorganic salt (draw solute) was measured out thoroughly to the nearest 0.01 gram on a Mettler analytical balance using weigh boats. Following the mixing of the draw solutions, the pH was tested to ensure the pH range aligned with the pH range of the membrane, Table 2. The pH was measured by a Thermo Scientific Orion Versa Star Pro pH meter, shown in Figure 6. The meter was calibrated

before each pH test using the buffer solutions. All set-up, calibrations, and electrode storage were performed following the equipment procedures in the user manual.



Figure 6. Thermo Scientific Orion Versa Star Pro pH meter (electrode not pictured)

Draw Solution (DS)	Feed Solution	Temperature (Celsius)	DS pH Before Experiment	mV DS Before Experiment	DS pH After Experiment	DS mV After Experiment
2M NaCl	Seawater	25.0	6.841	7.8 mV	6.506	28.9
2M KCl	Seawater	25.0	6.321	38.7 mV	6.219	44.2 mV
2M NH ₄ Cl	Seawater	25.0	4.935	11.95 mV	5.114	109.0

Table 2. The pH values of draw solutions before and after FO experiments. The pH of filtered seawater was 8.152.

2.3 Fabrication of Forward Osmosis System

The three main components of the FO system are draw solution, feed solution, and a semipermeable membrane. The Forward Osmosis system utilized in the experiments

consisted of two flasks, one holding the feed solution (left of the membrane) and one holding the draw solution (right of the membrane) as seen in Figure 7. The system was connected via tygon tubing with the dimensions of a $\frac{3}{8}$ inch inner diameter, $\frac{5}{8}$ inch outer diameter, and wall thickness of $\frac{1}{8}$ inch. The semipermeable membrane was a FTSH2O flat sheet membrane manufactured by Sterlitech. The membrane was made of the polymer Cellulose Triacetate of CFO16-A size with a surface area of 20.6 cm^2 (Sterlitech.com).

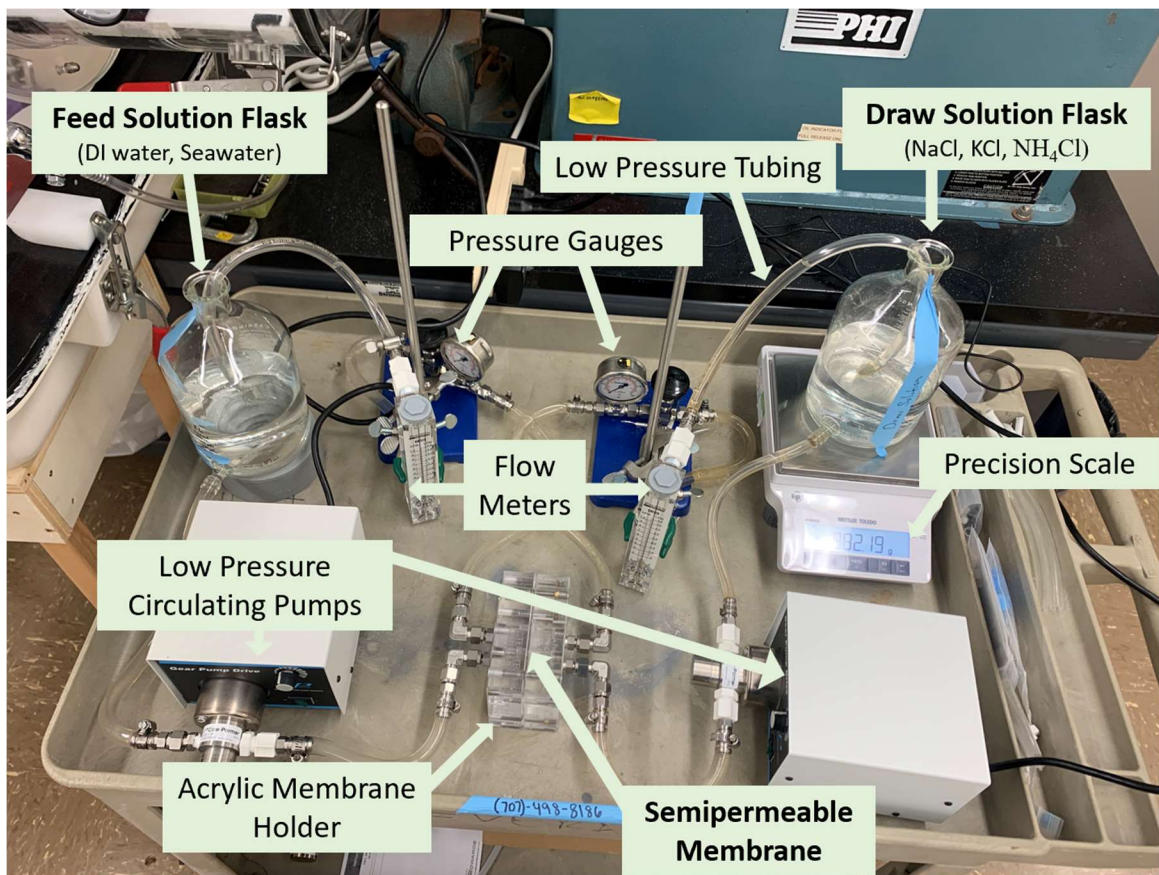


Figure 7. The components of the fabricated forward osmosis system used in experiments.

2.3.1 Determining Liquid Volume of the FO System

Once the FO apparatus was set up and all connections were secure, the internal volume of the system was determined by measuring the volume of the tubing and

components of the system using DI water. The process involved filling the draw and feed flasks with 700 mL of deionized water. The pumps were then switched on and adjusted to ensure equal flow rates from each pump and the FO system was ran for two minutes. Once the water circulated completely through the system, the pumps were shut off and each bottle was carefully tilted less than 90 degrees over the tubing connected to the valve at the bottom of the bottle to ensure not to empty the water from the tubing. The water remaining in the bottle/flask was emptied into a beaker and measured. The amount of water measured with the beaker was subtracted from the total 1400mL of DI water. This process was performed a total of two times with an average volume approximation outcome for the tubing and connections of the FO apparatus of approximately 250mL of water. This measurement process was performed to provide insight into the minimum volume of water needed to flush the system between experiments.

2.3.2 Marking/Graduating the Feed Solution and Draw Solution Flasks

To correctly observe the volume changes of the solutions in the draw and feed flasks during FO experiments, lines were marked on both the feed and draw flasks in increments of 100 mL starting at 250 mL to 1 liter (Figure 8). This process involved filling the FO system with deionized water and emptying the remaining water in flasks individually using the same bottle tilting method as was performed when measuring the volume of the complete system (see section 2.3.1) as not to empty water from the tubing. The deionized water was measured in a graduated cylinder and then poured into the draw flasks, and once the waterline was steady, a line was marked (Figure 8). The volume lines

served to observe how the feed and draw solutions were changing and thus observing how the FO process was performing.



Figure 8. The feed flask with labeled volume lines for visual observation.

2.4 The Forward Osmosis Experiment

To prepare the FO system for an experiment, the apparatus was cleaned, and the tubing and flasks were emptied as shown Figure 7. Next, the membrane holder was dismantled using an appropriately sized wrench and a clean semipermeable membrane was taken out of the fridge and placed in the membrane holder. The membrane holder was then reattached to the tubing connections of the FO system. The next step was to prepare the Feed solution of either DI water or field collected Seawater from Ala Moana beach park.

About 700 ml of the feed solution was poured into the feed flask on the left of the membrane. The draw solution was then measured out to 700 ml as well and poured into the draw solution flask. The draw solutions were always prepared in advance to FO experiments to save time on the days of experiment runs. The pressure gauges were checked to ensure pressure was not building up in the system. Finally, the pump on the side of the draw solution was turned on and the scale was tared multiple times in the first 30 seconds to adequately calibrate for the movement of water. The feed solution pump was then turned on, and the stopwatch immediately started. Each pump was set to a flow rate of 1 liter per minute (LPM). Once the pumps were on, the stopwatch was immediately started. The increase in mass of the draw solution was recorded every 5 minutes for 1 hour during the DI feed experiments and 5 hours for the seawater feed experiments. The experiments were performed in each inorganic salt category from lowest to highest concentration.

Immediately following each experiment, the membrane holder was disassembled. The membrane was cleaned by physically wiping the membrane off in the sink with tap water to remove any biofouling and salt buildup then rinsing it with DI water. The cleaned membrane was then placed in the same bag that was sent by the manufacturer containing storage solution and stored in the refrigerator.

When necessary, the system was completely flushed with DI water. For example, after the NaCl draw solutions were tested, the tubing and FO components were flushed before preparing for the next draw solution of KCl. The system was flushed by pouring 1 liter of DI water into each flask and singularly running one pump on one side at a time draining the water into an empty beaker until the water level in the flask went down to

about 300 ml mark to ensure the pumps never ran dry. Additionally, all liquids were drained from the system including the tubing and connections. This was done by pouring out the liquid in each flask as well as the liquid in the tubing connected to the base of the flask and placing the end tube fragment that was connected to the flow meters on each side of the system in a secondary container. Each side was individually drained by pouring in an additional 250 ml into the starting solution volume and then pouring the solution into the empty flask. It was also vital that the pumps were never turned on without water in the tubing as it is damaging to run the pumps dry. Once the proper solution was poured into the draw/feed solution flasks, the pressure gauges were checked and open, and there was liquid in the tubing surrounding the pumps, the pumps were plugged in and turned on until 250 ml of the solution is drained into a secondary container. This ensured that the solution tested was not diluted with the deionized water in the system and only the solutions being tested remained in the system. Once 250 ml were drained into the secondary container, the pump was shut off and the end tubing was placed into the mouth of the respective draw/feed solution flask with the very end of the tubing submerging in the solution to ensure an accurate weight on the draw solution side. It was important that each side was drained one at a time following these steps.

3.0 RESULTS AND DISCUSSION

3.1 Draw Solution Selection Process

The inorganic draw solutes (NaCl, KCl, and NH₄Cl) were selected for a variety of reasons. The selected inorganic salts are stable, nontoxic, and have potential for high osmotic pressure hence high-water flux (Shaffer, 2014). Potassium chloride has been shown to perform well in FO processes with useful applications from the final diluted draw product for agriculture fertilization (Phuntsho et al., 2015). Both the potassium chloride and ammonium chloride have the potential to be used as fertilizer in agriculture irrigation, Figure 9. The draw solutions can add vital nutrients to the soil, potassium from the potassium chloride and nitrogen from the ammonium chloride.

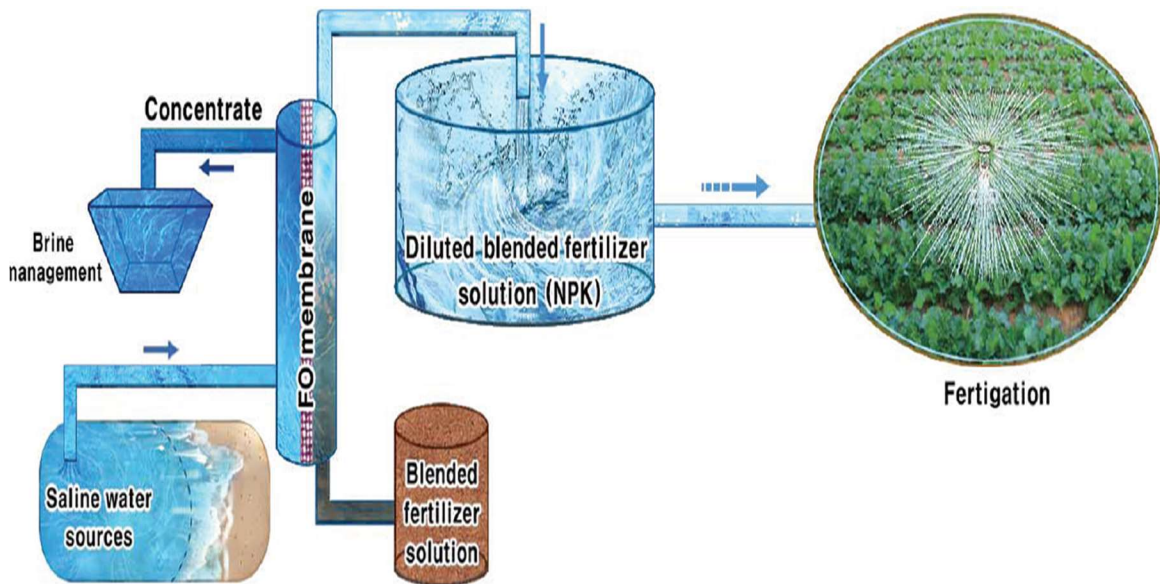


Figure 9. illustrated schematic of use of forward osmosis desalination process in fertigation (Phuntsho et al., 2015).

3.2 Screening of Performance of Selected Draw Solutions

To determine the best concentration of each inorganic salt draw solution category (NaCl, KCl, and NH₄Cl), experiments were performed using DI water as feed solution. The concentrations tested were 0.6M, 1M and 2M of each draw solute. In the preparation period of this research, the max solubility of NaCl in freshwater was calculated for to be 6.16M. To prevent quick degradation of membrane performance, the concentrations of $\leq 2\text{M}$ were chosen. As the FO system ran, fresh water moved from the feed solution through the semipermeable membrane to the draw solution. The movement of this water through the membrane was powered by osmosis, specifically by variations in osmotic pressure across the membrane (Cath et al, 2006). The membrane selectively allowed water to pass through while rejecting the majority of ions and molecules across the membrane (Cath et al, 2006). As the water moved into the draw solution flask, the volume and mass of the draw solution flask increased continually. This increase in the mass was measured and recorded over time.

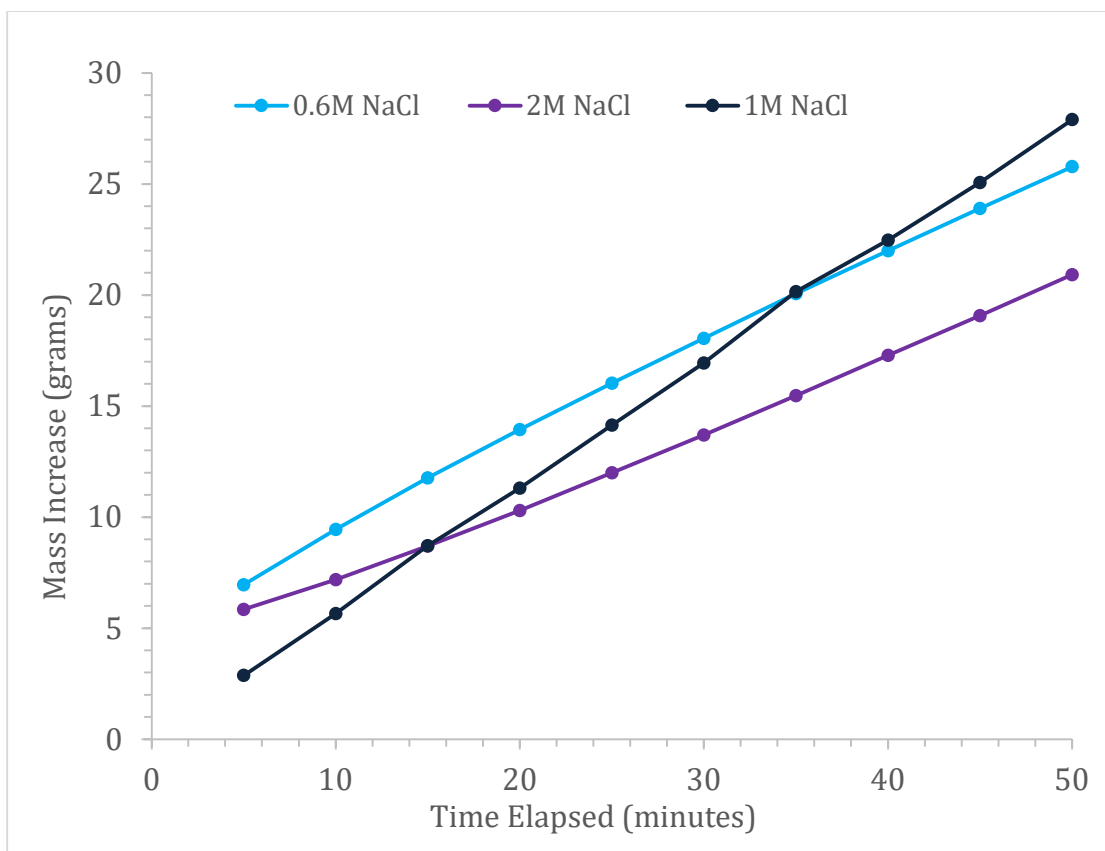


Figure 10. Comparison of weight increase of 0.6M, 1M, and 2M of NaCl draw solution with DI water as feed solution.

The best performance of the sodium chloride draw solutions was the 1M solution despite having the lowest initial mass increase, Figure 10. The mass difference with the 1M solution from the end time and the starting time was a difference of 25.03 grams. The mass difference of the 0.6M solution was 18.82 grams and the difference with the 1M solution was the lowest at 15.07 grams. The mass increase rate was close between the 0.6M and the 2M solutions whereas the rate of 1M increase was much greater.

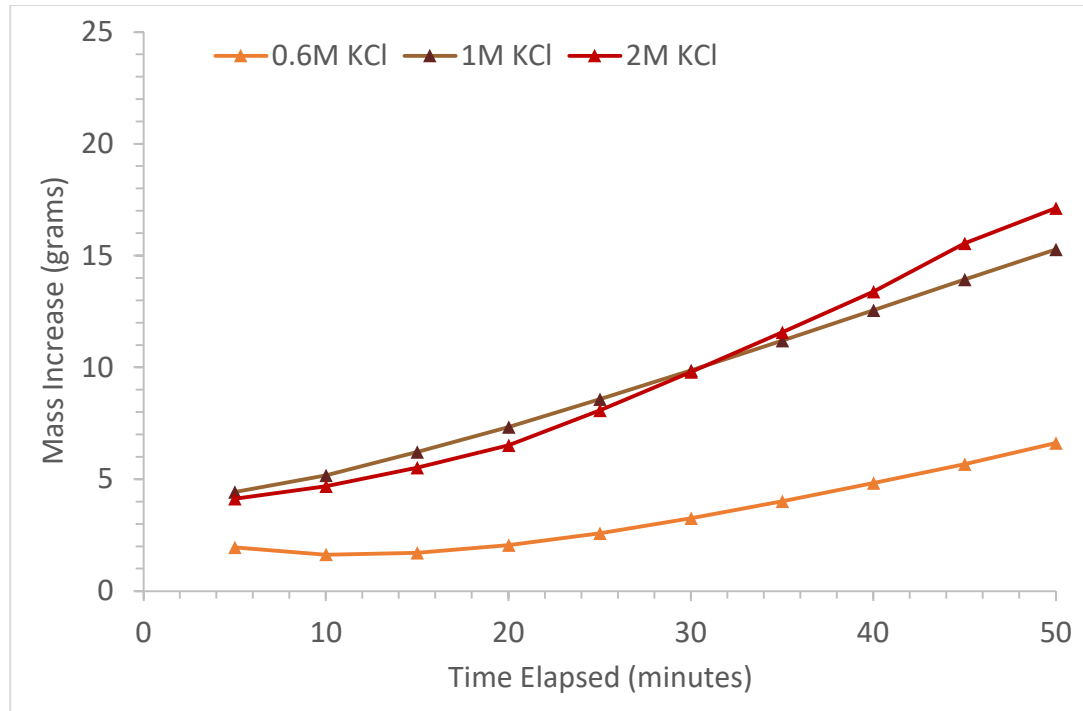


Figure 11. Comparison of weight increase of 0.6M, 1M, and 2M of KCl draw solutions with DI water feed.

The concentrations of 1M and 2M draw solutions performed the best for KCl. The two draw solutions performed similarly in the beginning of the experiment, however, the mass of the 2M KCl was overall lower in the initial 30 minutes, Figure 11. The 2M solution ended with an overall greater mass difference of 16.87 grams and thus was selected to be the best concentration of KCl for testing in the seawater experiments. The 0.6M solution performed poorly comparatively, with a dip in mass in the first 15 minutes. The curvature of the graphs is likely due to the polarization of the membrane explained further in Section 3.2.1. With the DI water feed, the KCl draw solutions had less mass difference in all three concentrations compared the NaCl solutions.

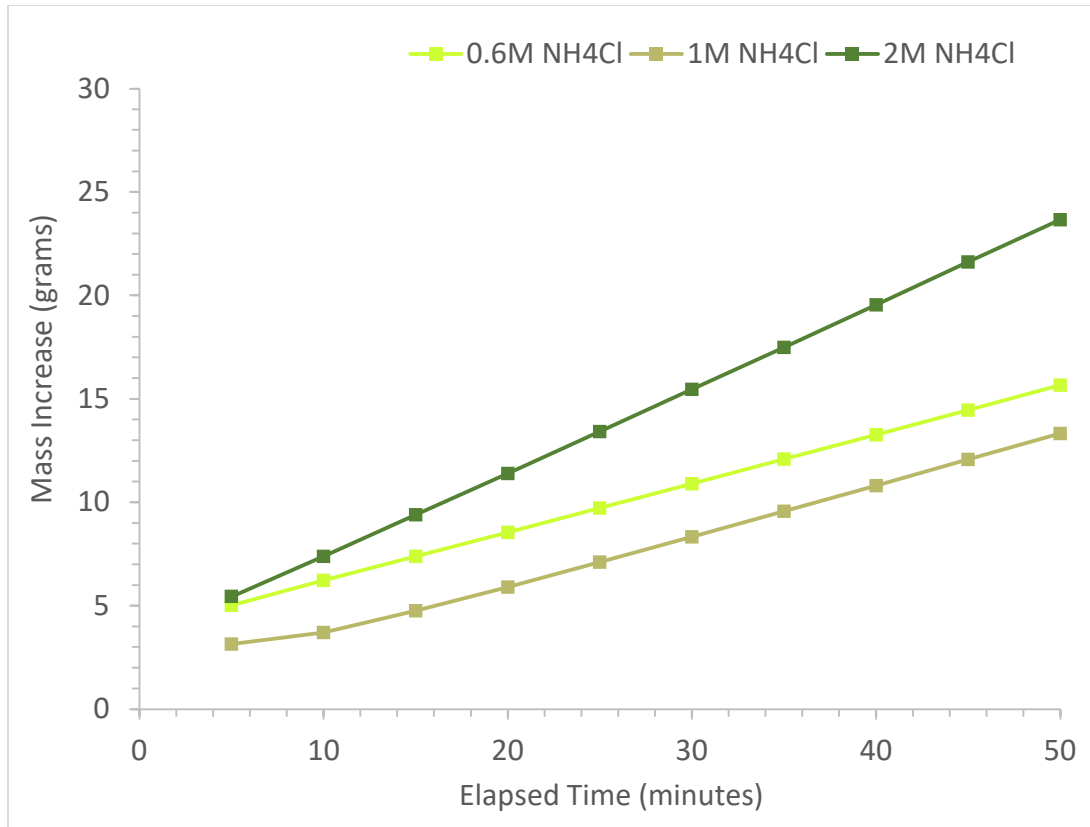


Figure 12. Comparison of weight increase of 0.6M, 1M, and 2M of NH_4Cl with DI water feed.

The best performing NH_4Cl draw solution concentration was the 2M solution with a steady and steep increase compared to the 0.6M and 1M solutions, Figure 11. The mass difference achieved by the 2M NH_4Cl solution was 22.39 grams, while the 0.6M and 1M had a mass difference of 13.02grams and 12.76 grams respectively. The 0.6M NH_4Cl solution reached an overall greater mass increase but the 1M had a greater slope. The trends of the NH_4Cl draw solutions were linear similar to NaCl solutions, indicative of minimum negative effects to membrane performance.

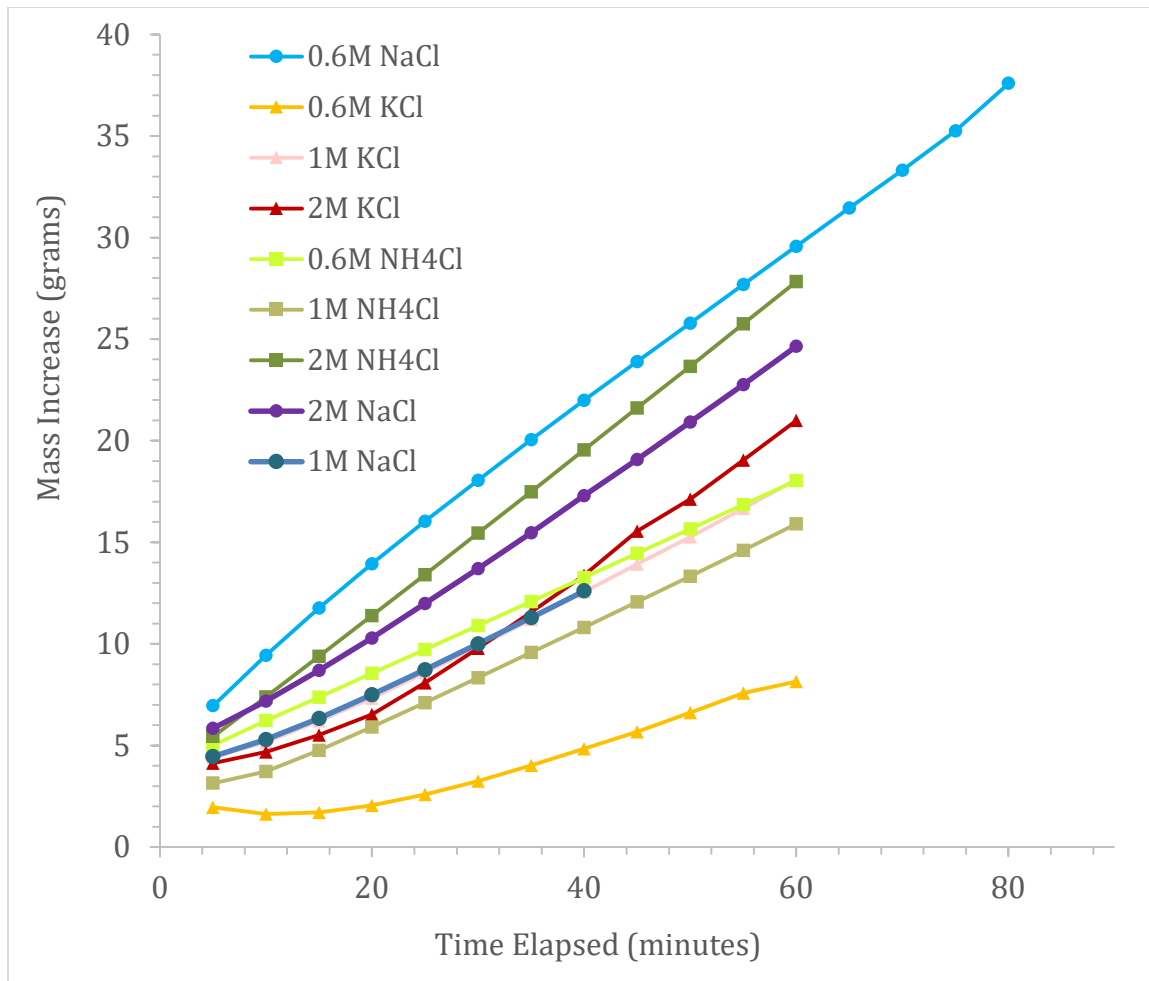


Figure 13. Comparison of weight increase of all tested draw solutes with DI water feed.

All draw solutions of all tested concentrations successfully pulled water from the feed solution into the draw solution flask. This proved the system was operating correctly and provided data to select the best performing concentrations of each draw solution to be tested in seawater desalination experiments.

3.2.1 Water Flux Estimation of DI Water Feed Solution Experiments

The water flux is the movement of water through the semipermeable membrane flowing from the feed solution to the draw solution. Water flux can be lower than expected

due to concentration polarization. This polarization occurs when the osmotic pressure at the membrane is lower than the overall bulk osmotic pressure due to the buildup of solute particles (Cath et al, 2006). The water flux can be influenced by permeate build such as salt particles on the feed solution side of the membrane in the case of utilizing seawater feed resulting in the dilution of the draw solution in the membrane holder (Cath et al, 2006). This specific case of osmotic pressure polarization is common when using active membranes that were used in all FO experiments of this research.

T.Y. Cath et al. / Journal of Membrane Science 281 (2006) 70–87

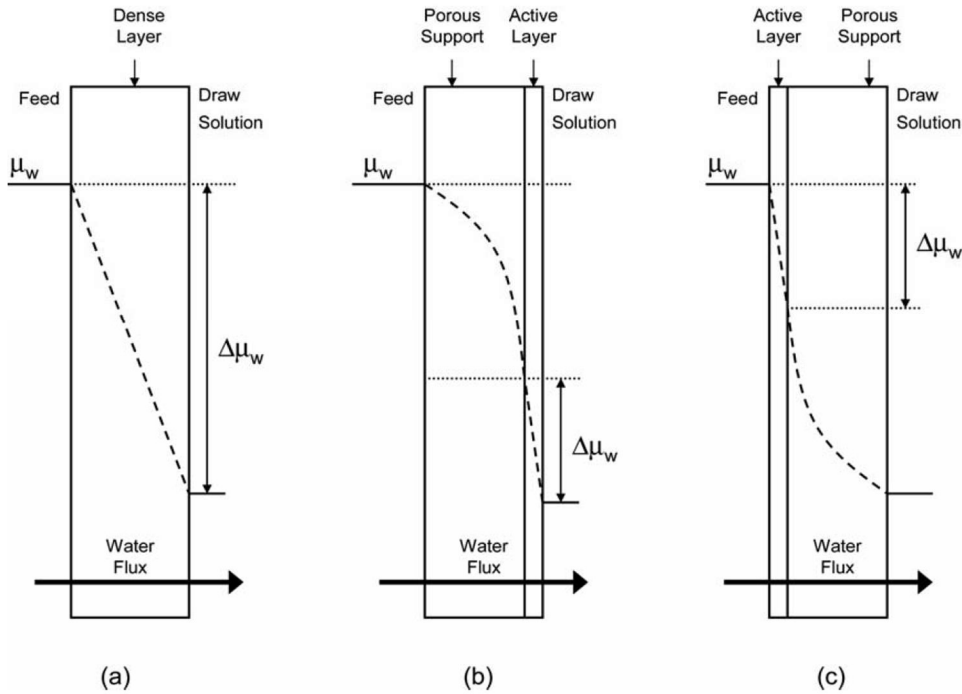


Figure 14. Illustration of water flux profiles of different membrane types and configurations (Cath et al, 2006).

Water flux data is utilized to provide insight to the performance of the Forward Osmosis system especially the draw solutions. The water flux can be determined by the theoretical calculation (O’Hare et al, 2005):

$$J_{w,exp} = \frac{V_{d,t+\Delta t} - V_{d,t}}{S\Delta t} \quad (2)$$

where $J_{w,exp}$ represents the water flux through the experimental membrane, t represents time and Δt time represents difference. S is the filtration area and the volume of draw solution at t and $V_{d,t}$ are represented by $V_{d,t+\Delta t}$ and $t+\Delta t$, respectively. The time and mass data from the FO experiments were applied to this equation using excel and the graph of the fluxes are seen in figures 15-17.

The water flux trend seen in Figure 14 of the NaCl draw solutions show dips in performance. This can be seen specifically in the 0.6M NaCl experiment with a steady dip in flux after five minutes until the last data point was collected where the flux increased dramatically. This 0.6 M curve demonstrates an expected flux trend of a system with an active membrane as discussed in section 3.2. The 1M and 2M concentrations increase with flux and the 1M flux specifically shows an irregular trend. The 0.6M and 1M KCl fluxes have increasing trends with a rapidly increase flux in the first 15 minutes then a more constant and steadier rate for the remainder of time. The 2M concentration flux however is irregular similarly to the 1M NaCl flux trend with more of a smooth curve in the first 30 minutes. The NH_4Cl flux rates are the most constant of the three inorganic salt solution with nearly flat linear trends. The 0.6M and 1M lines have nearly identical values with major differences in the first data point. Typically, FO systems run for 5-10 hours, and these DI water feed experiments were performed for 1 hour thus providing short term data trends that differ than what would be expected for longer runs.

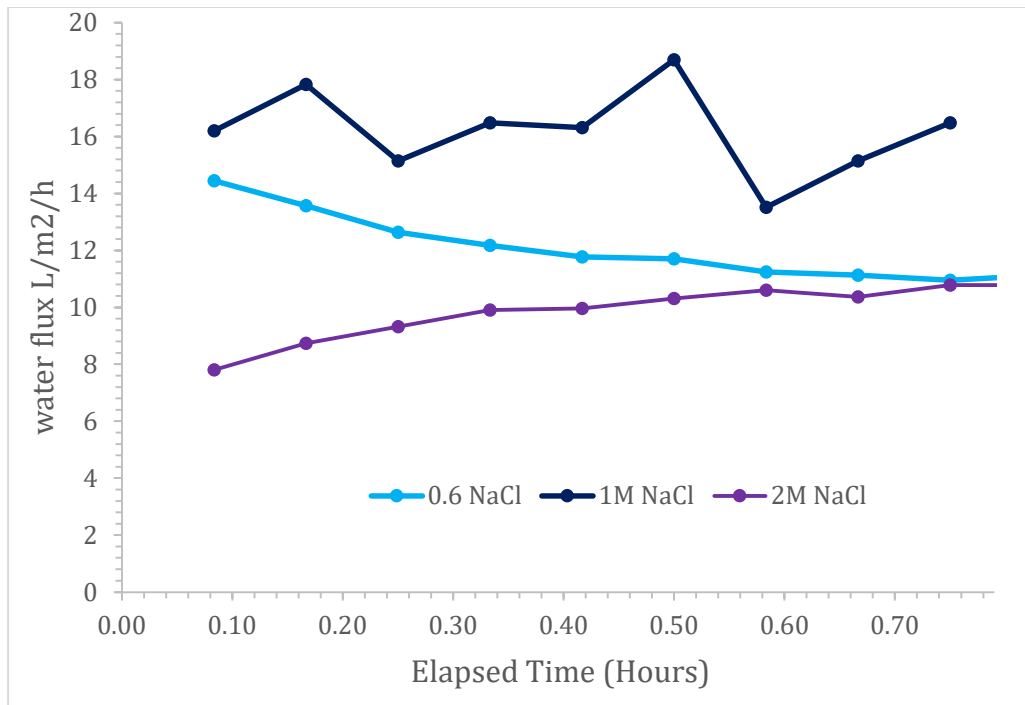


Figure 15. Comparison of the water flux trends 0.6M, 1M, and 2M of NaCl draw solution with DI water feed solution.

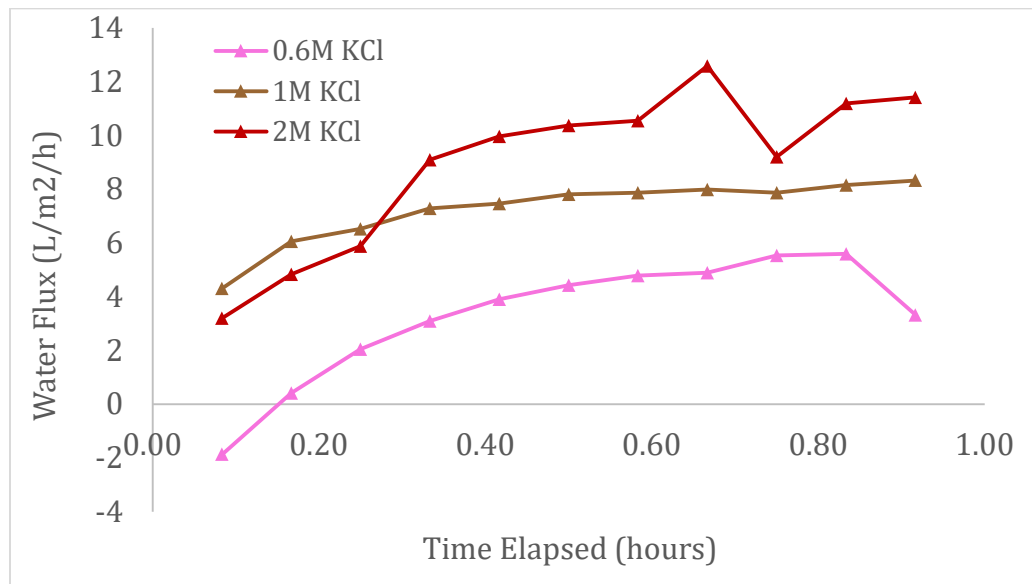


Figure 16. Comparison of the water flux trends 0.6M, 1M, and 2M of KCl draw solution with DI water feed solution.

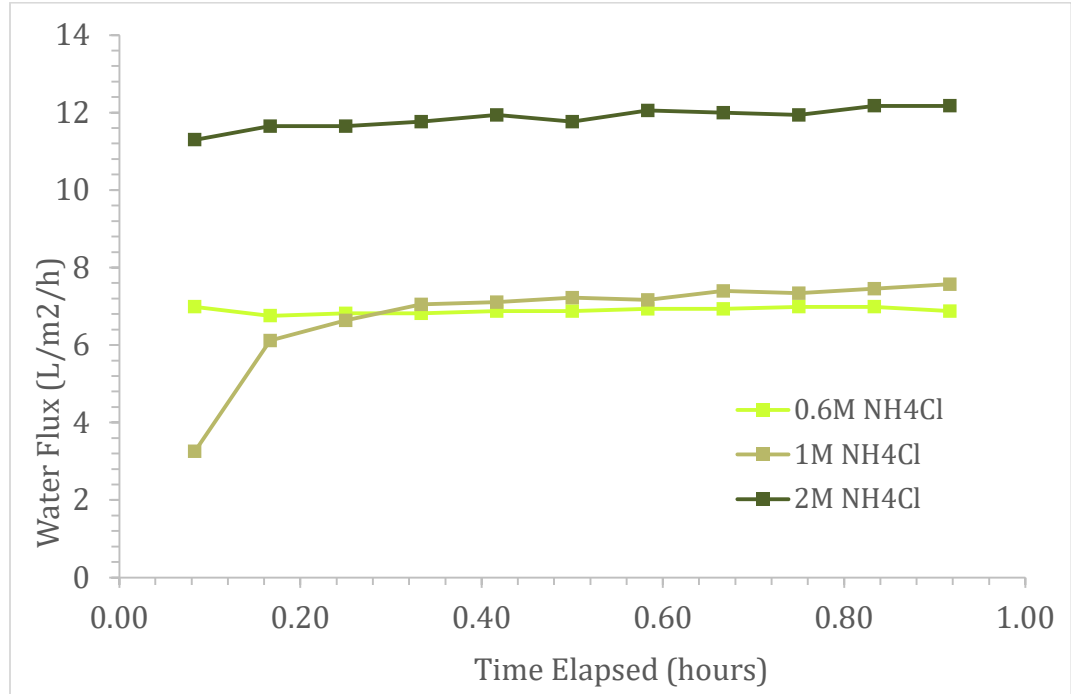


Figure 17. Comparison of the water flux trends 0.6M, 1M, and 2M of NH_4Cl draw solution with DI water feed solution.

3.3 Testing of Performance of Best Draw Solutions: Seawater Feed

The FO experiments with seawater feed were performed identically to the DI water feed FO experiments with the adjustment of a longer run time of five hours. The best draw solutions (1M NaCl, 2M KCl and 2M NH_4Cl) from DI water feed were selected for testing with seawater as feed solution. Seawater served as the feed solution as it is abundant in the state of Hawai'i and has very practical applications for desalination. FO has many uses in filtering wastewater and other industrial waste, but seawater was the determined feed solution to optimize the process of membrane-based filtration. With the growing prevalence of drought and shifting precipitation patterns desalination could alleviate the pressure of drawing from scarce freshwater sources. The more common membrane

filtration of water is reverse osmosis that is predominantly powered physically with pumps but the potential in chemically powered forward osmosis could be greater energy efficiency.

In the seawater feed experiments, the best performing concentrations of the inorganic salt solutes were used as the draw solutions and compared. The 1M and 2M NaCl, 2M KCl, and 2M NH₄Cl were tested. Of the four, KCl performed the best with the greatest overall mass difference of 94.52 grams followed by 2M NaCl with an increase of 80.86 grams then NH₄Cl at a 77.46-gram increase. The 1 M NaCl had the least performance. The mass increases of the draw solution of the 2M NaCl and 2M NH₄Cl were very similar.

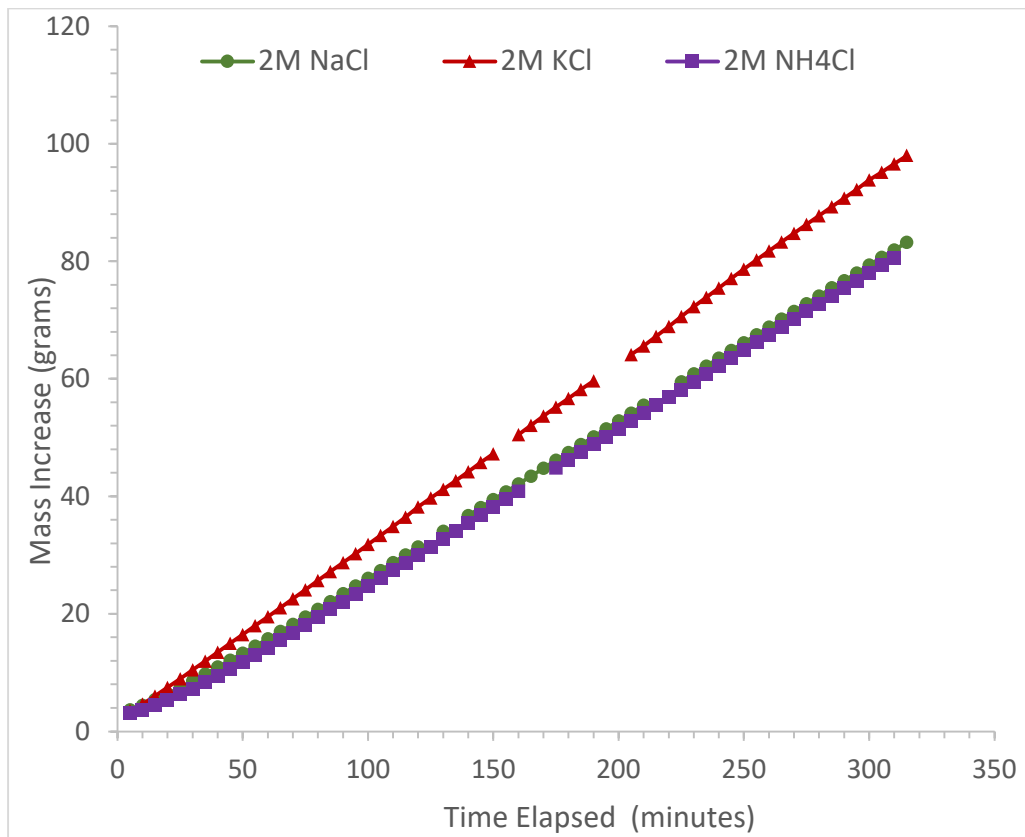


Figure 18. Comparison of weight increase of all tested draw solutes with Seawater feed.

3.3.1 Water Flux Estimation of Seawater Feed Solution Experiments

The water flux trends of the 2M NaCl and 2M NH₄Cl draw solutions for the seawater feed runs shows the flux rapidly increased initially then steadied and started to slowly decrease until the end of the experiment as seen in Figure 19. The KCl draw solution shows the same general curvature but started with a noticeably greater initial flux and had a less steady trend from about the 1.5-hour mark. The initial water flux trends (< 1 hour after start time) of the seawater experiments were not what was expected. The water flux is anticipated to be highest at start of experiment and decrease with time. The difference could be due to the possible dilution of the draw solutions by liquid already the lines. Hence flushing of the FO system lines for longer time with same draw solution is needed to further optimize the FO system.

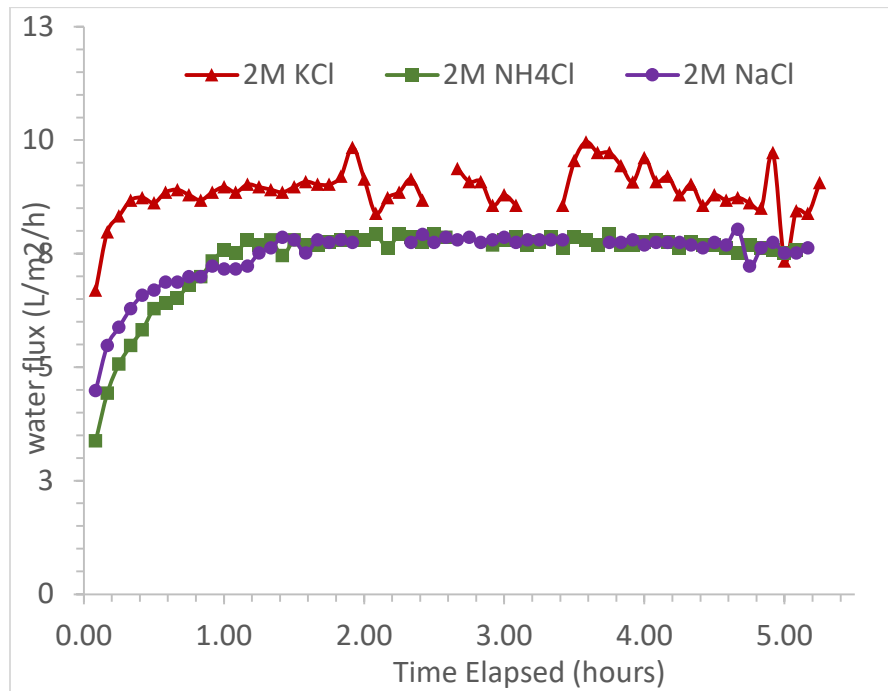


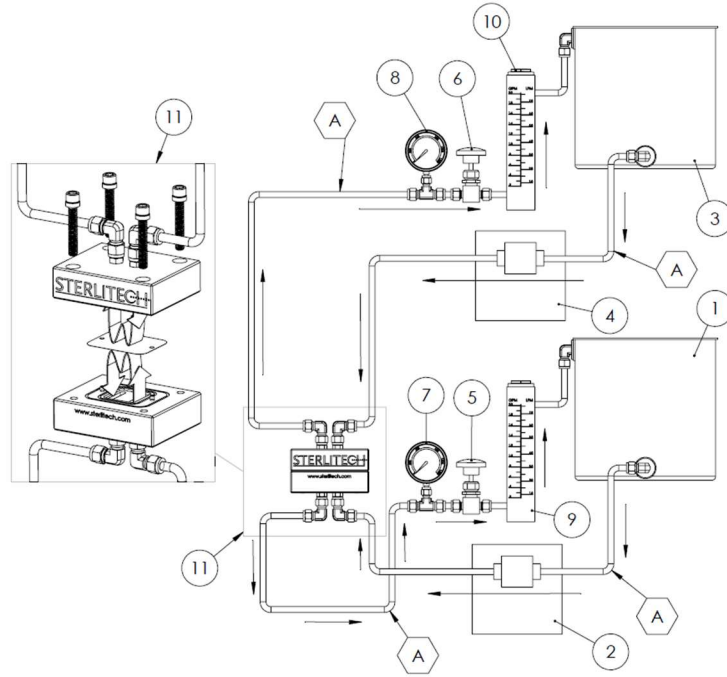
Figure 19. Comparison of the water flux trends 1M NaCl, 2M of NaCl, 2M of KCl, and 2M of NH₄Cl draw solutions with DI seawater feed solution.

4.0 CONCLUSION

A forward osmosis system was fabricated, and procedures developed for its operation. Forward osmosis draw solution performance of various concentrations (0.6M, 1M and 2M) of NaCl, KCl and NH₄Cl, with DI water and seawater feed solutions were studied using the fabricated system. The studies showed that the higher concentrations (e.g 2M draw solutions) generally perform better than the lower concentration draw solutions (e.g.0.6M). The best draw solutions for DI water feed were the 1M NaCl, 2M KCl and 2M NH₄Cl. The water flux performance of the best draw solutions were tested against the practical feed solution, seawater. The 2M KCl draw solution performed best with the seawater feed solution. Suggested improvement and future work include; (1) longer running times (up to 24 hours) for the experiments to observe the maximum mass change and the point where the water flux decrease; (2) investigating the osmotic pressure polarization near the membrane during the experimental process to minimize curvature of the water flux curves; (3) running multiple repeat experiments to determine the limitations of the FO system; (4) the automation of data collection by connecting the analytical balance to a computer for data logging with time; (5) Performing thermal regeneration of draw solution or applying the desalinated dilute draw solution, especially (KCl and NH₄Cl) in fertigation.

APPENDICES

APPENDIX 1



CF016A/ CF016SS/ CF016HAS FO FLOW DIAGRAM	
Item No.	Part Description
1	Feed Tank
2	Feed Pump
3	Draw Solution Tank
4	Draw Solution Pump
5	Concentrate Pressure Control Valve
6	Draw Solution Pressure Control Valve
7	Concentrate Pressure Gauge
8	Draw Solution Pressure Gauge
9	Concentrate Flow Meter
10	Draw Solution Flow Meter
11	CF016A-FO Cell Assembly
A	3/8" Low Pressure Tubing



Appendix 1. Flow diagram of FO system provided by the Sterlitech manufacturers.

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