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Investigating the Performance of Hydroponic Nutrient Solutions as Potential Draw Solutions for Fertilizer Drawn Forward Osmosis

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Investigating the performance of hydroponic nutrient solutions as potential draw solutions for fertilizer drawn forward osmosis

A Thesis Submitted to
Graduate Program in Sustainable Development
in partial fulfillment of the requirements for
the degree of Master of Science in Sustainable Development

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List of Abbreviations

B	Boron
C	Carbon
Ca	Calcium
CEDI	Continuous Electrodeionization
CHE	Chekli
Cl	Chlorine
Cu	Copper
DI	De-ionized
DS	Draw Solution
ECP	External Concentration Polarization
ED	Electrodialysis
FAO	Food and Agriculture Organization
FDFO	Fertilizer Drawn Forward Osmosis
Fe	Iron
FO	Forward Osmosis
FS	Feed Solution
GERD	Grand Ethiopian Renaissance Dam
H	Hydrogen
ICP	Internal Concentration Polarization
Js	Solute Flux
Jv	Water Flux
K	Potassium
MED	Multi-Effect Distillation
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
MSF	Multi-Stage-Flash Evaporation
N	Nitrogen
NF	Nano-filtration
O	Oxygen
P	Phosphorous
ppm	Parts per million
ppt	Parts per trillion
RA	Resh Anguila
Re	Salt Rejection
RF	Resh Florida/California
RO	Reverse Osmosis
ROB	Robbins
RSF	Reverse Solute Flux
RTD	Resh Tropical Dry
RTW	Resh Tropical Wet
S	Sulphur
SDG	Sustainable Development Goal
SRSF	Specific Reverse Solute Flux
TDS	Total Dissolved Solids
UN	United Nations
WEF	Water-Energy-Food
Zn	Zinc

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Abstract

This research project aims at investigating the performance of hydroponic nutrient solutions as draw solutions for desalination using the fertilizer drawn forward osmosis (FDFO) process. Six different lettuce and leafy greens hydroponic nutrient stock solutions were prepared according to the literature and used in this study and tested on a bench-scale forward osmosis unit as draw solutions for the process. The feed solutions for the process was de-ionized water mixed with Sodium Chloride in different concentrations to represent different salinities of brackish groundwater. The draw efficiency of each solution was measured based on water flux, reverse solute flux, water recovery, and salt rejection. This research project aims at reaching an efficient nutrient solution that would be economically feasible to be used in hydroponic agriculture of leafy greens, in non-arable areas which have access to brackish groundwater or seawater. By achieving this goal and developing a model for implementation, the burden that is currently being exerted on freshwater resources by inefficient agriculture in Egypt will hopefully be diminished, which would provide more drinking water. It was concluded that of the six tested nutrient solutions, the “Resh Florida, California (RF)” solution is the recommended solution to be used as draw solution for fertilizer drawn forward osmosis, due to its high performance in terms of water recovery (35.1 ml) & flux (11 $l/m^2/h$), salt rejection (92%) & specific reverse solute flux (SRSF) (highest recorded SRSF for a specific ion (SO_4^{2-}) was 7.3 g/l), as well as its low cost, relative to the other highly performing draw solution “Chekli (CHE)” ($1.07/l vs. $3.73/l). Future research endeavours could be directed at experimenting with other hydroponic nutrient solutions, experimenting with different types of membranes, testing the same solutions from this research on the pilot-scale, performing a life cycle analysis of the membrane after operation, and using the resultant draw solution from this process to grow crop hydroponically.

1. Introduction

1.1. Background

Sustainable development is a concept that was first introduced in 1987, in the World Commission on Environment and Development, which is often referred to as the "Brundtland Report" (Santillo, 2007).While sustainable development is estimated to currently have approximately three hundred definitions (Santillo, 2007), the most widely used definition is that it is "development that meets the needs of the present without compromising the ability of future generations to meet their own need" (United Nations, 2015). The core of sustainable development is the three pillar approach. The three pillars are: economic growth, social inclusion, and environmental protection, and sustainable development is only achieved when these three pillars are balanced. In order to provide a blueprint for achieving sustainable development worldwide, the United Nations created the sustainable development goals (SDGs). Sustainable Development Goals are 17 goals that are all interconnected, and are an action-oriented map (Lim, Jørgensen, and Wyborn, 2018) to achieve a "better and more sustainable future for all" (United Nations, 2015).

Water is among the most essential natural resources, and is utilized in nearly all human activities; it is necessary for domestic use, agriculture and industry, is one of the sustainers for ecosystems, and sometimes even is a hazard, such as in the cases of floods and droughts (Anandhi and Kannan, 2018). The water cycle is affected by many factors, including pollution, land use changes, population growth, climate change, urbanization, and industrial growth (Navarro-Ortega et al., 2015; Koutroulis et al., 2013). Globally, water demand is projected to increase by 55% by the year 2050 compared to 2018, mainly due to growing demands from manufacturing (increasing by about 400%), thermal electricity generation (increasing by about 140%) and domestic use (increasing by about 130%) (Shahzad, Burhan, Ang and Ng, 2018).

Water is the most essential resource for agricultural production and is very critical to food security; irrigated agriculture forms about 20% of the total cultivated land and it contributes about 40% of the total global food production (The World Bank, 2020). Agriculture is the biggest consumer of freshwater ("blue" water), where almost 90% of diverted freshwater in the world is used for irrigated agriculture (Traitler et al., 2018). This led to the introduction of the Water-Energy-Food Nexus, which is a concept that is central to sustainable development; the tangled connection between those 3 crucial domains means that managing water resources is essential for food security, while water resources are affected by climate change, which in turn, is affected by global energy usage and production.

Many societies now face the issue of water scarcity, which is a situation defined as having the water availability in a country or region be less than 1000 m^3/person/year (Pereira, Cordery and Iacovides, 2009). Almost a quarter of the human population, approximately 1.6 billion people, live under water scarcity, and this number may double in two decades (Roson and Damania, 2017). It is also projected that by 2050, more than 40% of the world's population will be living in areas of severe water stress (Shahzad et al., 2018). In figure 1, it is noticed that hundreds of millions of people around Earth cannot reliably obtain clean water, which also exposes them to waterborne diseases (Gilbert, 2012).

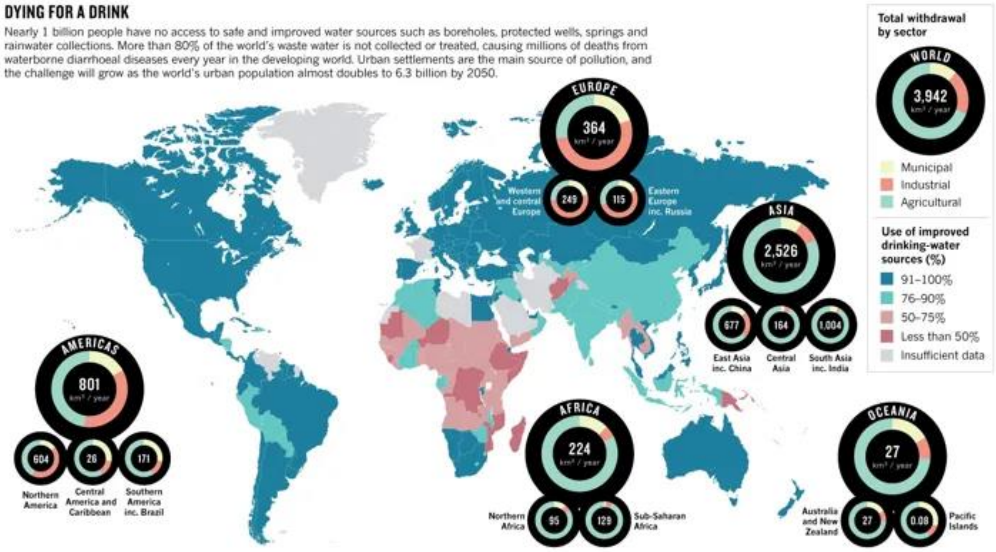


Figure 1 - Global Water Resources Usage (Gilbert, 2012)

In order to combat shortages in clean freshwater resources, more countries are resorting to desalination, as demonstrated in figure 2, where desalination widens the potential of utilisation of water resources by producing freshwater from saline or brackish natural water sources (Burns et al., 2015).

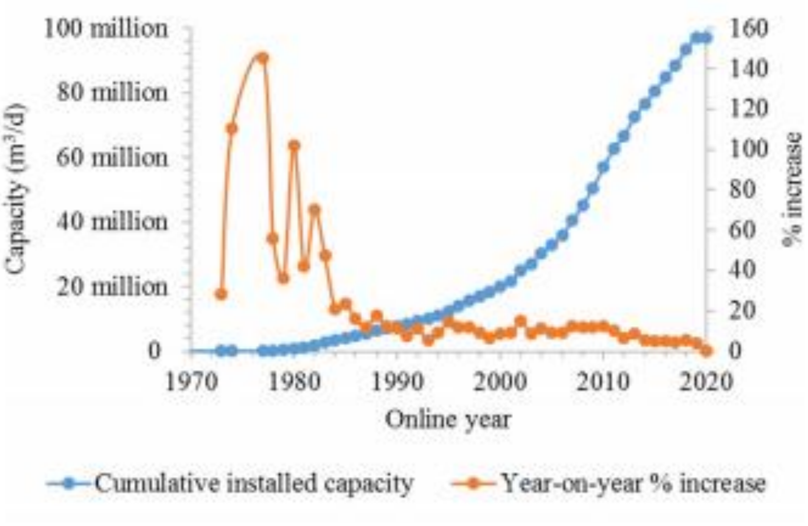


Figure 2 - Global cumulative installed desalination capacity and year-on-year increase (Eke et al., 2020)

However, commercially established desalination thermal technologies, such as Multi-Effect-Distillation (MED), and Multi-Stage-Flash Evaporation (MSF) and membrane desalination technologies, such as Reverse Osmosis (RO) and Electrodialysis (ED) are energy intensive and often require sizable capital investments (Cotruvo, 2016; Burn et al., 2015). Desalination is considered to be the most energy-intensive water treatment process, where its global consumption is 75.2 TWh/year, which is about 0.4% of the global electricity consumption (Shahzad et al., 2018). Moreover, fossil-fuel-operated desalination processes are the major source of CO_2 emissions; contributing approximately 76 million tons of CO_2/year, and is expected to grow to 218 million tons by 2040 (Shahzad et al., 2018). This means that their negative pollution effects further affect the already stressed water resources, due to climate change, which would subsequently lead to these processes being unsustainable, unless clean energy is utilized.

Hence, recent efforts have been directed at developing less energy and capital costly desalination processes, such as Forward Osmosis (FO). FO has the advantage of operating without the need for hydraulic energy, and operating at a lower pressure than RO, which decreases the capital cost (Shon, Phuntsho, Zhang and Surampalli, 2015). The disadvantages of FO are that the resultant of the process is a diluted draw solution, from which freshwater would need to be separated, which requires further processing. Moreover, membrane technologies and draw solutions are still in need of further development before FO could be commercially widespread (Phuntsho et al., 2012a; Nasr and Sewilam, 2015).

Fertilizer Drawn Forward Osmosis (FDFO) is an application of FO in which the draw solution is a highly concentrated fertilizer solution, which is diluted by drawing freshwater from the feed solution (saline or brackish water). It is a method of overcoming the inherent disadvantage of FO, in which the resultant end product is diluted draw solution, not freshwater. This diluted draw solution could hypothetically be used directly to grow agricultural crops, if it was diluted to the required concentration for agriculture. FDFO will be discussed in detail in section (2.4).

1.2. Statement of the Problem

Water resources globally are stressed, especially by agriculture, hence, the need to find alternative sources of freshwater is crucial. While desalination provides a solution for the water resources problem, commercially available desalination technologies are highly energy intensive, and could lead to further increasing the levels of global pollution if fossil fuel is utilized to power them. On the other hand, low energy desalination techniques, such as forward osmosis, could be the solution, however, further research needs to be undertaken before such techniques could achieve commercial success. The viability of commercial application of forward osmosis is dependent on draw solution selection and membrane technology. Hence, research on which draw solution is the most efficient is detrimental to mitigating the decline of water resources.

1.3. Research Significance

One of the major drawbacks of forward osmosis is the fact that the process does not yield freshwater, but instead yields a diluted draw solution which requires further processing. Hence, fertilizer drawn forward osmosis (FDFO) is one way to claim water from saltwater, while decreasing the need for further processing, which in turn decreases the energy and economic requirements of FO. However, in order to increase the efficiency of the process, researchers have to experimentally investigate which fertilizers are the most efficient at recovering water. Various fertilizers have been tested as draw solutions, such as single organic salts (Phuntsho et al., 2011; Nasr, and Sewilam, 2016), blended fertilizer salts (Phuntsho et al., 2012a; Amin, Nasr, and Sewilam, 2020), and commercial hydroponic fertilizer solutions (Chekli et al., 2017a). It has been proven that blended fertilizer solutions, such as hydroponic nutrient solutions, have higher water flux performance when used in the draw solution of forward osmosis, when compared to single fertilizer solutions, due to the higher osmotic potential of the mixture as demonstrated in the work done by Amin et al. (Amin et al., 2020).

This project investigates further using hydroponic nutrient solutions as the draw solution for forward osmosis, by comparing between different nutrient solutions. By successfully achieving that, freshwater can be recovered from saline brackish groundwater, and the diluted draw solution can be used for hydroponic agriculture. However, all hydroponic nutrient solutions differ in terms of their composition, and thusly, perform distinctively in FDFO process in terms of water flux, RSF and fouling (Chekli et al., 2017a). Therefore, the aims of this project are to build upon the work conducted by Chekli (Chekli et al., 2017a), where a single commercial nutrient solution was used as draw solution and wastewater as feed solution for FDFO, and reclaiming water using hydroponic nutrient solutions and forward osmosis was proven feasible. This project will further investigate the application, but by using brackish groundwater as the feed solution, in order to assess the viability of using these technologies for desalination. The performance will be measured based on: a. **water flux:** the volume of water per unit area per unit time that permeates through the membrane from the feed side to the draw side, b. **reverse solute flux:** the volume of draw solute per unit area per unit time that permeates through the membrane from the draw side to the feed side, c. **salt rejection**: the percentage of feed solutes that permeates from the feed side to the draw side.

1.4. Research Questions

- Is there a significant variability in the performance of different lettuce and leafy greens hydroponic nutrient solutions, when used as draw solutions for desalination of brackish groundwater through forward osmosis?
- Is it feasible to utilize forward osmosis as an alternative source of water for dilution of hydroponic nutrient stock solutions through desalination?

1.5. Hypothesis

There is significant variability in draw efficiency among hydroponic nutrient solutions when used as draw solutions for Forward Osmosis, using brackish groundwater as a feed solution for the process.

1.6. Specific Aims

1. Investigate which of the selected formulae of hydroponic nutrient solutions for lettuce and leafy greens is the most efficient draw solution for forward osmosis desalination of brackish groundwater. Efficiency will be judged based on water flux, reverse solute flux, water recovery, salt rejection, and the cost of each solution.
2. Propose a model for hydroponic agriculture of lettuce and leafy greens in non-arable areas with limited access to freshwater and an abundance of brackish groundwater in Egypt.

1.7. Objectives

- Build upon the work carried out by Laura Chekli (Chekli et al., 2017) to investigate the viability of hydroponic nutrient solutions as draw solutions for fertilizer drawn forward osmosis.
- Provide a method of utilizing Egypt's abundant brackish groundwater, which provides an alternative source for agricultural water, which in turn, would provide more water for other sectors.
- The proposed model of hydroponic agriculture using brackish groundwater in non-arable areas would provide Egypt with a solution for the rapid decrease of agricultural land.

1.8. Scope of the Study

This project mainly focuses on using brackish groundwater and hydroponic nutrient solutions as FS and DS, respectively, for fertilizer drawn forward osmosis (FDFO). Six hydroponic solutions and three concentrations of brackish groundwater were investigated, Moreover, the experiments were run on the bench scale scope.

1.9. Limitations of the Study

The selected hydroponic nutrient solutions are not the only formulae available; there are hundreds of different formulae. Results are only limited to bench scale; a larger scale, such as pilot scale or industrial scale, might yield different results. Moreover, the actual performance of each solution as a nutrient solution for hydroponic agriculture was not tested. Finally, the brackish groundwater used in this study is not a real groundwater sample.

2. Literature Review

2.1. Water Scarcity in Egypt

Egypt is among the countries dealing with severe water scarcity, with water resources measured at around 670 m^3/capita/year in 2016 (Abdel-Shafy and Kamel, 2016). This could be attributed to an unevenness in the distribution of water resources, misuse of water and highly inefficient irrigation methods (Dakkak, 2017). In 2017, 79.16% of Egypt's total water withdrawal was used by the agricultural sector (FAO, 2017). Moreover, it is estimated that building and operating the Grand Ethiopian Renaissance Dam (GERD), a 170-m tall dam, would cause Egypt's annual Nile water share to decrease by an approximate 18.7% (Nashed, Sproul, and Leslie, 2014). It is also projected that during GERD filling, the food production could decrease by 9% to 19%, and hydropower generation could decrease by 3% to 9%, depending on the fill rate (Elsayed et al., 2020). During the GERD operation, food production would be reduced by 4%, and hydropower generation by 7%, when compared to a case where the GERD did not exist (Elsayed et al., 2020) Hence, researchers have been studying and experimenting with novel sources of freshwater, such as desalination, in order to mitigate the decline in water resources.

2.2. Groundwater in Egypt

It is believed that water will soon be the oil equivalent of the twenty-first century (Aly, 2015), and hence, developing countries such as Egypt have to successfully manage their water resources, in order to guarantee a sustainable economic and social growth. Fresh groundwater resources represent 20% of the total potential water resources in Egypt (Allam, Saaf, and Dawoud, 2003), and they can be classified into two main categories: renewable groundwater resources, which are located in the Nile valley and Delta areas, and nonrenewable groundwater resources, which are located in the Nubian Sandstone Aquifer in the Western Desert (Abdel-Shafy and Kamel, 2016). Figure 3 demonstrates the aquifers that Egypt has access to.

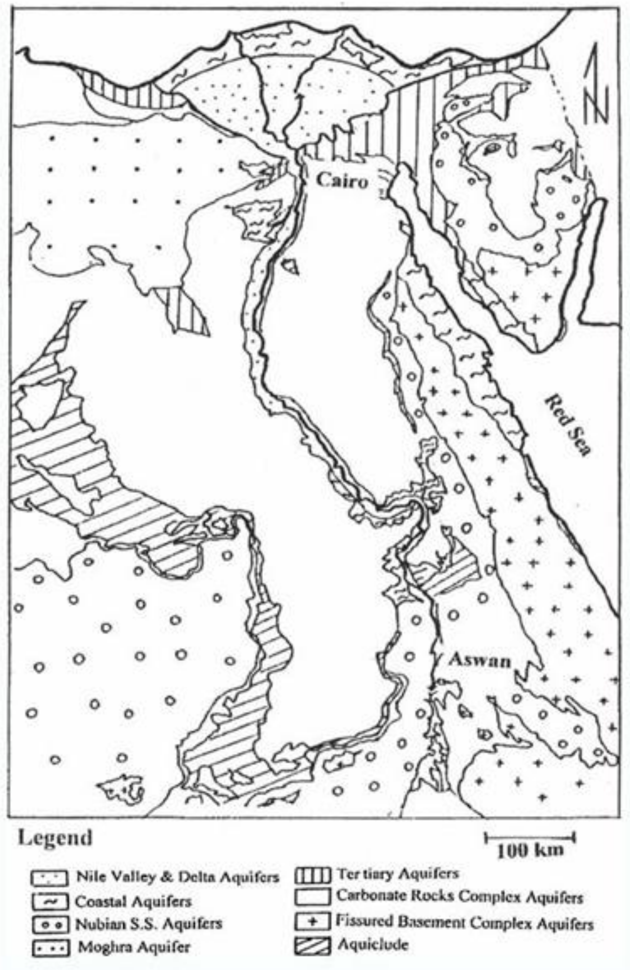
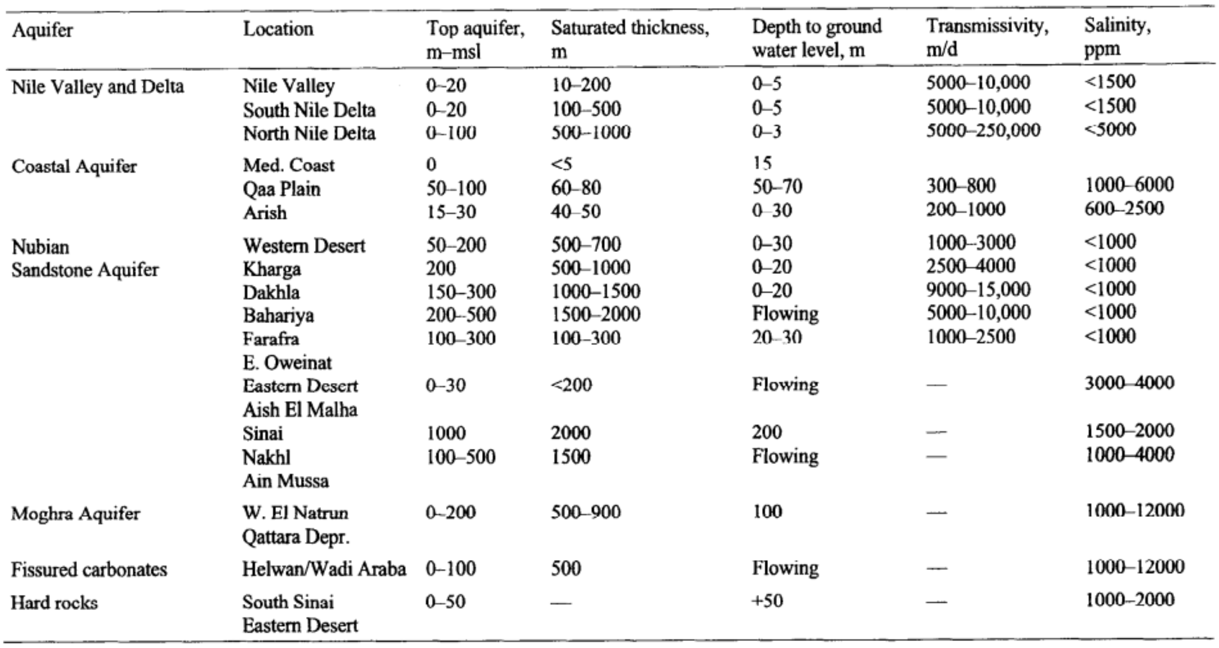


Figure 3 – Hydrogeological Map of Egypt (Tahlawi et al., 2008)

The capacity of the renewable groundwater resources is estimated at 200 billion m^3 and the water is at an average of 800 ppm salinity for the Nile Valley Aquifer system and at 300 billion m^3 for the Delta Aquifer (Allam et al., 2003). Abdel-Shafy and Kamel (2016) state that the major sources of renewal for those aquifers are "rainwater seepage, irrigation water, sanitary drainage water and industrial effluents" (Abdel-Shafy and Kamel, 2016). This means that the quality of the groundwater is highly affected by the activities and the type of water that feeds the groundwater reservoirs (Abdel-Shafy and Kamel, 2016). According to Allam (2003), the majority of the non-renewable groundwater resources is located in the Nubian Sandstone Aquifer in the Western Desert, and it is deep seated (Allam et al., 2003). Shown in table 1 are the aquifers in Egypt and their characteristics.

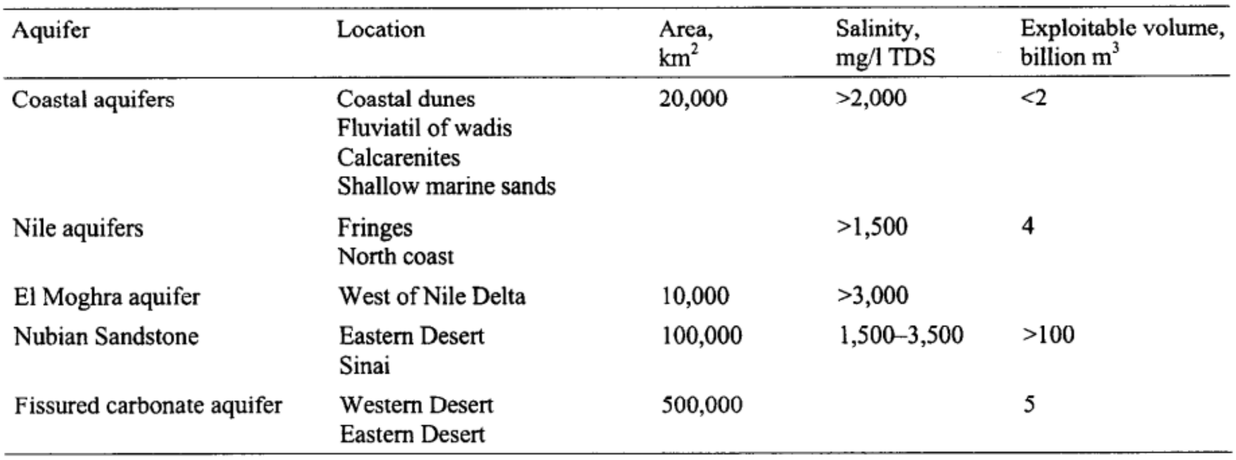
Table 1 - Hydrogeological Characteristics of Main Aquifers (Allam et al., 2003)



Aquifer	Location	Top aquifer, m–msl	Saturated thickness, m	Depth to ground water level, m	Transmissivity, m/d	Salinity, ppm
Nile Valley and Delta	Nile Valley	0–20	10–200	0–5	5000–10,000	<1500
	South Nile Delta	0–20	100–500	0–5	5000–10,000	<1500
	North Nile Delta	0–100	500–1000	0–3	5000–250,000	<5000
Coastal Aquifer	Med. Coast	0	<5	15		
	Qaa Plain	50–100	60–80	50–70	300–800	1000–6000
	Arish	15–30	40–50	0–30	200–1000	600–2500
Nubian Sandstone Aquifer	Western Desert	50–200	500–700	0–30	1000–3000	<1000
	Kharga	200	500–1000	0–20	2500–4000	<1000
	Dakhla	150–300	1000–1500	0–20	9000–15,000	<1000
	Bahariya	200–500	1500–2000	Flowing	5000–10,000	<1000
	Farafra	100–300	100–300	20–30	1000–2500	<1000
	E. Oweinat					
	Eastern Desert	0–30	<200	Flowing	—	3000–4000
	Aish El Malha					
	Sinai	1000	2000	200	—	1500–2000
	Nakhl	100–500	1500	Flowing	—	1000–4000
	Ain Mussa					
Moghra Aquifer	W. El Natrun	0–200	500–900	100	—	1000–12000
	Qattara Depr.					
Fissured carbonates	Helwan/Wadi Araba	0–100	500	Flowing	—	1000–12000
Hard rocks	South Sinai	0–50	—	+50	—	1000–2000
	Eastern Desert					

In Egypt, the salinity of the groundwater ranges between 200 and 12,000 ppm, and all the major aquifers contain vast amounts of brackish groundwater (Abdel-Shafy and Kamel, 2016). Table 2 demonstrates the volume and salinity of usable brackish groundwater in Egypt.

Table 2 - Exploitable Volumes of Brackish Groundwater (Allam et al., 2003)



Aquifer	Location	Area, km^2	Salinity, mg/l TDS	Exploitable volume, billion m^3
Coastal aquifers	Coastal dunes Fluviatil of wadis Calcarenites Shallow marine sands	20,000	>2,000	<2
Nile aquifers	Fringes North coast		>1,500	4
El Moghra aquifer	West of Nile Delta	10,000	>3,000	
Nubian Sandstone	Eastern Desert Sinai	100,000	1,500–3,500	>100
Fissured carbonate aquifer	Western Desert Eastern Desert	500,000		5

2.3. Water Desalination

Almost 97% of Earth's water is seawater, and 80% of the remaining water resources is trapped as snow, which means that only 0.5% of Earth's water is available for direct use (Kucera, 2014). Hence, applications of desalination have become extremely crucial, especially in recent years, where factors such as population growth, food security issues, climate change, overuse of freshwater resources, and land degradation (Burn et al., 2015) are threatening Earth's water resources. Desalination processes can be categorized into two main categories:

1. Thermal desalination processes, which involve multistep distillation methods (Cotruvo, 2016), such as:
    a. Multiple-Effect Distillation (MED).
    b. Multi-Stage-Flash Evaporation (MSF).
    c. Multiple-Effect Distillation with Thermally Driven Vapour Compression (MED-TVC) (Kucera, 2014).
2. Membrane desalination processes, which involve the pressurized passage of water through a semipermeable membrane (Cotruvo, 2016), such as:
    a. Reverse Osmosis (RO)
    b. Nanofiltration (NF)
    c. Forward Osmosis (FO)
    d. Electrodialysis (ED) (Cotruvo, 2016)
    e. Continuous Electrodeionization (CEDI) (Kucera, 2014).

Thermal desalination processes are generally characterized by high costs and being energy intensive, hence, new facilities have been designed to utilize more membrane desalination processes (Cotruvo, 2016). On the other hand, membrane desalination technologies have started to gain momentum as the preferred desalination technology in the past few decades, due to advancements in membrane technologies. The commercially established membrane desalination technologies are Reverse Osmosis (RO), Nanofiltration (NF), and Electrodialysis (ED) (Burn et al., 2015).

2.3.1. Thermal Desalination

2.3.1.1. Multiple-Effect Distillation (MED)

MED desalination plants consist of variable sequence of stages, usually between 5 and 10. The conventional MED effect is depicted in figure 4 below. Cold brine enters the effect from the top and falls on the surface of the tubes, where the brine film absorbs the condensation enthalpy of the vapour flowing inside, and part of it evaporates (Nannarone, Toro and Sciubba, 2017). The vapour produced is then filtered by a demister (Nannarone, Toro and Sciubba, 2017). The remaining brine, along with the droplets that were separated in the demister, continuously fall down to the brine pool, where it is collected and exits the effect (Nannarone, Toro and Sciubba, 2017).

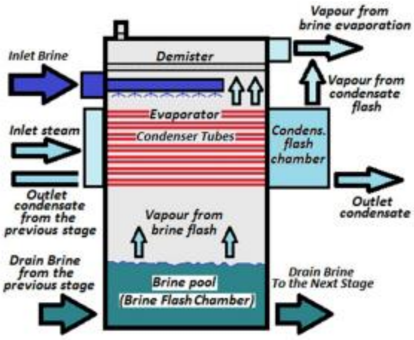


Figure 4 - Scheme of an MED Effect (Nannarone, Toro and Sciubba, 2017)

2.3.1.2. Multi-Stage-Flash Evaporation (MSF)

In MSF desalination plants, demonstrated in figure 5, seawater enters a sequence of saturated stages, in which the pressure is lower due to a throttle (Warsinger et al., 2015). This decline in pressure, known as flash, causes the water to evaporate (Warsinger et al., 2015). In order to cause the vapor to condensate and the feed to be preheated, a counter-current heat exchanger is utilized to transfer the heat from the flashed water vapor to the inlet seawater (Warsinger et al., 2015). Moreover, additional heat is provided by a heater to the hot feed before the first and hottest stage, and a regenerator after the coldest stage exchanges heat between the exiting and entering streams (Warsinger et al., 2015).

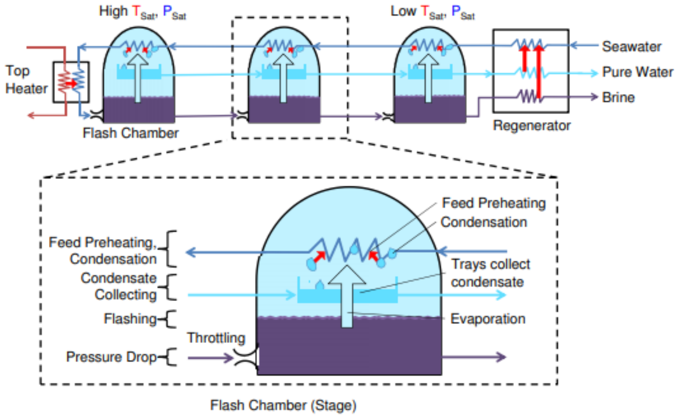


Figure 5 - Scheme of once-through MSF desalination (Warsinger et al., 2015)

2.3.2. Membrane Desalination

2.3.2.1. Electrodialysis (ED)

ED, demonstrated in figure 6, is a process that is driven by electricity in which an ED unit typically consists of a chain of ion-selective anion and cation exchange membranes (Campione et al., 2018). The exchange membranes are interleaved with alternating concentrate and dilute solution compartments and end at both sides with an electrode compartment (Campione et al., 2018). When the electrodes are connected to a power source, the electrical current flows through the ED stack, which causes electrically charged solutes to move according to the electric field (Campione et al., 2018).

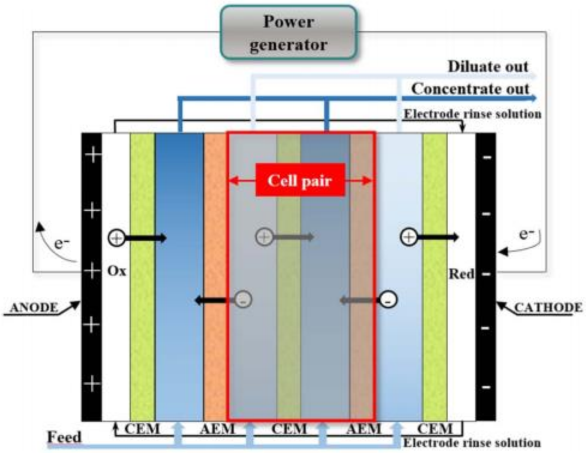


Figure 6 - Scheme of an electrodialysis system (Campione et al., 2018)

2.3.2.2. Nanofiltration (NF)

Nanofiltration (NF) is a membrane desalination technology that is driven by pressure, and is between ultrafiltration and reverse osmosis in terms of its rejection of molecular or ionic species (Nagy, 2012). An ultrafiltration membrane has a pore size of around 0.01 micron, nanofiltration membrane has a pore size of around 0.001 micron, while a reverse osmosis membrane has a pore size of around 0.0001 micron (Safewater, 2017). Nanofiltration membranes are characterised by the both a very high rejection for multivalent ions (>99%), low to moderate rejection for monovalent ions (<=about 70%), and a high rejection (>90%) of organic compounds that possess molecular weight greater than the molecular weight of the membrane (Nagy, 2012).

2.3.2.3. Reverse Osmosis (RO)

Reverse Osmosis (RO), shown in figure 7, is a desalination technology that uses a membrane to remove salt ions, large molecules, bacteria and disease-causing pathogens from sea water by adding a pressure to the water on the feed side of the semi-permeable membrane, which causes the salt to remain on the concentrated side of the membrane and pure water passes to the other side (Burn and Gray, 2015). Reverse Osmosis is energy intensive, where the main energy consumption is in the need to pump the feed water at a high pressure condition (Wenten and Khoiruddin, 2016), where seawater has an osmotic pressure of 27 bar, so hydraulic pressure must exceed that (Shon, Phuntsho, Zhang, and Surampalli, 2015). Other shortcomings of Reverse Osmosis are that the membrane could allow the passage of neutrally charged compounds such as boron, requiring further treatment, and RO removes all the salts that naturally are present in water, making it inappropriate to drink, and requiring the addition of the minerals back to the water (Burn and Gray, 2015). Moreover, RO is capital intensive, and faces problems with membrane fouling and biofouling (Shon et al., 2015).

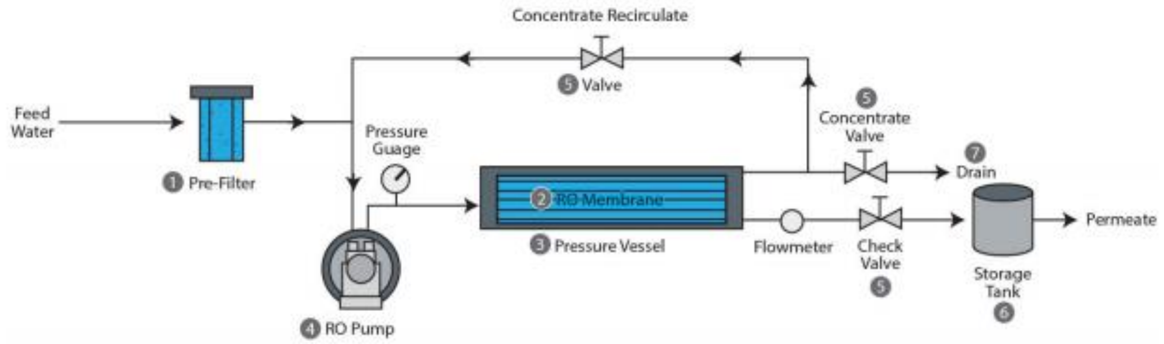


Figure 7 - Schematic Diagram of Reverse Osmosis (Stoughton et al., 2013)

2.3.2.4. Forward Osmosis (FO)

Osmosis is the resultant movement caused by a variation of osmotic pressure of water across a membrane that is selectively permeable, where it allows the passage of water molecules, but rejects solute molecules or ions (Cath, Childress, and Elimelech, 2006). The Forward Osmosis (FO) process, demonstrated in figure 8, is a manufactured osmotic process, where a synthetically high concentrated solution, called the draw solution (DS), is utilized on one side of the semi-permeable membrane, and on the opposite side of the membrane is the water that is desired to be treated (Shon et al., 2015), called the feed solution (FS). FO utilizes the naturally occurring osmotically induced water transport across a semi-permeable membrane, from a solution of low osmotic pressure to one of higher osmotic pressure (Chung et al., 2015). In an ideal situation, the semi-permeable membrane allows water to pass through it, while rejecting all salts or unwanted elements (Chung et al., 2015). Forward Osmosis is also sometimes referred to as Manipulated Osmosis (Johnson, Suweilah, Mohammed, and Hilal, 2018).

Most FO membranes are manufactured by traditional phase inversion (Chung et al., 2012, ac cited in Chung et al., 2015) and thin-film-composites (TFC) via interfacial polymerization methods (Yip et al., 2010; Wang et al., 2010, ac cited in Chung et al., 2015). FO membranes that are fabricated from the layer-by-layer method have been studied, and their reverse salt fluxes tend to be high (Qiu et al., 2011; Cui et al., 2013). The utilization of hydrophilic materials as substrates in the manufacture of FO membranes is essential to achieved an enhanced water flux (Widjojo et al., 2011; Ong et al., 2015). More recently, TFC FO membranes fabricated on nano-fiber (Huang et al., 2014) and multi-bore (Luo et al., 2014) substrates have demonstrated good mechanical properties (Chung et al., 2015). Future R&D efforts in membrane technologies are directed at further developing membranes with minimal fouling and concentration polarization.

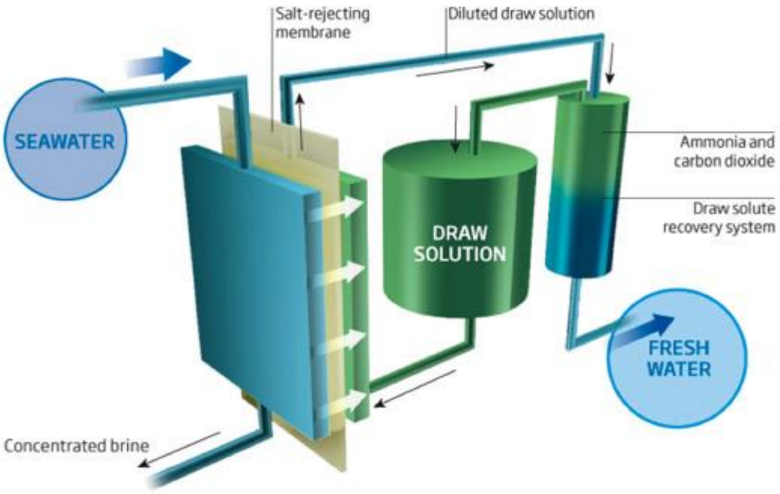


Figure 8 - Schematic Diagram of Forward Osmosis (Mandell and McGinniss, 2011)

When comparing FO to RO, it is found that FO has many advantages over RO (Shon et al., 2015), which are:

1. FO functions without needing any hydraulic energy, decreasing the energy consumption.
2. FO functions at low pressure, which decreases the capital needed for pumps and connections, decreasing the overall capital cost.
3. Fouling issues are less prevalent in FO than in RO, because in FO fouling can be reversed physically, which decreases the need for costly chemical cleaning.
4. While RO technology has evolved to significantly improve its energy efficiency, it is believed that any further attempt to decrease its energy consumption would lead to an increase in the total cost of water (Shon et al., 2015).

The main disadvantage of FO is that removing the diluted draw solutes from the desalted water in order to recover and regenerate them is not a simple task, where it requires extra processing, hence requiring extra energy that makes this separation only feasible from an economic point of view if low grade heat can be obtained from sources such as waste heat from thermal power plant (Phuntsho et al., 2012a). Other challenges facing the widespread application of Forward Osmosis technology include concentration polarization, membrane fouling, reverse solute diffusion, and need for membrane and draw solution development (Nasr and Sewilam, 2015).

2.3.2.4.1. Potential FO Applications and their Positive Sustainability Impacts

Hoover et al. (Hoover et al., 2011) highlight some possible applications of forward osmosis by coupling them with other desalination processes, and their positive environmental and economic impacts, in relation to water, energy, and waste reuse.

2.3.2.4.1.1. Diluting RO Desalination Plants Input Stream

By diluting the input seawater stream for RO using FO, we can guarantee significantly decreasing the amount of energy needed to desalinate the diluted seawater, when compared to the full salinity seawater (Hoover et al., 2011). This is due to the fact that dilution decreases the osmotic pressure of the solution, which is the main force that has to be overcome by an applied hydraulic pressure in RO (Cath et al., 2010; Bamaga et al., 2011). This can be demonstrated in the difference in energy usages between desalting seawater and brackish water with RO. The energy usage of an RO desalination plants ranges from 3 to 7 kWh/m^3 of seawater, and from 0.5 to 3 kWh/m^3 of brackish water (National Research Council (US), 2008). Ideally, the feed solution for the dilutive FO would be a source with almost no alternative use, such as wastewater or other impaired sources of water (Cath et al., 2010), while the DS for FO would be seawater.

This application has many positive impacts on the sustainability and Water-Energy nexus; which can be summarised as follows (Hoover et al., 2011):

- **Water:** Increases the pool of available water resources, by utilizing water that has little to not alternative use.
- **Energy:** Reduces RO operating pressure, by diluting the inlet feed of seawater, which decrease its osmotic pressure.
- **Waste Utilization:** Reclaims potable water from impaired water sources (Hoover et al., 2011).

2.3.2.4.1.2. Diluting Desalination Plants Brine

One of the primary environmental issues with desalination is the disparity between the discharged brine and the natural body of water in which the brine is discharged in terms of salinity and temperature (Hoover at al., 2011). This issue is inherent to both thermal and membrane desalination processes; they both necessitate the return of a more concentrated feedwater back to the environment, which would also have an elevated temperature in the case of thermal desalination processes (Hoover et al., 2011). While aquatic organisms are often able to adapt to minor variations in salinity and temperature, major and continuous changes are devastative to species populations at many different levels of an ecosystem (Lattemann, and Hopner, 2008). This issue can be mitigated by osmotic dilution of the brine using forward osmosis. By utilizing the brine as DS for forward osmosis, and picking an FS of lower salinity, the brine can be diluted to a lower salinity, making it safer to discharge into the environment. Moreover, this process can be utilized to save energy for another process, by utilizing a feed solution that needs to be concentrated, such as anaerobic digester centrate (Cath et al., 2006; Holloway et al., 2007).

Diluting the brine of desalination processes by using FO has many environmental benefits that can be summarised as follows (Hoover et al., 2011):

- **Energy:** Provides low-energy concentration for a partner process through the concentration of the feed solution.
- **Waste Utilization:** Provides a useful use of impaired water (brine).
- **Environmental Protection:** Dilutes the brine and helps its dispersion, which reduces the harm to marine life (Hoover et al., 2011).

2.3.2.4.1.3. Osmotic Cleaning of Fouled RO membranes

During the operation of an RO plant, biological and chemical foulants build up on the surface of the membrane over time, and this layer of foulant increases resistance to the mass transfer across the membrane, which causes both water flux and efficiency of the desalination plant to decrease (Hoover et al., 2011). This effect is often reversed by using harsh chemicals such as metal chelating agents (e.g. EDTA), detergents (e.g. SDS), biocides, acids and bases, or scale inhibitors (Hoover et al., 2011). Antiscalants, which are utilized in both thermal & membrane desalination plants, can cause eutrophication in the discharge environment (Lattemann, and Hopner, 2008). Moreover, discharging solutions of extreme pH, detergents, and oxidants can disrupt the balance of aquatic ecosystems (Hoover et al., 2011). Osmotic backwashing of RO membranes through FO can help decrease the utilization and disposal of cleaning chemicals for fouled membranes. This can be achieved by reversing the direction of water permeation from a hydraulic pressure gradient, which is the acting force in reverse osmosis, to an osmotic pressure gradient, which is the acting force in forward osmosis. Experimental investigations and modeling of the process have concluded that fast and effective removal of membrane foulants can be achieved with osmotic backwashing (Ramon et al., 2010; Qin et al., 2010; Sagiv, and Semiat, 2005).

Osmotic backwashing of RO membranes has the following positive impacts on the environment (Hoover et al., 2011):

- **Energy:** Reduces the operating pressure of RO.
- **Environmental Protection:** Replaces the need to use hazardous cleaning chemicals, which have a negative effect on the ecosystem they are discharged in (Hoover et al., 2011).

2.3.2.4.1.4. Cultivating and Broth Dewatering for Production of Algae Biofuels

Although biofuels are considered by many to be the most promising source of sustainable energy (Demirbas, 2009), the cultivation of biofuel crops by using arable lands and deforestation could disturb the global food supply negatively, and instead increase GHG emissions (Johansson, and Azar, 2007). However, algae are another source of biofuel that does not necessitate the usage of soil that is fertile, and can be grown using wastewater, which is often full of nutrients but is outlawed to be used in irrigating food crops (Hoover et al., 2011). Hence, producing biofuel from algae decreases the competition over the valuable resource of arable land (Aaronson, and Dubinsky, 1982; Pienkos, and Darzins, 2009). This also allows the utilization of an impaired source of water (wastewater) (Clarens et al., 2010; Wiley et al., 2011).

A system known as “OMEGA: Offshore Membrane Enclosure for Growing Algae” was proposed by the Ames Research Center of the National Aeronautics and Space Administration (NASA) for feasible production of biofuels from algae. This system optimizes the growing and harvesting of microalgae while also cleaning wastewater (Hoover et al., 2011), and could potentially mitigate several of the issues of algae cultivation on land by providing a low energy and impact engineering solution (Aaronson, and Dubinsky, 1982; Pienkos and Darzins; Wiley et al., 2011; Miao, and Wu, 2006). OMEGAs consist of transparent plastic containers with water-selective membranes that are integrated into its sides; these containers are filled with the municipal wastewater that is rich in nutrients and seeded with algae that grow and produce lipids (Trent et al., 2010; Trent, 2009). These plastic containers are then deployed in highly saline aquatic environments, where the water provides both the structural support through floatation and the temperature control (Trent et al., 2010,), and mixing through the wave action (Hoover et al., 2011). This way, OMEGAs can have an unlimited source of draw solution in the form of seawater, in order to concentrate the algae broth, which is a cost and energy intensive process (Trent et al., 2010; Trent, 2009). The membranes which are part of the containers allow the sunlight to be accessible by the algae, as well as allow exchanging CO_2 and O_2 (Trent et al., 2010), and the dense selective layer of the membrane stops the wastewater contaminants from leaking (Hoover et al., 2011). It was found that during the period of algae incubation of 10-20 days, the water content of the algae culture was decreased by more than 75% through forward osmosis (Trent, 2009). However, some challenges still face the OMEGA application, which is present in the fouling and scaling of the support layer of the FO membrane, and also the membranes need to withstand the pounding forces of the waves and cold temperatures (Zou et al., 2011; Howell, 2009; NASA-NAVY, 2010).

This application has the following positive impacts on the water-energy nexus (Hoover et al., 2011):

- **Water:** Reduces the amount of freshwater used in cultivation of algae for biofuel production.
- **Energy:** Aids in producing fuel sources, and decreases the energy needed to concentrate algae broth.
- **Environmental Protection:** Bolsters the production of alternative fuels, while also avoiding stressing arable lands (Hoover et al., 2011).

2.3.2.4.1.5. Using Brackish Water for Irrigation of Crops with Fertilizer

This is an application that is often referred to as fertilizer drawn forward osmosis (FDFO), and is discussed in detail in the following section (2.4).

2.4. Fertilizer Drawn Forward Osmosis

FO does not always require separation of the draw solutes; if a draw solute is utilized in a way that adds value to the extracted water, the diluted draw solution could be used as it is (Hoover, Phillip, Tiraferri, Yip, and Elimelech, 2011). One such application to mitigate the need for further processing after FO is Fertilizer Drawn Forward Osmosis (FDFO), demonstrated in figure 9; by using fertilizers as draw solutes, the diluted draw solution after desalination can be used directly for fertigation, without the need to separate and recover the draw solutes (Phuntsho et al., 2012a). This method leads to significantly decreasing the energy cost of implementing FO technology, by bypassing the need for removal of the draw solutes from the diluted draw solution (Hoover et al., 2011). Moreover, by choosing the feed solution of forward osmosis to be brackish groundwater, which is often an unutilized resource, this replaces/supplements the need for freshwater resources for agriculture (Moody, and Kessler, 1976; Bar-Yosef, 1999). While studies on FDFO have proven that most fertilizers are suitable to be used as draw solutes in FO, the final nutrient concentration was found to be limited by the osmotic equilibrium between the feed and draw solutions, and the final concentration was often found to not meet the standards for irrigation (Chekli et al., 2017b).

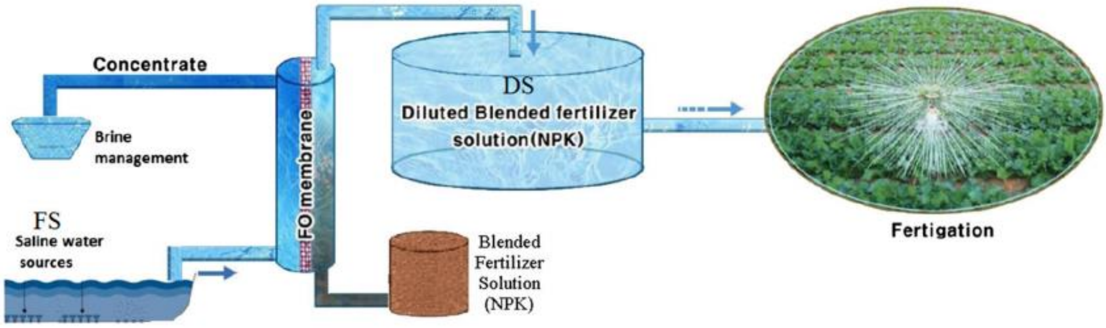


Figure 9 - Standard FDFO Setup (Phuntsho et al., 2012b)

2.5. Hydroponic Agriculture

Another possible application for FDFO is hydroponic agriculture, demonstrated in figure 10. Hydroponics is defined as the "*practice of growing plants without using soil, either by using an inert medium, such as gravel, sand, peat, vermiculite, pumice, perlite, coco coir, sawdust, rice hulls, or other substrates, to which a nutrient solution that contains all the essential elements needed by the plant is provided*" (Resh, 2012). Hydroponic systems are divided into liquid systems, which have no supporting medium for the plant, and aggregate systems, which have a solid medium for support (Jensen, 1997).

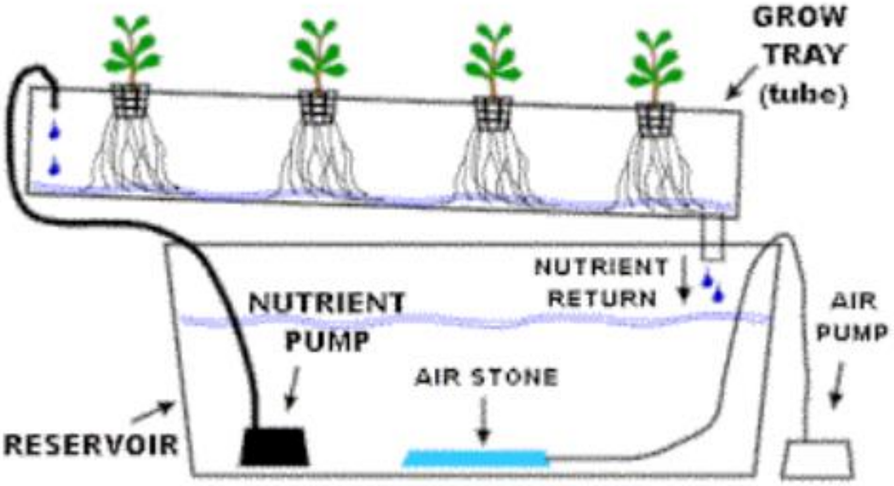
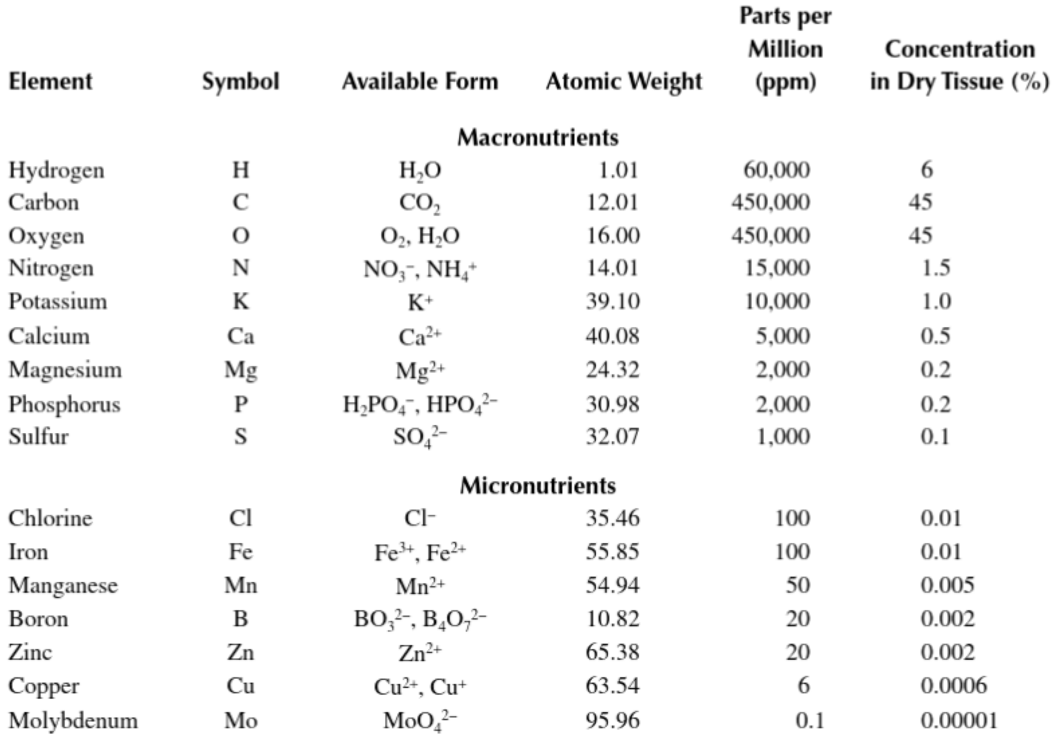


Figure 10 - Schematic Diagram of Hydroponic System (Simplyhydro, 2019)

2.5.1. Hydroponic Nutrient Solutions

In order to supply the plants with the essential elements in hydroponics, fertilizer salts are dissolved in water to form hydroponic nutrient solutions (Resh, 2012) and many researchers have developed basic formulae for nutrient solutions, such as Hoagland, Arnon, Robbins, Hewitt, Cooper, Steiner, Bollard, Middleton, Shive, and Tollens. These nutrient solutions are often referred to as standard nutrient solutions. While there is a plethora of fertilizer salts that can be used in the nutrient solutions, the choice of salts is affected by their solubility. Solubility is defined as a “measure of the concentration of the salts that remains in solution when dissolved in water” (Resh, 2012). Solubility is an important factor to consider when choosing fertilizer salts for hydroponic nutrient solutions, since hydroponics require that fertilizer salts have high solubility in order to remain in solution and be available to be absorbed by the plants (Resh, 2012). It is well established that the external concentration of each of the nutrients that is required to satisfy the internal demands of plants vary between different species; there cannot be a single nutrient solution that is effective under all circumstances (Smith, Johnston, and Cornforth, 1983). Sixteen elements have been identified as detrimental for the growth of higher plants, and they are categorised into macronutrients, nutrients required in relatively large quantities, and micronutrients, nutrients required in smaller quantities (Resh, 2012). These elements are shown in table 3

Table 3 - Essential Elements for Most Higher Plants (Resh, 2012)



Element	Symbol	Available Form	Atomic Weight	Parts per Million (ppm)	Concentration in Dry Tissue (%)
		Macronutrients			
Hydrogen	H	H_2O	1.01	60,000	6
Carbon	C	CO_2	12.01	450,000	45
Oxygen	O	O_2, H_2O	16.00	450,000	45
Nitrogen	N	NO_3^-, NH_4^+	14.01	15,000	1.5
Potassium	K	K^+	39.10	10,000	1.0
Calcium	Ca	Ca^{2+}	40.08	5,000	0.5
Magnesium	Mg	Mg^{2+}	24.32	2,000	0.2
Phosphorus	P	$H_2PO_4^-$, HPO_4^{2-}	30.98	2,000	0.2
Sulfur	S	SO_4^{2-}	32.07	1,000	0.1
		Micronutrients			
Chlorine	Cl	Cl^-	35.46	100	0.01
Iron	Fe	Fe^{3+}, Fe^{2+}	55.85	100	0.01
Manganese	Mn	Mn^{2+}	54.94	50	0.005
Boron	B	BO_3^{2-}, $B_4O_7^{2-}$	10.82	20	0.002
Zinc	Zn	Zn^{2+}	65.38	20	0.002
Copper	Cu	Cu^{2+}, Cu^+	63.54	6	0.0006
Molybdenum	Mo	MoO_4^{2-}	95.96	0.1	0.00001

3. Theory

3.1. Forward Osmosis

3.1.1. Flux

When a feed solution of a low osmotic pressure is separated from a draw solution of high osmotic pressure by a semi-permeable membrane, the concentration of the draw solution decreases and the concentration of the feed solution increases due to the solvent transfer caused by the difference in osmotic pressure ($\Delta\pi$) (Shon et al., 2015), where osmotic pressure (π) can be defined as “the amount of pressure that is required to prevent the transport of pure water through an ideal semi-permeable membrane into a specific solution” (Mulder, 1996, as cited in Shon et al., 2015).

The model that is commonly used to describe mass transfer through an FO membrane is the solution-diffusion model; in an FO process, the water flux ($\boldsymbol{J}_v$) and solute flux ($\boldsymbol{J}_s$) can be calculated by (Lee et al., 1981, as cited in Shon et al., 2015):

$$J_v = A(\sigma\Delta\pi - \Delta P) \tag{1}$$

$$J_s = B\Delta C \tag{2}$$

where A is the membrane water permeability coefficient, σ is the reflection coefficient, B is the solute permeability coefficient, C is the solute reflection coefficient, usually assumed to be unity; ΔP is the applied hydraulic pressure, which is zero (P = 0) in the FO process, and hence, water flux can be expressed as the multiplication of the membrane water permeability and the difference in osmotic pressure.

$$J_v = A(\pi_{draw} - \pi_{feed}) \tag{3}$$

Where π_{draw} and π_{feed} are the osmotic pressures of the draw solution and feed solution, respectively (Shon et al., 2015). Osmotic pressure profile across the membrane in an ideal FO process is demonstrated in figure 11.

Equation 3, however, only describes the theoretical ideal situation. In experiment, the FO water flux is found to be much lower than that ideal value of product of membrane water permeability coefficient and the osmotic potential difference of the draw and feed solutions, due to the concentration polarization phenomenon (Shon et al., 2015). In FO process, concentration polarization exists on the both external sides of the membrane when there are solutes in both the feed and draw solutions (Shon et al., 2015). The build-up of solutes on the feed side of the membrane is defined as concentrative external concentration polarization (concentrative ECP), while the depletion of solutes on the draw side of the membrane is referred to as dilutive ECP (McCutcheon and Elimelech, 2006, as cited in Shon et al., 2015). Osmotic pressure profile across an FO membrane in the presence of ECP is demonstrated in figure 12. However, the effect of ECP on the FO flux is relatively small, and could be mitigated through manipulating the flux and mass transfer coefficient, through approaches such as adjusting the crossflow velocity, using spacers, vibrations, or ultrasound, etc. (Lee et al., 1981; Sablani et al., 2001; Cath et al., 2006, as cited in Shon et al., 2015). These approaches are further explored in section (6.2.2.1).

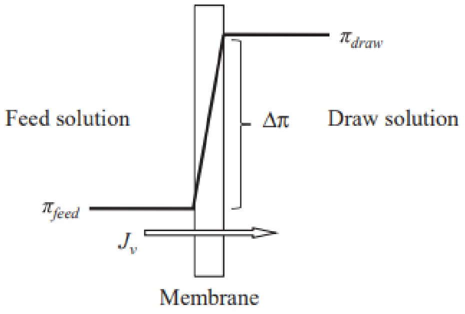


Figure 11 - Osmotic Pressure Profile across the Membrane in Ideal FO Processes (Shon et al., 2015)

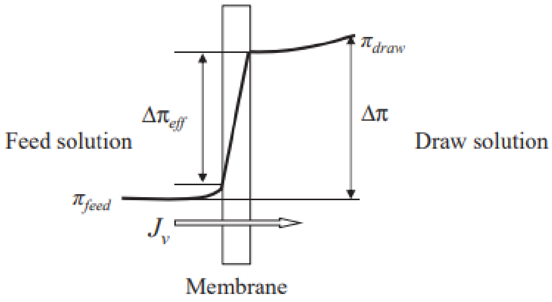


Figure 12 - Osmotic Pressure Profile across the FO Membrane in the Presence of ECP (Shon et al., 2015)

A more severe problem compared to ECP that contributes to low FO water flux is internal concentration polarization (ICP); semi-permeable membranes often have a thicker and porous support layer underneath the thin selective layer, in order to provide enough support strength (Shon et al., 2015). The support layer often inhibits mass diffusion and hence, lead to the accumulation of a concentration polarization layer within it (Shon et al., 2015), which is the phenomenon that is referred to as ICP, demonstrated in figure 13. In FO, the asymmetric semi-permeable membrane can be installed with the active rejection layer (AL) facing either the draw solution (referred to as AL-DS) or the feed solution (AL-FS).

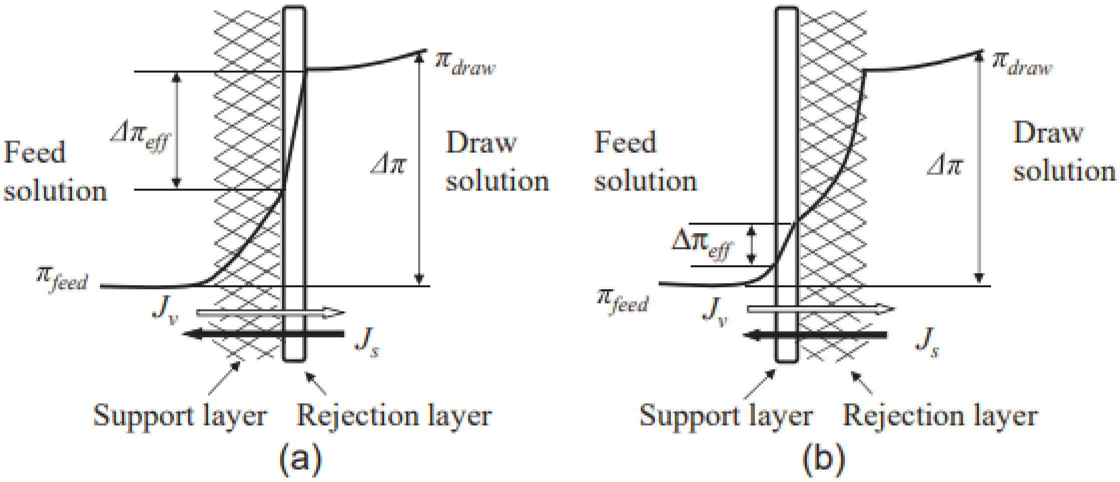


Figure 13 - Osmotic Pressure Profiles Across an FO Membrane in the (a) AL-FS and (b) AL-DS orientations (Shon et al., 2015)

In the ICP model, water flux can be modelled (Lee et al., 1981; Loeb et al., 1997, as cited in Shon et al., 2015):

Concentrative ICP (AL-DS):

$$J_v = K_m \ln\left(\frac{A\pi_{draw} - J_v + B}{A\pi_{feed} + B}\right) \tag{4}$$

Dilutive ICP (AL-FS):

$$J_v = K_m \ln\left(\frac{A\pi_{draw} + B}{A\pi_{feed} + J_v + B}\right) \tag{5}$$

Where A is water permeability coefficient; B is solute permeability coefficient; and K_m is the mass transfer coefficient, defined as:

$$K_m = \frac{D}{S} \tag{6}$$

Where D is the solute diffusion coefficient; S is the structural parameter of membrane, defined as:

$$S = \frac{\tau l}{\varepsilon} \tag{7}$$

Where τ, l and ε are the tortuosity, the actual thickness and porosity of the porous support layer, respectively.

3.1.2. Reverse Solute Flux (RSF)

Reverse solute flux (RSF) is an important parameter to consider in the FO process; since a reverse diffusion of the draw solutes would cause an economic loss due to the inability to recover these draw solutes (Cath et al., 2006, as cited in Nasr and Sewilam, 2016). Moreover, reverse solute permeation increases the occurrence of fouling by creating complexes between draw and feed ions (Cath et al., 2006; Lay et al., 2010, as cited in Nasr and Sewilam, 2016). The FO solute flux can be determined by (Tang et al., 2010, as cited in Shon et al., 2015):

$$J_s = \frac{B}{A\,.\,\beta R_g T} J_v \tag{8}$$

Where β is the van't Hoff coefficient; R_g is the universal gas constant; T is the absolute temperature.

3.1.3. Specific Reverse Solute Flux (SRSF)

Specific reverse solute flux (SRSF) is the ratio between RSF and water flux. SRSF is a measurement that was created to signify the mass of draw solutes that was lost through reverse permeation per unit volume of water extracted from the FS (Cath et al., 2006, as cited in Nasr and Sewilam, 2015). SRSF can be calculated by using the equation below:

$$\text{SRSF} = \frac{Js}{Jv} \tag{9}$$

By combining equations (8) and (9), SRSF can be expressed as:

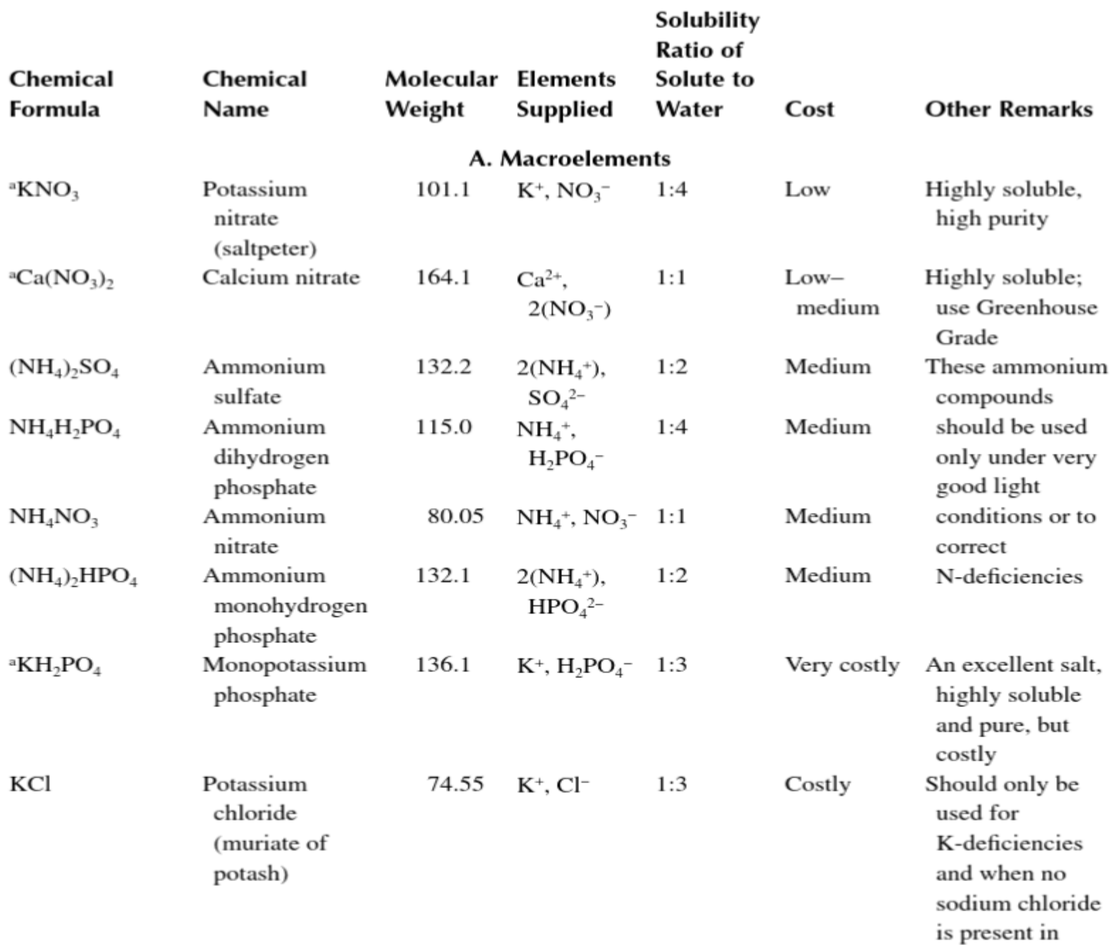
$$SRSF = \frac{B}{A\,.\,\beta R_g T} \tag{10}$$

3.2. Hydroponic Nutrient Solutions

3.2.1. Solubility

Solubility of fertilizer salts is a property that dictates the amount of the salt that remains in solution when they are dissolved in water; in hydroponics, fertilizer salts with a high solubility are necessary in order for them to remain in solution and be available to be absorbed by the plants (Resh, 2012). Shown in table 4 below is some of the solubilities of fertilizer salts

Table 4 - Summary of Fertilizer Salts (Resh, 2012)



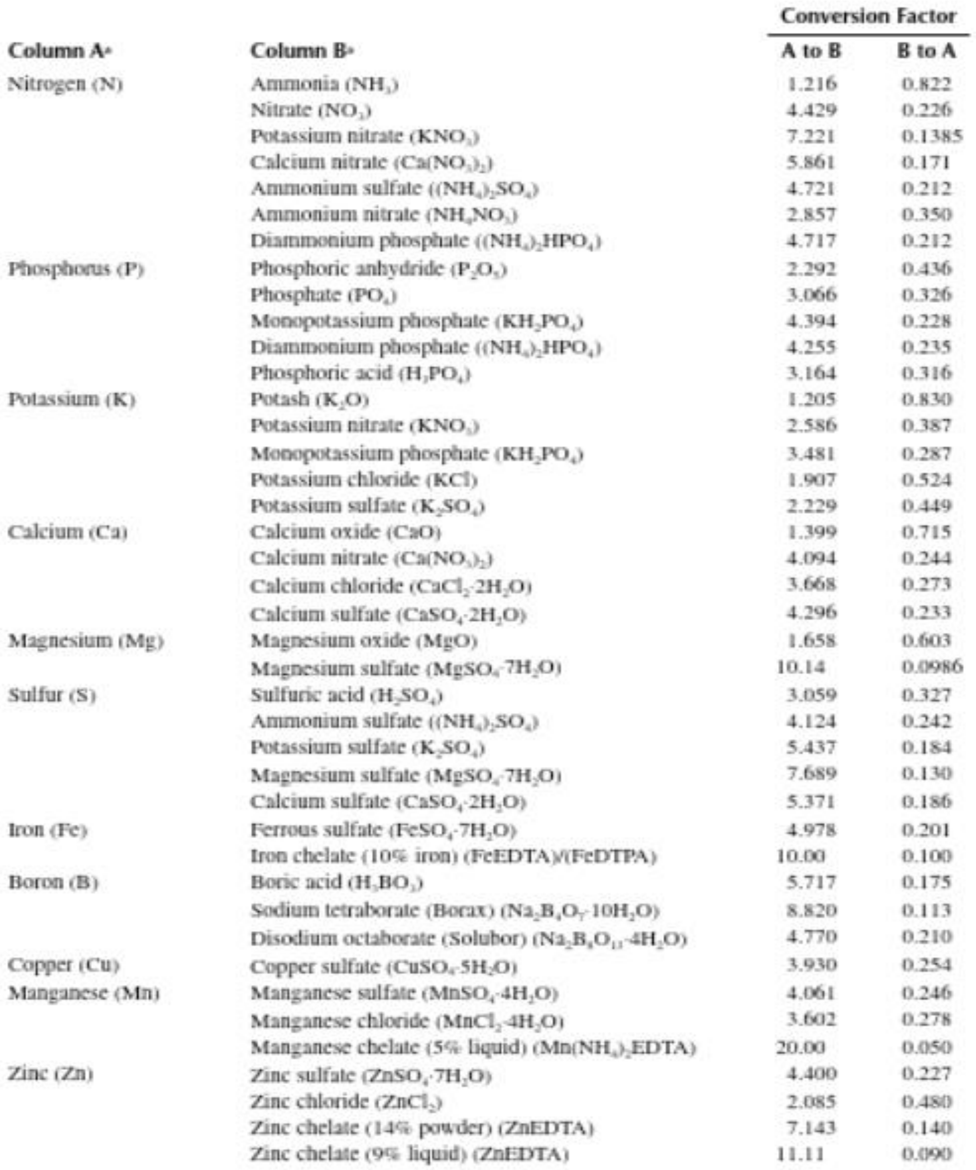
Chemical Formula	Chemical Name	Molecular Weight	Elements Supplied	Solubility Ratio of Solute to Water	Cost	Other Remarks
			A. Macroelements			
$^{a}KNO_3$	Potassium nitrate (saltpeter)	101.1	K^+, NO_3^-	1:4	Low	Highly soluble, high purity
$^{a}Ca(NO_3)_2$	Calcium nitrate	164.1	Ca^{2+}, $2(NO_3^-)$	1:1	Low–medium	Highly soluble; use Greenhouse Grade
$(NH_4)_2SO_4$	Ammonium sulfate	132.2	$2(NH_4^+)$, SO_4^{2-}	1:2	Medium	These ammonium compounds should be used only under very good light conditions or to correct N-deficiencies
$NH_4H_2PO_4$	Ammonium dihydrogen phosphate	115.0	NH_4^+, $H_2PO_4^-$	1:4	Medium	
NH_4NO_3	Ammonium nitrate	80.05	NH_4^+, NO_3^-	1:1	Medium	
$(NH_4)_2HPO_4$	Ammonium monohydrogen phosphate	132.1	$2(NH_4^+)$, HPO_4^{2-}	1:2	Medium	
$^{a}KH_2PO_4$	Monopotassium phosphate	136.1	K^+, $H_2PO_4^-$	1:3	Very costly	An excellent salt, highly soluble and pure, but costly
KCl	Potassium chloride (muriate of potash)	74.55	K^+, Cl^-	1:3	Costly	Should only be used for K-deficiencies and when no sodium chloride is present in

Moreover, the proportion of ions that is provided by each of the salts is important to consider when designing the nutrient solution; for example, one molecule of calcium nitrate ($Ca(NO_3)_2$) will yield one ion of calcium (Ca^{2+}) and two ions of nitrate $2(NO_3^-)$ (Resh, 2012), and depending on the type of plant that is being grown, different combinations and concentrations of fertilizer salts will have to be used in order to achieve optimum growth.

3.2.2. Concentrations

The amount of nitrogen (N) in an ion of nitrate (NO_3^-) can be calculated by calculating the percentage that each element represents within the source compound, and in table 5 is a list of conversion factors that can be used to calculate that fraction (Resh, 2012).

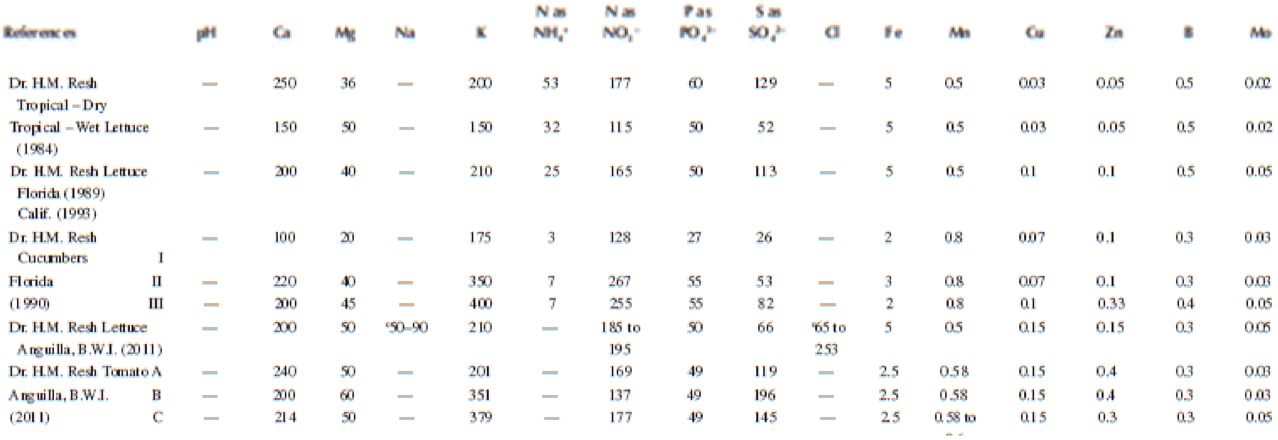
Table 5 - Conversion Factors for Fertilizer Salts (Resh, 2012)



		Conversion Factor	
Column A	**Column B**	**A to B**	**B to A**
Nitrogen (N)	Ammonia (NH_3)	1.216	0.822
	Nitrate (NO_3)	4.429	0.226
	Potassium nitrate (KNO_3)	7.221	0.1385
	Calcium nitrate ($Ca(NO_3)_2$)	5.861	0.171
	Ammonium sulfate ($(NH_4)_2SO_4$)	4.721	0.212
	Ammonium nitrate (NH_4NO_3)	2.857	0.350
	Diammonium phosphate ($(NH_4)_2HPO_4$)	4.717	0.212
Phosphorus (P)	Phosphoric anhydride (P_2O_5)	2.292	0.436
	Phosphate (PO_4)	3.066	0.326
	Monopotassium phosphate (KH_2PO_4)	4.394	0.228
	Diammonium phosphate ($(NH_4)_2HPO_4$)	4.255	0.235
	Phosphoric acid (H_3PO_4)	3.164	0.316
Potassium (K)	Potash (K_2O)	1.205	0.830
	Potassium nitrate (KNO_3)	2.586	0.387
	Monopotassium phosphate (KH_2PO_4)	3.481	0.287
	Potassium chloride (KCl)	1.907	0.524
	Potassium sulfate (K_2SO_4)	2.229	0.449
Calcium (Ca)	Calcium oxide (CaO)	1.399	0.715
	Calcium nitrate ($Ca(NO_3)_2$)	4.094	0.244
	Calcium chloride ($CaCl_2 \cdot 2H_2O$)	3.668	0.273
	Calcium sulfate ($CaSO_4 \cdot 2H_2O$)	4.296	0.233
Magnesium (Mg)	Magnesium oxide (MgO)	1.658	0.603
	Magnesium sulfate ($MgSO_4 \cdot 7H_2O$)	10.14	0.0986
Sulfur (S)	Sulfuric acid (H_2SO_4)	3.059	0.327
	Ammonium sulfate ($(NH_4)_2SO_4$)	4.124	0.242
	Potassium sulfate (K_2SO_4)	5.437	0.184
	Magnesium sulfate ($MgSO_4 \cdot 7H_2O$)	7.689	0.130
	Calcium sulfate ($CaSO_4 \cdot 2H_2O$)	5.371	0.186
Iron (Fe)	Ferrous sulfate ($FeSO_4 \cdot 7H_2O$)	4.978	0.201
	Iron chelate (10% iron) (FeEDTA)/(FeDTPA)	10.00	0.100
Boron (B)	Boric acid (H_3BO_3)	5.717	0.175
	Sodium tetraborate (Borax) ($Na_2B_4O_7 \cdot 10H_2O$)	8.820	0.113
	Disodium octaborate (Solubor) ($Na_2B_8O_{13} \cdot 4H_2O$)	4.770	0.210
Copper (Cu)	Copper sulfate ($CuSO_4 \cdot 5H_2O$)	3.930	0.254
Manganese (Mn)	Manganese sulfate ($MnSO_4 \cdot 4H_2O$)	4.061	0.246
	Manganese chloride ($MnCl_2 \cdot 4H_2O$)	3.602	0.278
	Manganese chelate (5% liquid) ($Mn(NH_4)_2EDTA$)	20.00	0.050
Zinc (Zn)	Zinc sulfate ($ZnSO_4 \cdot 7H_2O$)	4.400	0.227
	Zinc chloride ($ZnCl_2$)	2.085	0.480
	Zinc chelate (14% powder) (ZnEDTA)	7.143	0.140
	Zinc chelate (9% liquid) (ZnEDTA)	11.11	0.090

The conversion factors (A to B or its inverse B to A) can be utilized to find the ppm concentration of each element that is obtained by dissolving a specific compound. For example, if 100 mg of calcium nitrate ($Ca(NO_3)_2$) is dissolved in 1L of water, the concentration of Ca will be 24.4 mg/L (24.4 ppm) and the concentration of N will be 17.1 mg/L (17.1 ppm). Table 6 list the ppm concentration of the elements in some of the standard hydroponic nutrient solutions.

Table 6 - Compositions of Nutrient Solutions in ppm (Resh, 2012)



References	pH	Ca	Mg	Na	K	N as NH_4^+	N as NO_3^-	P as PO_4^{3-}	S as SO_4^{2-}	Cl	Fe	Mn	Cu	Zn	B	Mo
Dr. H.M. Resh Tropical – Dry	—	250	36	—	200	53	177	60	129	—	5	0.5	0.03	0.05	0.5	0.02
Tropical – Wet Lettuce (1984)	—	150	50	—	150	32	115	50	52	—	5	0.5	0.03	0.05	0.5	0.02
Dr. H.M. Resh Lettuce Florida (1989) Calif. (1993)	—	200	40	—	210	25	165	50	113	—	5	0.5	0.1	0.1	0.5	0.05
Dr. H.M. Resh Cucumbers I	—	100	20	—	175	3	128	27	26	—	2	0.8	0.07	0.1	0.3	0.03
Florida II	—	220	40	—	350	7	267	55	53	—	3	0.8	0.07	0.1	0.3	0.03
(1990) III	—	200	45	—	400	7	255	55	82	—	2	0.8	0.1	0.33	0.4	0.05
Dr. H.M. Resh Lettuce Anguilla, B.W.I. (2011)	—	200	50	‘50–90	210	—	185 to 195	50	66	‘65 to 253	5	0.5	0.15	0.15	0.3	0.06
Dr. H.M. Resh Tomato A	—	240	50	—	201	—	169	49	119	—	2.5	0.58	0.15	0.4	0.3	0.03
Anguilla, B.W.I. B	—	200	60	—	351	—	137	49	196	—	2.5	0.58	0.15	0.4	0.3	0.03
(2011) C	—	214	50	—	379	—	177	49	145	—	2.5	0.58 to	0.15	0.3	0.3	0.05

4. Materials and Methods

4.1. Apparatus

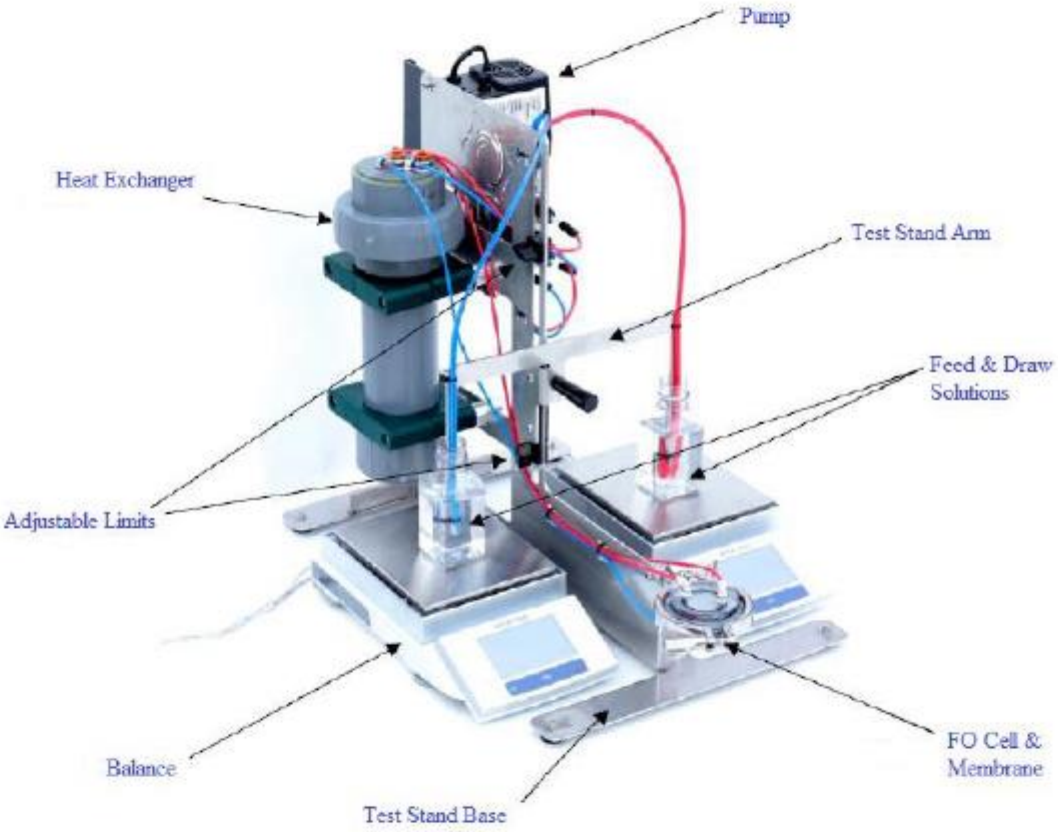


Figure 14 - Bench-scale Crossflow Filtration Unit (Porifera Inc., 2015)

For this experiment, a bench-scale crossflow filtration unit with an FO cell was used, illustrated in figure 14. On both sides of the membrane, two channels are connected to allow flow of feed solution on one side, and draw solution on the other side. Crossflows were operated in counter-current flow directions, by using a variable speed peristaltic pumps (Stenner, model 170DMP5, 25 psi, 1.7 bar, 50 Hz, USA). All solutions were kept at a temperature of 25 $^{\circ}$C through a temperature water bath controlled by a heater/chiller (Polyscience temperature controller, model 9106A12E). Experiments were operated at a crossflow rate of 400 mL/min, which can be converted to a crossflow velocity of 8.5 cm/s. The change in the volumes of the DS in the DS tank and FS in the FS tank were continuously recorded by placing the DS and FS on a digital mass scale, which was connected to a computer for online data logging at intervals of 3 minutes. This change of volume was used to calculate the water flux across the membrane.

The initial volume of both the DS and the FS was 250 mL, and most experiments were run for 2.5 to 3 hours, since a stable flux was usually achieved after the first hour of operation. Experiments were conducted under (AL-FS) orientation, where the active layer was facing the feed solution

Water flux J_v (in L/m^2/h) was calculated using:

$$J_v = \frac{\Delta V}{membrane\ area\ \times time} \tag{11}$$

Solute flux was calculated as follows:

$$J_s = \frac{(V_i - \Delta V) \times C_s}{membrane\ area \times time} \tag{12}$$

Where V_i is the initial volume of FS, ΔV is the total volume of water displaced from the FS to the DS, and C_s is the concentration of the draw solutes in the FS at the end of the experiment.

The FO membrane that will be used in this study was purchased from Porifera Inc. Its active layer is made out of polyamide, and its support layer is made out of a porous hydrophilic polymer (Tayel, Nasr and Sewilam, 2019; Porifera Inc., 2015). The average total thickness of the membrane is 70±10 µm (Tayel, Nasr and Sewilam, 2019; Porifera Inc., 2015). Properties of the membrane, as provided by the manufacturer, are listed in table 7 (Porifera Inc., 2015)

Table 7 - Membrane Properties (Porifera Inc., 2015)

Pure water permeability coefficient, A (L/m^2/h/bar)	2.2 ± 0.01
Salt permeability coefficient of active layer, B (m/s)	1.6×10^{-7}
Total membrane thickness (µm)	70 ± 10
Structural parameter, S (µm)	215 ± 30
Material of active layer	Polyamide (PA)
Material of support layer	Porous hydrophilic polymer

Moreover, since salt rejection is a crucial parameter in FO processes, it will be investigated by taking samples from the DS after every experiment, and analysing its Na^+ and Cl^- ions; the following equation will be used to calculate salt rejection percentage (Nasr and Sewilam, 2016):

$$Re(\%) = \frac{C_i - \left(\frac{C_{p,D}(V_i + \Delta V)}{\Delta V}\right)}{C_i} \times 100 \tag{13}$$

where C_i is the initial concentration of the ion in FS, $C_{p,D}$ is the final concentration of the ion in DS, V_i is the initial volume of the DS and ΔV is the total volume of water that entered the DS from the FS (Nasr and Sewilam, 2016).

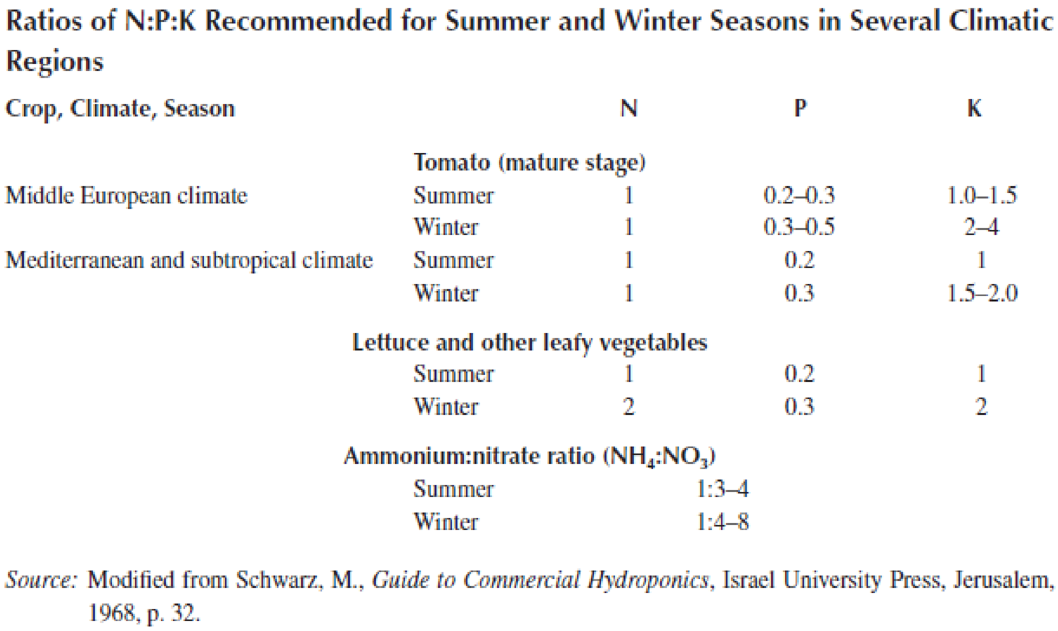
4.2. Draw Solutions

The chemicals and fertilizer salts were provided by the AUC WEF (Water-Energy-Food) Nexus Labs, and some additional salts were purchased from Science and Technology Center, Egypt. All chemicals used were laboratory & reagent grades.

The lettuce and leafy green nutrient solutions formulae were selected from table 6 (Resh, 2012). The first four formulae were selected because they were the available formulae for lettuce and leafy greens in Resh,2012. The formulae selected are:

- Dr. H.M. Resh, Tropical - Dry Lettuce - referred to as (RTD)
- Dr. H.M. Resh, Tropical - Wet Lettuce - referred to as (RTW)
- Dr. H.M. Resh Lettuce, Florida (1989), California (1993) – referred to as (RF)
- Dr. H.M. Resh Lettuce, Anguilla, B.W.I (2011) – referred to as (RA)
- Optimum Grow – twin pack hydroponic nutrient solution used in Chekli's paper, according to the formula of macro and micro nutrient mentioned in the paper (Chekli et al., 2017a) - – referred to as (CHE). This solution was selected in order to test the performance of commercial nutrient solutions in relation to the prepared solutions.
- Robbins (1946). This solution satisfies the ratio of macro and micro nutrient recommended for growing lettuce in Mediterranean climate in the summer, shown below in table 8 (Resh, 2012) -referred to as (ROB)

Table 8 - Ratios of NPK Recommended for Summer and Winter Seasons (Resh, 2012)



Ratios of N:P:K Recommended for Summer and Winter Seasons in Several Climatic Regions

Crop, Climate, Season		N	P	K
	Tomato (mature stage)			
Middle European climate	Summer	1	0.2–0.3	1.0–1.5
	Winter	1	0.3–0.5	2–4
Mediterranean and subtropical climate	Summer	1	0.2	1
	Winter	1	0.3	1.5–2.0
	Lettuce and other leafy vegetables			
	Summer	1	0.2	1
	Winter	2	0.3	2
	Ammonium:nitrate ratio (NH_4:NO_3)			
	Summer	1:3–4		
	Winter	1:4–8		

Source: Modified from Schwarz, M., *Guide to Commercial Hydroponics*, Israel University Press, Jerusalem, 1968, p. 32.

Listed in table 9 are the macro and micro nutrient compositions (in mg/L) of the selected formulae:

Table 9 - Selected Hydroponic Nutrient Solutions (Resh, 2012; Chekli et al., 2017a)

	Ca	**Mg**	**Na**	**K**	**N as NH_4**	**N as NO_3**	**P as PO_4**	**S as SO_4**	**Cl**	**Fe**	**Mn**	**Cu**	**Zn**	**B**	**Mo**
Resh Tropical Dry Lettuce (RTD)	250	36	0	200	53	177	60	129	0	5	0.5	0.03	0.05	0.5	0.02
Resh Tropical Wet Lettuce (RTW)	150	50	0	150	32	115	50	52	0	5	0.5	0.03	0.05	0.5	0.02
Resh Florida, Calif Lettuce (RF)	200	40	0	210	25	165	50	113	0	5	0.5	0.1	0.1	0.5	0.05
Resh Anguilla Lettuce (RA)	200	50	90	210	0	195	50	66	253	5	0.5	0.15	0.15	0.3	0.05
Chekli (CHE)	183	51.7	0	311	26	211.5	45	64.5	0	5	0.5	0.03	0.05	0.5	0.02
Robbins (ROB)	200	48	0	195	0	196	31	64	0	0.5	0.25	0.02	0.25	0.25	0.01

Stock solutions are prepared in different strengths, depending on the size of the application. 50, 100, 200 are the most common, but strengths as high as 800 times can be used in large scale applications. Stock solutions are then diluted accordingly when used for hydroponic agriculture (Resh, 2012).

Hydroponic nutrient stock solutions are prepared in two solutions; A and B solutions. This is done to avoid any precipitation that might occur between different compounds, such as Nitrates and Sulphates. The problem of precipitation is especially likely when these compounds are used in very high concentrations (eg. for 100 and 200 strength solutions). Solution B of each nutrient solution was selected as the draw solution for the forward osmosis process, due to the fact that they include all macronutrients (N, P, K, Ca, Mg, S), as well as most micronutrients (Mn, B, Zn, Cu, Mo). While solution A was found to have higher theoretical osmotic pressure in the RTD, ROB, and CHE solutions, the presence of high concentrations of Ca in A solutions could lead to excessive fouling of the membrane if diffusion to the feed solution occurs through bridging mechanisms that occur with organic compounds (Chekli et al., 2017a).

In order to prepare the stock solutions, calculations for each formulae were made, in order to determine how much of each of the available compounds should be used to achieve the required ratio. Solutions were prepared in 100 times strength. Listed in table 10 below is the chemicals that make up each solution, as well as the theoretical osmotic pressure of each solution, estimated using Lenntech osmotic pressure calcuator (Lenntech, n.d.):

Table 10 - Chemicals Comprising the Selected Solutions

Resh Anguila Lettuce (RA)	**Part A (g/L)**	**Part B (g/L)**	**Resh Florida, Calif. Lettuce (RF)**	**Part A (g/L)**	**Part B (g/L)**	**Resh Tropical Wet Lettuce (RTW)**	**Part A (g/L)**	**Part B (g/L)**
K_2HPO_4	0	29.6	**$Ca(NO_3)_2.4H_2O$**	120.2	0	**$Ca(NO_3)_2.4H_2O$**	98.9	0
$Ca(NO_3)_2.4H_2O$	120.2	0	**K_2HPO_4**	0	29.6	**K_2HPO_4**	0	30
$MgSO_4.7H_2O$	0	53.4	**K_2SO_4**	0	18.7	**KOH**	2	2
Iron Chelate (13.5%)	3.7	0	**$(NH_4)_2SO_4$**	0	11.9	**$(NH_4)_2SO_4$**	0	15.2
Manganese Chelate (13%)	0	0.4	**$MgSO_4.7H_2O$**	0	40.5	**$MgSO_4.7H_2O$**	0	97.4
Zinc Chelate (14%)	0	0.1	**MgO**	0	0.3	**MgO**	6.5	0
$CuSO_4.5H_2O$	0	0.6	**Iron Chelate (13.5%)**	3.7	0	**Iron Chelate (13.5%)**	3.7	0
Boric Acid	0	0.2	**Manganese Chelate (13%)**	0	0.4	**Manganese Chelate (13%)**	0	0.4
Na_2MoO_4	0	0.01	**Zinc Chelate (14%)**	0	0.1	**Zinc Chelate (14%)**	0	0.04
			$CuSO_4.5H_2O$	0	0.4	**$CuSO_4.5H_2O$**	0	0.1
			Boric Acid	0	0.3	**Boric Acid**	0	0.03
			Na_2MoO_4	0	0.01	**Na_2MoO_4**	0	0.005
Osmotic Pressure (bar)	10.52	13.57	**Osmotic Pressure (bar)**	10.52	20.19	**Osmotic Pressure (bar)**	8.64	15.42

Table 11 (continued) - Chemicals Comprising the Selected Solutions

Resh Tropical Dry Lettuce (RTD)	Part A (g/L)	Part B (g/L)	Robbins (ROB)	Part A (g/L)	Part B (g/L)	Chekli (CHE)	Part A (g/L)	Part B (g/L)
KNO_3	26.1	26.1	**K_2HPO_4**	0	18.4	**KNO_3**	40.6	40.6
$Ca(NO_3)_2.4H_2O$	90.6	0	**KNO**	15.25	15.25	**$Ca(NO_3)_2.4H_2O$**	86.1	0
$(NH_4)_2HPO_4$	0	25.3	**$Ca(NO_3)_2.4H_2O$**	132.6	0	**$CaSO_4.2H_2O$**	17.4	0
$MgSO_4.7H_2O$	0	38.4	**$MgSO_4.7H_2O$**	0	51.8	**$(NH_4)2SO_4$**	0	12.3
$CaSO_4.2H_2O$	43.5	0	**Iron Chelate (13.5%)**	0.4	0	**MgO**	8.7	0
Iron Chelate (13.5%)	3.7	0	**Manganese Chelate (13%)**	0	0.2	**Iron Chelate (13.5%)**	3.7	0
Manganese Chelate (13%)	0	0.4	**Zinc Chelate (14%)**	0	0.18	**Manganese Chelate (13%)**	0	0.4
Zinc Chelate (14%)	0	0.04	**$CuSO_4.5H_2O$**	0	0.1	**Zinc Chelate (14%)**	0	0.04
$CuSO_4.5H_2O$	0	0.1	**Boric Acid**	0	0.2	**$CuSO_4.5H_2O$**	0	0.1
Boric Acid	0	0.03	**Na_2MoO_4**	0	0.002	**Boric Acid**	0	0.3
Na_2MoO_4	0	0.005				**Na_2MoO_4**	0	0.005
Osmotic Pressure (bar)	22.97	14.57	**Osmotic Pressure (bar)**	13.798	12.94	**Osmotic Pressure (bar)**	28.594	16.434

It is worth noting that solution A contains high amount of Calcium, while solution B contains the phosphates and sulphates, which can both lead to the creation of insoluble precipitations if mixed in such high concentrations. Hence, solutions A and B have to be processed separately in FO in parallel stages, or only one of the solutions can be used as DS for FO, and the other solution can be added afterwards in diluted form to complete the nutrient solution (Chekli et al., 2017a). The latter option was opted for, in order to avoid fouling of the membrane caused by the Ca in A solutions.

4.2.1. Cost of Draw Solutions

Shown in figure 15 below is the cost per liter in USD of each of the draw solutions used, according to Science and Technology Center, Egypt. The conversion rate utilized was 1 USD = 15.86 EGP. It is worth noting that these prices are for laboratory/reagent grade chemicals. In an industrial scale application, technical grade chemicals would be used, which could be obtained for prices lower than those listed below. It is observed that CHE and RTD solutions are the 2 most expensive solutions, while RA and RF are the cheapest 2.

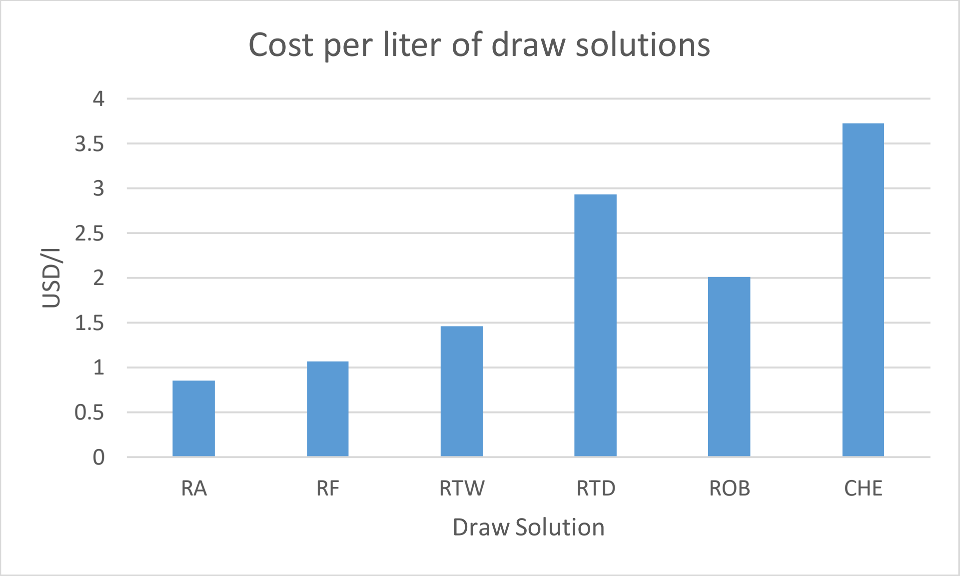


Figure 15 - Cost per liter of draw solutions

5. Experimental Plan

Feed solutions were synthesized by dissolving NaCl in DI (De-Ionized) water in 3 concentrations: 5, 10 and 15 g/L. These concentrations represent different salinities of brackish groundwater. Six different hydroponic nutrient solutions were investigated as DS for the process. 18 experiments were carried out. All solutions were synthesized by dissolving the salts in DI water, and stirred with a magnetic stirrer for at least 30 minutes, in order to ensure complete dissolution. Solutions were then stored in plastic bottles.

For each experiment, 250 mL of both the FS and DS were poured into plastic bottles, and both were weighed using a digital scale. Moreover, TDS was measured with a portable TDS and EC meter (Hach HQ40D multi). Then, bottles were covered with Parafilm, in order to minimise evaporation. Both bottles were then placed on the crossflow filtration unit, and the unit was run for 2.5 to 3 hours for each experiment. After the experiment was over, the system was drained from the remaining feed and draw solutions into the corresponding beakers. After the system was completely drained of draw and feed solutions, which usually took around 20 to 30 minutes, the bottles were carefully removed and replaced with bottles of DI water. The system was then operated again with DI water, in order to flush the membrane. This flushing was repeated 3 to 4 times, and each flush was between 10 and 20 minutes. The final weights and TDS of the feed and draw solutions was then measured and recorded. Samples of each solution before and after processing was stored for ion analysis. Ion analysis was performed through spectrophotometry at the Agircultural Research Center (ARC), Egypt.

6. Results & Discussion

6.1. Results

6.1.1. Water Recovery

The volume of water recovered through forward osmosis was calculated through the weight of FS and DS before and after each experiment. The results are shown in figure 16 below. The highest water recovery was achieved in Chekli solution, with a recovered pure water volume of 39.57 ml. This can be explained by its high osmotic pressure, which is demonstrated in table 11. It is observed that water recovery decreased as the concentration of the FS increased. This can be explained by the lower osmotic potential gradient between FS and DS, which leads to a lower water flux.

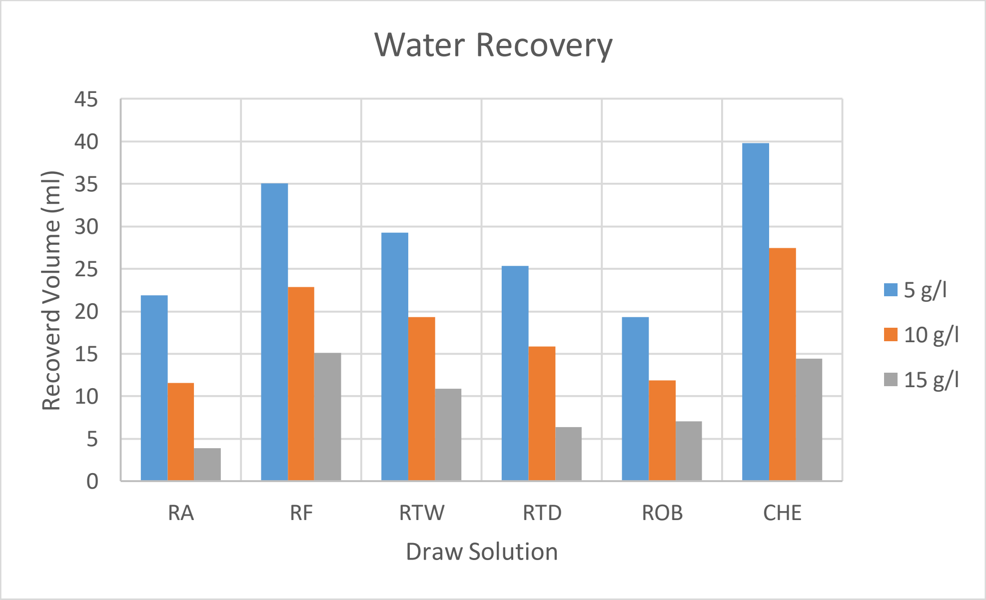


Figure 16 - Water Recovery Volume & Percentage

6.1.2. Water Flux

Water flux was calculated using equation 11. The average water flux for each draw solution is shown in figure 17 below. The highest recorded average water flux (12.28 $l/m^2/h$) was observed in the CHE solution when the feed solution was 5 g/l NaCl (FS1), due to the high osmotic pressure (16.43 bar). The lowest value of average water flux (1.5 $l/m^2/h$) was observed in RA draw solution when coupled with a feed solution of 15 g/l NaCl (FS3), which is expected due to the low osmotic pressure of this solution (13.57 bar). While RF had a higher theoretical osmotic pressure, it exhibited slightly lower flux than CHE, and this could be explained by biofouling or scaling occurring in the membrane over the period of operation. It has been proven that while having the active layer of the membrane be facing the feed side (AL-FS) generally generates a more stable water flux performance than (AL-DS) orientation, the ICP levels are also more severe in this orientation (AL-FS), which leads to relatively lower water flux (Zhang et al., 2012).

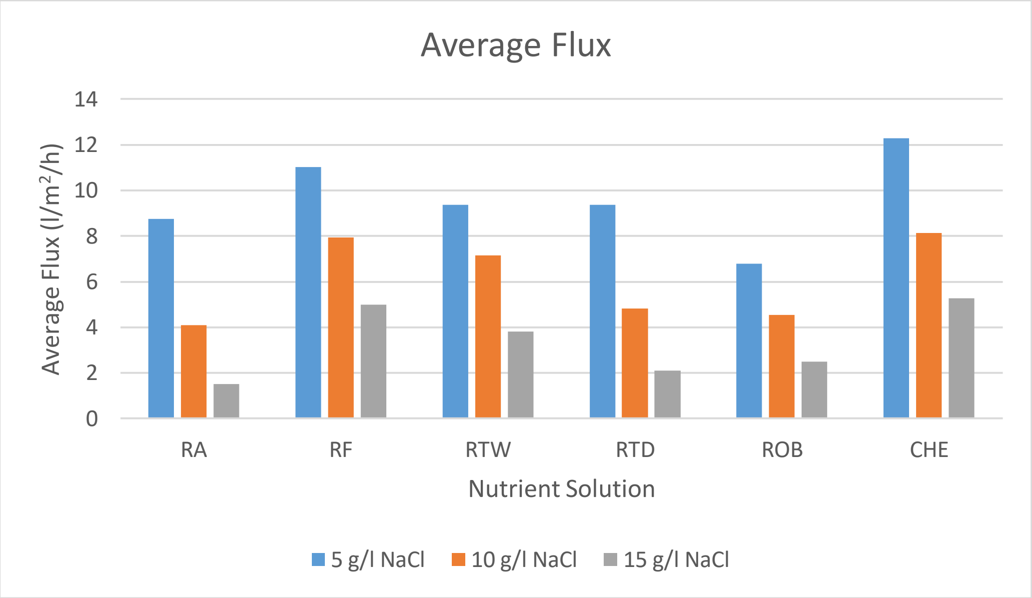


Figure 17 - Average Flux

Water flux was plotted against the TDS of each of the draw solutions. As predicted, the draw solution with the highest TDS exhibited the highest water flux, since water flux is dependent on the osmotic pressure of the draw solution (π_{draw}). The correlation between flux and TDS is logarithmic. This is demonstrated in figure 18 below.

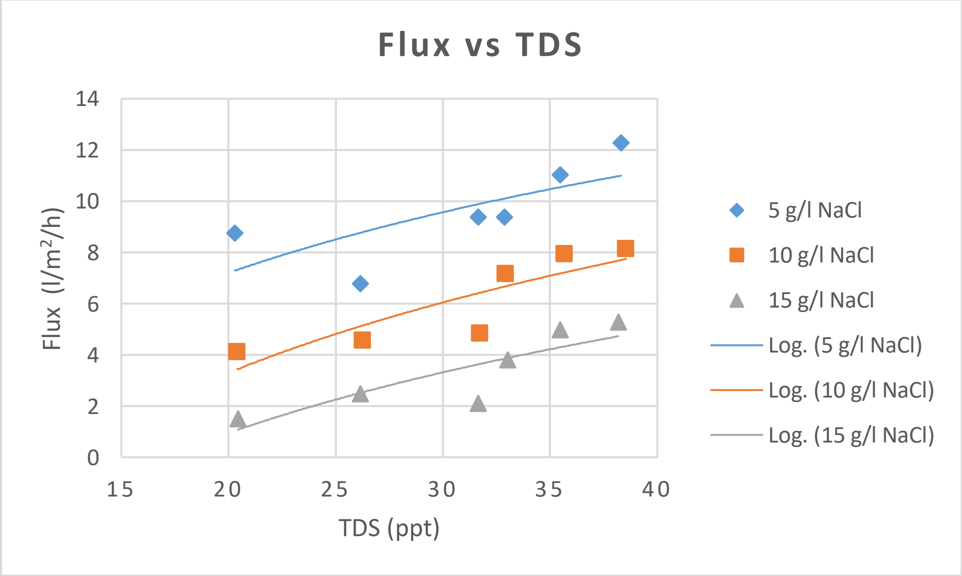


Figure 18 - Flux vs TDS

Figures 19, 20, and 21 are plots of flux vs. time, and they demonstrate the behaviour of the water flux over the duration of the experiment for each of the feed and draw solutions. The data also is represented by a logarithmic fit. It is noticed that flux starts very high in the beginning, then decreases with a high slope till around 40 minutes, at which point, flux becomes almost constant. It is also noticed that the water flux had not reached zero yet, indicating that osmotic equilibrium was not yet reached, and the process could still be operated for a longer period of time. It is also worth noting that in the case of using the 15 g/l NaCl solution as FS, and RTD as DS, flux increased after 60 minutes, instead of the expected behaviour of falling off. This could be explained by some membrane scaling that was present at the beginning of this experiment, and was removed by the flow of both solutions on the membrane. The dispersion of the data points in the figure can be explained by vibrations in the system produced by peristaltic pumps. The effect of the vibration is apparent due to the relatively small size of FS and DS tanks utilized.

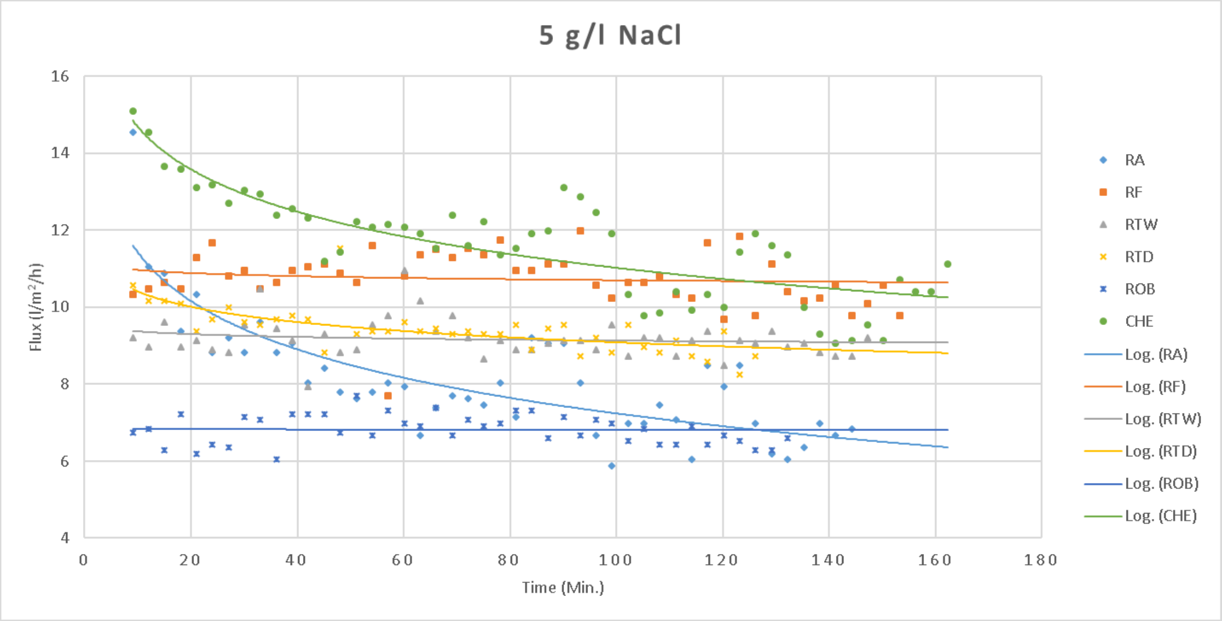


Figure 19 - Flux for 5 g/l FS

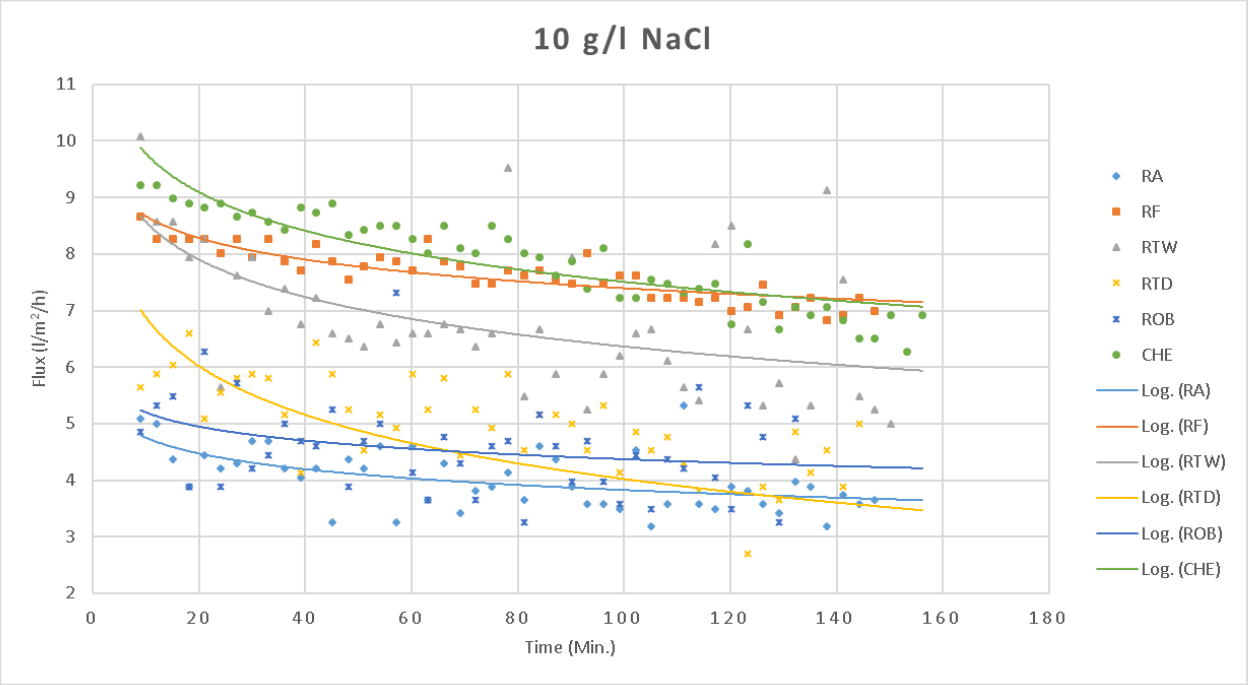


Figure 20 - Flux for 10 g/l FS

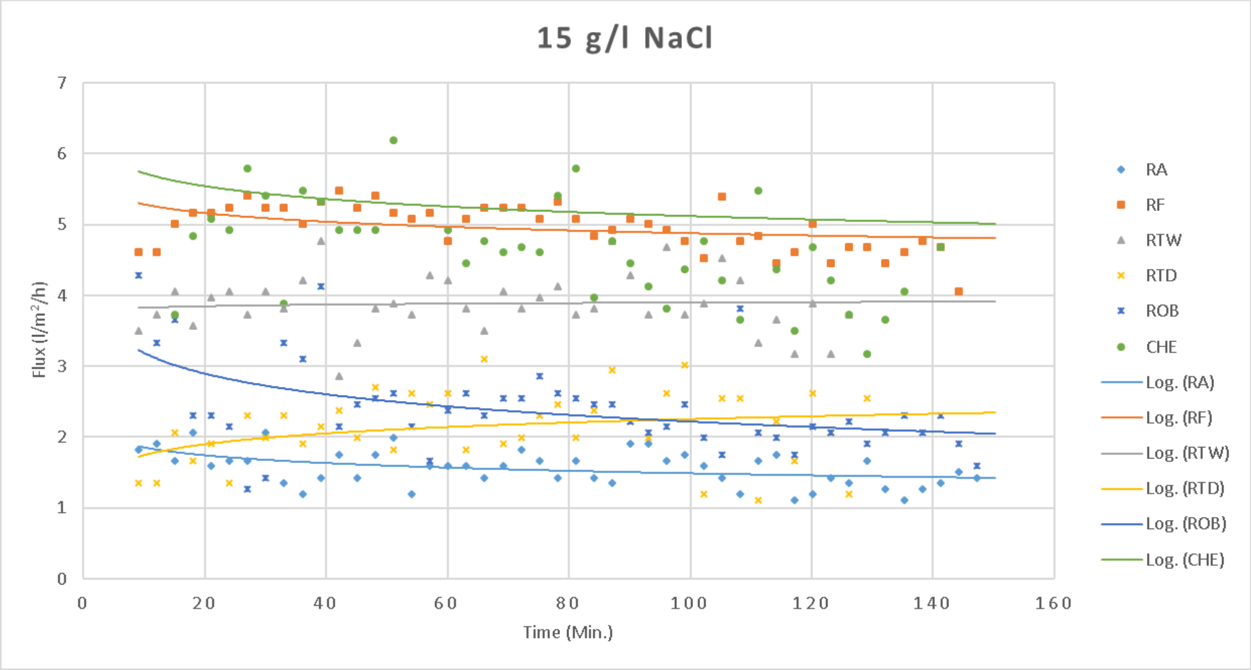


Figure 21 - Flux for 15 g/l FS

6.1.3. Specific Reverse Solute Flux

Reverse solute flux (RSF) was calculated from equation 12 and demonstrated in figure 22. Specific reverse solute flux (SRSF) was calculated through equation 9 for SO_4^{2-}, Mg^{2+}, K^+, PO_4^{3-}, NH_4^+, and NO_3^-, and plotted vs. flux in figure 23. Figure 23 demonstrates detailed graphs for the separate ions. It can be observed that SRSF for SO_4 and NO_3 was significantly higher than the other ions. It should be noted that the higher the membrane selectivity, the lower the SRSF value should be. From figure 23, it is noticed that at high flux ($\geq$9 L/m^2/h), SRSF values for all ions range between 0 and 6 g/L. Meanwhile, at lower fluxes (< 9 L/m^2/h), SRSF values for all ions are relatively higher, with the highest value being 23 g/L. This indicates a high reverse flux of the draw solutes at low water flux, which is an issue inherent to forward osmosis. The attraction between the different ions could also have generated an additional slight driving force across the membrane (Kim et al. 2015; Tan and Ng 2008, as cited in Nasr and Sewilam, 2015). Moreover, dilutive ECP & ICP might have also contributed in the reverse solute flux. This could be explained by the orientation of the membrane utilized (AL-FS), which might have led to accumulation of ions on the draw side of the membrane.

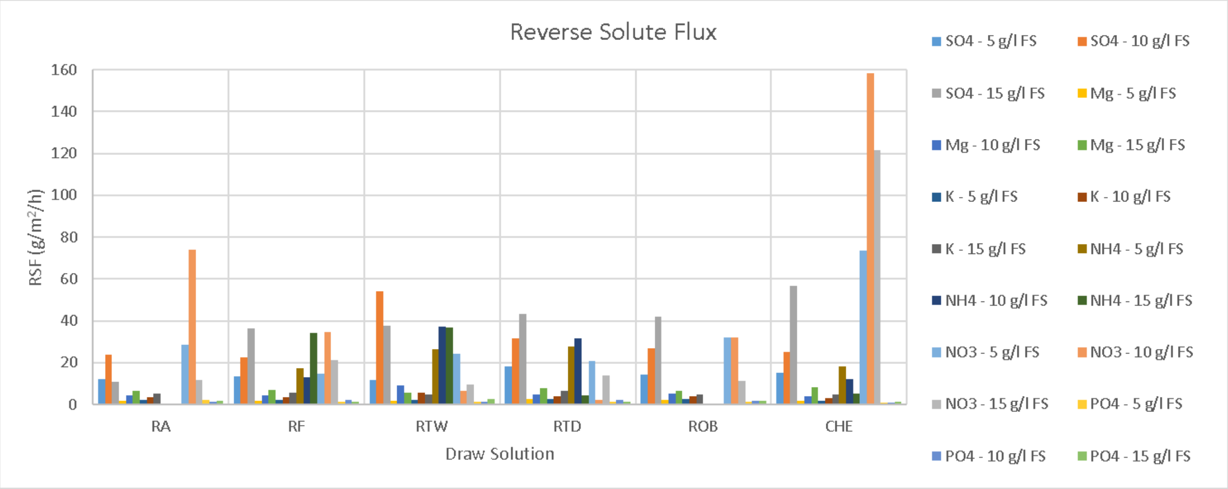


Figure 22 - Reverse Solute Flux

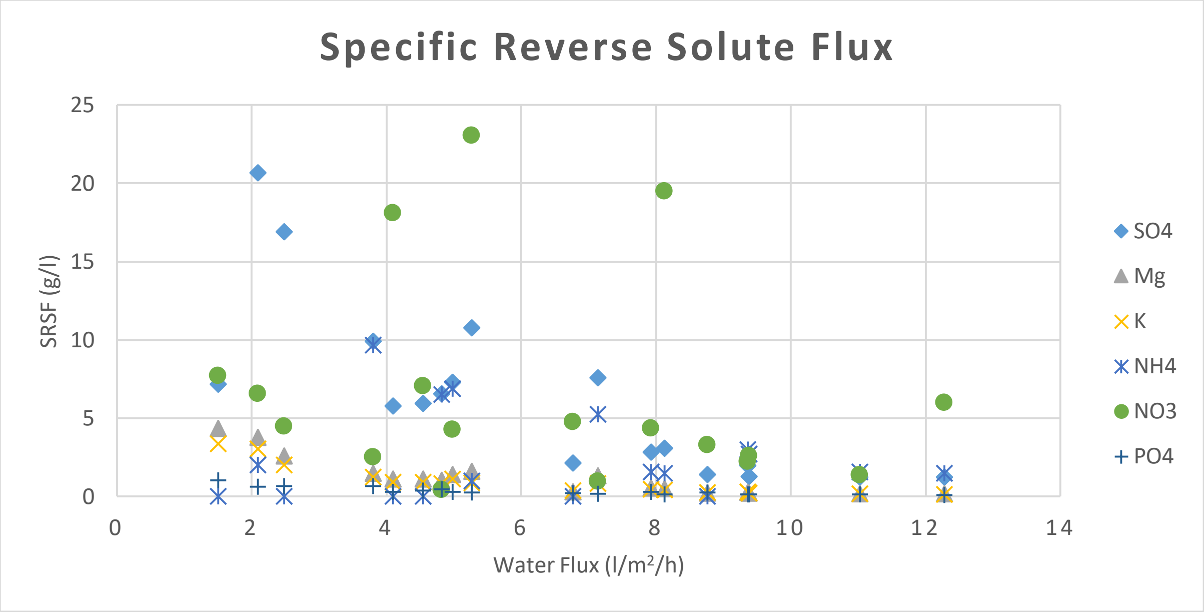


Figure 23 - Overview of SRSF of salt ions

6.1.4. Salt Rejection

FS ions (Na^+ and Cl^-) were calculated using equation 13, and the results are shown in figure 24 below. As can be observed in figure 24, high rejection of FS ions was achieved in almost all draw solutions, which indicates that the used membrane has high selectivity against feed ions. However, RA and RTD solutions achieved a lower rejection in Cl^- ions (82.6% and 83.7%, respectively), when operated with FS3 (15 g/l NaCl due to their low osmotic pressures (13.57 and 14.57 bars, respectively), which lead to the decrease in the osmotic potential gradient ($\Delta\pi$), which is the main source of force in the FO process. This in turn affects the rejection of the membrane against feed ions.

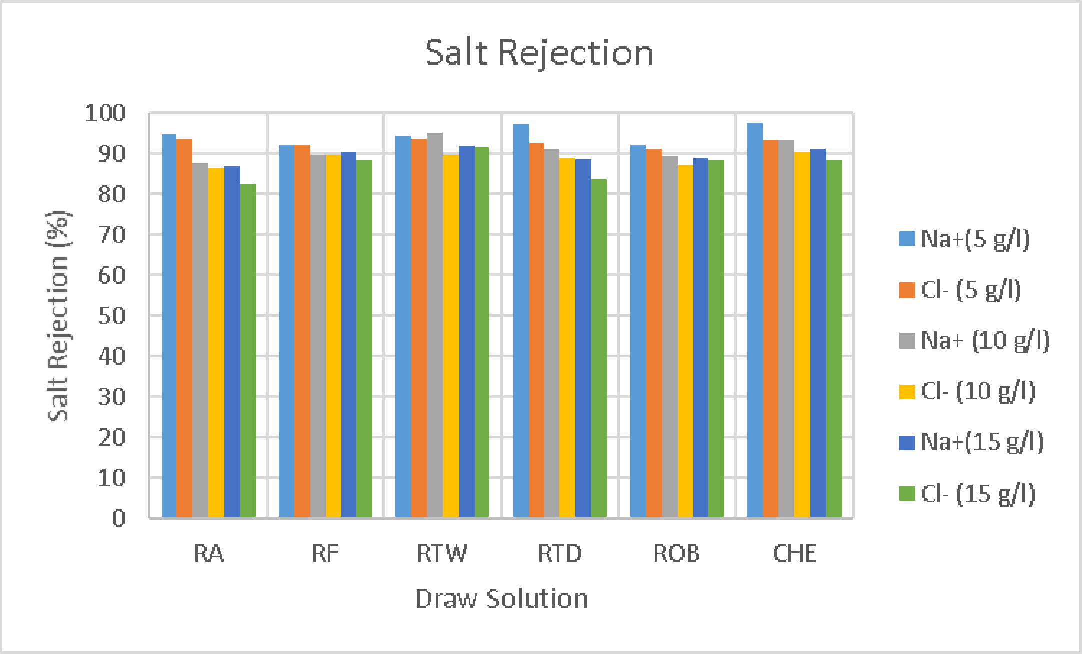


Figure 24 - Forward rejection of FS ions for the different DS solutions

6.2. Discussion

6.2.1. Water Flux

From figure 18, it is concluded that as a general rule of thumb, when comparing between different hydroponic nutrient solutions, it is expected that the nutrient solution with the higher TDS would usually have the higher water flux. This is demonstrated by the CHE solution having the highest flux, across all feed solutions. This is due to the fact that the main driving force in forward osmosis is the osmotic potential gradient between the FS and the DS $(\pi_{draw} - \pi_{feed})$ in equation 3. However, the interactions between the different salt ions could possibly generate minor driving forces, which could affect the overall water flux. The water flux of each of the draw solutions during each individual experiment could have also been affected due to membrane scaling caused by monovalent ions (Phuntsho et al., 2014). In order to minimise the occurrence of inorganic scaling between experiments, DI water flushing was performed several times between each experiment.

6.2.2. Specific Reverse Solute Flux

SRSF values for all salt ions were higher at low fluxes, and lower when operated at high flux, which is the favourable condition. Moreover, it can be observed that across all draw solutions, SRSF values increased as the concentration of the FS increased. This can be explained by the fact that flux decreases as the concentration of the FS increases, and the inversely proportional relation between SRSF and water flux, demonstrated in equation 9. Reverse diffusion of draw solutes is also an important factor when considering membrane scaling, which leads to flux decline, hence, physical cleaning of the membrane after FDFO is crucial to maintaining the flux of the membrane (Phuntsho et al., 2014). Moreover, SRSF causes negative environmental impacts upon the discharge of the feed solution back into the environment (Chekli et al., 2018). Also, SRSF causes negative economic impacts, due to the cost of replenishing the draw solution, the loss of osmotic driving force, and damage of the membrane through membrane fouling and scaling (Chekli at al., 2018).

6.2.2.1. Strategies for RSF Reduction

Due to the negative environmental and economic implications of reverse solute flux (RSF), Zou et al. (Zou, Qin, and He, 2018) propose some operational strategies that could be utilized in order to reduce RSF in forward osmosis.

6.2.2.1.1. Pressure-assisted Osmosis (PAO)

In pressure-assisted osmosis, an energy-efficient enhancement of the forward osmosis process (using approximately 2kWh.m^{-3}) can be executed by adding a relatively low hydraulic pressure to the feed side (<10 bar) (Zou et al., 2018). In one case study, J_s was reduced by 85.7% by applying a 15-bar hydraulic pressure (Shibuya et al., 2015, 18). However, pressure-assisted osmosis (PAO) might have a negative impact on RSF, if the membrane is operated in AL-DS orientation, due to the possibility of structural failure in the supportive layer, due to the hydraulic pressure causing localized stretching in the membrane (Zou et al., 2018). Moreover, the magnitude of the exerted hydraulic pressure is also a variable in yielding a positive RSF reduction; a low hydraulic pressure (≤1 bar) resulted in an increase in RSF (Zou et al., 2018).

6.2.2.1.2. Electrolysis-assisted Osmosis (EAO)

Electrolysis-assisted Osmosis (EAO), also known as e-FO, uses an electric field and the electrolysis in order to control ion migration through the membrane with the purpose of reducing reverse solute permeation (Zou et al., 2018). By introducing an electric field to the feed and draw solutions, the direction of flow of the salt ions can be manipulated, in order to reduce reverse diffusion of draw solutes into the feed solution. It has been reported that in some cases, an RSF reduction of 57% was achieved by utilizing an applied voltage ≥1.5V (Zou and He, 2017). EAO could provide an energy-efficient solution (0.022 kWh/m^3 recovered water) for RSF. However, the DS for the process must be suitable for EAO, and is a topic that still needs further investigation.

6.2.2.1.3. Ultrasonic-assisted Osmosis (UAO)

SRSF can also be decreased by increasing the water flux. One method of achieving that is ultrasonic-assisted osmosis (UAO), which utilizes ultrasound in order to reduce ICP (Zou et al., 2018). By using UAO, water flux can be increased by up to 75%, but at the cost of slightly increasing RSF, due to a combination ofdimished ICP and local heating (Heikkinen et al., 2017). For example, in one of the cases, an SRSF reduction of 51.8% was achieved by applying a 20 kHz ultrasound in 1 minute on-and-off intervals, with an enhanced flux from 13 l/m^2/h (FO) to 24 l/m^2/h (UAO) (Heikkinen et al., 2017). However, applications of ultrasound might lead to damage in the membrane integrity. (Zou et al., 2018).

6.2.2.1.4. Membrane Advancement

While the currently existing commercial FO membranes have progressed in terms of increased membrane performance and decreased cost, they still suffer from relatively high ICP and reverse solute permeation, which leads to a decrease in the osmotic potential gradient, a gradual loss of DS, and an increase in operation costs (Zou et al., 2018). Hence, developing the new breed of FO membranes in a way that achieves a lower ICP and a higher water flux is detrimental towards achieving a more environmentally-friendly and economically-feasible FO water desalination processes (Zou et al., 2018). RSF reduction can be achieved by either modifying the existing membranes, or by fabricating new membranes (Zou et al., 2018).

6.2.2.1.4.1. Membrane Modification

Modification of existing membranes is usually achieved by covering the surface of the active layer of the membrane (mostly TFC membranes), in order to improve antifouling and increase surface hydrophilicity (Guo et al., 2016; Tiraferri et al., 2012). This would ultimately lead to reducing ICP and increasing water flux (Arena et al., 2014). In a case study of polydopamine (PDA) coated TFC membrane, an RSF reduction of 20.9% was achieved, compared to the pristine TFC membrane (Zou et al., 2018). In another case, silver nanoparticle decorated graphene oxide nanosheets (AgNP-GO) led to an RSF reduction of about 15.9%, under an AL-DS orientation (Soroush et al., 2016). However, in other cases of membrane coating, the coated layer hindered water permeation and increased salt permeation (Soroush et al., 2015; Zhang et al., 2013). In conclusion, more research is required in order to fully investigate and comperhend the mass transport and ion exchange within the covered layer of an FO membrane (Zou et al., 2018).

6.2.2.1.4.2. Membrane Fabrication

On the other hand, new membrane fabrication was found to offer more promising results in terms of reducing RSF (Zou et al., 2018). For example, the shift from CTA membranes to TFC membranes in the years between 2013 and 2018 was examined. It was found that the recently developed TFC FO membranes have displayed an average water flux of 30.7 ± 14.4 $l/m^2/h$ in AL-FS orientation, or 49.9 ± 19.0 $l/m^2/h$ in AL-DS orientation (Zou et al., 2018). This is much higher than those achieved by commercial TFC membranes (9.8 ± 4.0 and 20.7 ± 4.4 $l/m^2/h$) or commercial CTA membranes (9.5 ± 3.5 and 15.7 ± 1.8 $l/m^2/h$) (Zou et al., 2018). The highest recorded water flux was reported by using a TFC membrane with vertically oriented porous substrates (70.3 and 84.2 $l/m^2/h$, in AL-FS and AL-DS orientations respectively) (Liang et al., 2017). And despite having a much higher water flux, the recently developed TFC membranes also possess a comparable RSF to that of commercial TFC or CTA membranes (Zou et al., 2018). Hence, continuous research into membrane technology is promising, and is crucial to the commercial application of FO.

6.2.3. Salt Rejection

Salt rejection values for the studied draw solutions were within the acceptable range (≅90%), except at very low osmotic potential gradients. For example, for the RA and RTD solutions (TDS = 20.4 and 31.6 ppt, respectively) and FS 3 (TDS = 17.15 ppt), the salt rejection for Cl^- was 82.6% and 83.7%, respectively. This indicates that the membrane used in the experiment is highly selective against salt ions, and some permeation of salts through the membrane is always expected to happen. In addition, in a real world scenario, brackish groundwater would include dissolved salts other than NaCl, which was not investigated in this study, and might have a further effect on the performance of the membrane.

7. Conclusion & Recommendations

This study investigated the performance of six hydroponic draw solutions as draw solutions for the FDFO process. The feed solution for the process was chosen to be three different concentrations of NaCl, in order to represent different salinities of brackish groundwater.

This was done in order to assess the viability of utilizing forward osmosis to facilitate hydroponic agriculture in arid regions, by diluting the nutrient solutions using water recovered from groundwater through forward osmosis. While FDFO cannot be used independently as a desalination technique, due to the resultant draw solution being a diluted solution still containing salts, it can be used to replace some of the freshwater necessary for dilution of hydroponic nutrient solutions. Performance of the draw solutions was investigated by calculating the water flux, reverse solute flux, and the forward rejection of the salt ions in the feed solution. Moreover, the cost per litre of each of the solution was estimated. It was concluded that the TDS of the nutrient solution and the water flux can be related logarithmically.

As water flux increases, SRSF for all salt ions dropped, which is the desired outcome, since lower SRSF means lower loss of draw solute ions through reverse permeation through the membrane. Salt rejection for almost all experiments was in the 90% range, except when the FS and DS combination yielded a very low water flux.

It was concluded that of the six tested nutrient solutions for lettuce and leafy greens, the “Resh Florida, California (RF)” solution is the recommended solution to be used as draw solution for fertilizer drawn forward. It is recommended due to its high performance in terms of water recovery (15.75%) & flux (11 $l/m^2/h$), salt rejection (92%) & SRSF (highest recorded SRSF for a specific ion (SO_4^{2-}) was 7.3 g/l), as well as its low cost, relative to the other highly performing draw solution “Chekli (CHE)” ($1.07/l vs. $3.73/l). It is recommended to utilize this solution at fluxes higher than 9 $l/m^2/h$, in order to minimize SRSF.

7.1. Proposed Model for Large Scale Application of FDFO in Egyptian Arid Regions

In order to utilize Egypt’s abundant groundwater resources, as demonstrated in section 2.2, the following model is proposed:

In this model, hydroponic agriculture of lettuce and leafy greens can be performed in greenhouses built on arid lands, with forward osmosis units. There are arid lands that have access to both freshwater and groundwater, such as in the Eastern desert and Sinai, which have access to over 100 billion m^3 of groundwater, with salinities between 1,500 and 3,500 ppm, as shown in tables (1) & (2). Freshwater could be accessed from the already established networks in the area.

The hydroponic nutrient stock solutions would be prepared off site in high concentration (100-200 strength stock solution) and then transported to the greenhouses. Then, the forward osmosis unit in the greenhouses could be used to dilute the nutrient solutions using the groundwater as feed solution for the process. Finally, the final dilution of the nutrient solutions to the desired concentration can be performed by using the freshwater. This provides the benefit of decreasing the amount of freshwater required to dilute the stock solutions in order to perform hydroponic agriculture.

According to the work done in this research, it is suggested to use the Resh Florida, California hydroponic nutrient solution, which is suitable for the agriculture of lettuce and leafy greens as a draw solution for FDFO. This nutrient solution was selected due to its high performance and low price. While the Chekli solution performed better in terms of water flux (12.28 vs 11 $l/m^2/h$), the cost per liter of the Resh Florida solution is 28% that of the Chekli solution ($1.07/l vs. $3.73/l). Moreover, the SRSF and salt rejection values for the Resh Florida solution were comparable to those of the Chekli solution in all salt ions.

7.1.1. Sustainability Impacts of Large Scale Application of FDFO in Egyptian Arid Regions

A large scale application of FDFO, if made feasible, would have several positive and negative sustainability impacts, which are briefly highlighted in the following sections.

7.1.1.1. Environmental Impacts

The positive environmental impacts can be summarized as follows:

- **Water:** By applying FDFO on a large scale and utilizing brackish groundwater, some of the freshwater needed for agriculture can be diverted into another section, which helps mitigate water scarcity. Moreover, FDFO provides an alternative source of clean water for agriculture.
- **Energy:** By utilizing a low-energy desalination process such as FO, some of the carbon emissions produced by desalination processes can be avoided or decreased significantly.

On the other hand, negative environmental impacts can be summarised in:

- **Disturbance of Ecosystems:** Building and operating a manmade structure on arable lands might disrupt the cycles of the native species in an area. Hence, such consideration me be taken in mind.
- **Transportation Emissions:** Transporting solutions and crops to and from the greenhouses in remote areas would cause to an increase in GHG emissions

7.1.1.2. Economic Impacts

Positive economic impacts of FDFO are:

- **Job Creation:** Applying FDFO on a large-scale in arid regions opens up the possibilities for new jobs in the agricultural sector.
- **Saving Capital:** FO is significantly less capital-intensive than other desalination processes due to utilizing simpler equipment, and hence, the required investment for desalination is much less. Moreover, the operational costs of FO in terms of energy consumption is considerably less than RO.

However, this project might also have negative economic impacts:

- **Transportation Costs:** Transporting solutions and crops to and from the greenhouses in remote areas would incur some costs.

7.1.1.3. Social Impacts

The positive social impacts of large-scale FDFO can be summarized as follows:

- **Development of Arid Regions:** Any project carried out in arid regions would necessitate an improvement in the infrastructure of the area, which would definitely benefit inhabitants of the area.
- **Raising Awareness:** FDFO could also help raise awareness about water scarcity, and the need for development of green technologies to solve that issue.

7.2. Proposed Future Research Ventures

Future research in the field can be directed at:

- Utilizing a real brackish groundwater sample as the FS for the process.
- Experimenting with other leafy greens nutrient solutions from the literature
- Utilizing nutrient solutions designed for crops other than leafy greens, such as for tomatoes or pepper.

- Experimenting with different concentrations of stock solutions for the same nutrient solution, such as 50 and 200 strength stock solutions.
- Testing the Resh Florida/California (RF) nutrient solution as a draw solution on the pilot-scale.
- Life-cycle assessment of the membrane during FO.
- Growing crops with the resultant draw solutions.
- Experimenting with different types of membranes.
- Perform an economic analysis of draw solute consumed per area of production of lettuce.

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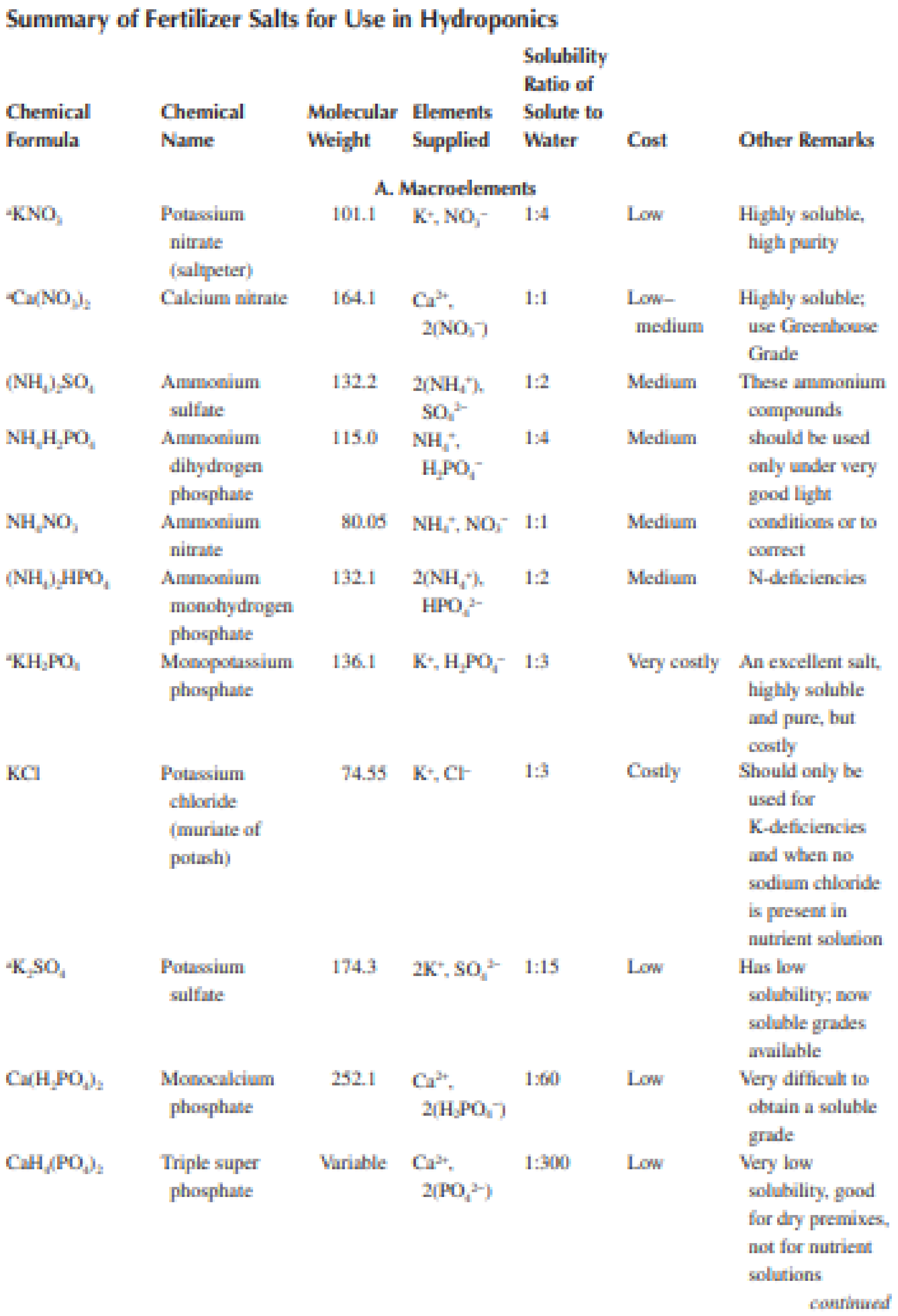
9. Appendix



Summary of Fertilizer Salts for Use in Hydroponics

Chemical Formula	Chemical Name	Molecular Weight	Elements Supplied	Solubility Ratio of Solute to Water	Cost	Other Remarks
			A. Macroelements			
${}^{a}KNO_3$	Potassium nitrate (saltpeter)	101.1	K^+, NO_3^-	1:4	Low	Highly soluble, high purity
${}^{a}Ca(NO_3)_2$	Calcium nitrate	164.1	Ca^{2+}, $2(NO_3^-)$	1:1	Low–medium	Highly soluble; use Greenhouse Grade
$(NH_4)_2SO_4$	Ammonium sulfate	132.2	$2(NH_4^+)$, SO_4^{2-}	1:2	Medium	These ammonium compounds should be used only under very good light conditions or to correct N-deficiencies
$NH_4H_2PO_4$	Ammonium dihydrogen phosphate	115.0	NH_4^+, $H_2PO_4^-$	1:4	Medium	
NH_4NO_3	Ammonium nitrate	80.05	NH_4^+, NO_3^-	1:1	Medium	
$(NH_4)_2HPO_4$	Ammonium monohydrogen phosphate	132.1	$2(NH_4^+)$, HPO_4^{2-}	1:2	Medium	
${}^{a}KH_2PO_4$	Monopotassium phosphate	136.1	K^+, $H_2PO_4^-$	1:3	Very costly	An excellent salt, highly soluble and pure, but costly
KCl	Potassium chloride (muriate of potash)	74.55	K^+, Cl^-	1:3	Costly	Should only be used for K-deficiencies and when no sodium chloride is present in nutrient solution
${}^{a}K_2SO_4$	Potassium sulfate	174.3	$2K^+$, SO_4^{2-}	1:15	Low	Has low solubility; now soluble grades available
$Ca(H_2PO_4)_2$	Monocalcium phosphate	252.1	Ca^{2+}, $2(H_2PO_4^-)$	1:60	Low	Very difficult to obtain a soluble grade
$CaH_4(PO_4)_2$	Triple super phosphate	Variable	Ca^{2+}, $2(PO_4^{2-})$	1:300	Low	Very low solubility, good for dry premixes, not for nutrient solutions

continued

TABLE 3.1 (continued)
Summary of Fertilizer Salts for Use in Hydroponics

Chemical Formula	Chemical Name	Molecular Weight	Elements Supplied	Solubility Ratio of Solute to Water	Cost	Other Remarks
[a]$MgSO_4 \cdot 7H_2O$	Magnesium sulfate (epsom salts)	246.5	Mg^{2+}, SO_4^{2-}	1:2	Low	Excellent, cheap, highly soluble, pure
$CaCl_2 \cdot 2H_2O$	Calcium chloride	147.0	Ca^{2+}, $2Cl^-$	1:1	Expensive	Highly soluble, good to overcome Ca-deficiencies, but used only if no NaCl is present in nutrient solution
$CaSO_4 \cdot 2H_2O$	Calcium sulfate (gypsum)	172.2	Ca^{2+}, SO_4^{2-}	1:500	Low	Very insoluble, cannot be used for nutrient solutions
H_3PO_4	Phosphoric acid (orthophosphoric acid)	98.0	PO_4^{3-}	Concentrated acid solution	Expensive	Good use in correction of P-deficiencies
			B. Microelements			
$FeSO_4 \cdot 7H_2O$	Ferrous sulfate (green vitriol)	278.0	Fe^{2+}, SO_4^{2-}	1:4	—	—
$FeCl_3 \cdot 6H_2O$	Ferric chloride	270.3	Fe^{3+}, $3Cl^-$	1:2	—	—
[a]FeDTPA	Iron chelate (sprint 330) (10% iron)	468.15	Fe^{2+}	Highly soluble	Expensive	Best source of ion; dissolve in hot water
[a]FeEDTA	Iron chelate (sequestrene) (10.5% iron)	382.1	Fe^{2+}	Highly soluble	Expensive	Good source of iron; dissolve in hot water
[a]H_3BO_3	Boric acid	61.8	B^{3+}	1:20	Expensive	Best source of boron; dissolve in hot water
$Na_2B_8O_{13} \cdot 4H_2O$	Disodium octaborate tetra hydrate (solubor)	412.52	B^{3+}	Very soluble	Inexpensive	—
$Na_2B_4O_7 \cdot 10H_2O$	Sodium tetraborate (borax)	381.4	B^{3+}	1:25	—	—
[a]$CuSO_4 \cdot 5H_2O$	Copper sulfate (bluestone)	249.7	Cu^{2+}, SO_4^{2-}	1:5	Inexpensive	—
[a]$MnSO_4 \cdot 4H_2O$	Manganese sulfate	223.1	Mn^{2+}, SO_4^{2-}	1:2	Inexpensive	—

TABLE 3.1 (continued)
Summary of Fertilizer Salts for Use in Hydroponics

Chemical Formula	Chemical Name	Molecular Weight	Elements Supplied	Solubility Ratio of Solute to Water	Cost	Other Remarks
$MnCl_2 \cdot 4H_2O$	Manganese chloride	197.9	Mn^{2+}, $2Cl^-$	1:2	Inexpensive	—
[a]$ZnSO_4 \cdot 7H_2O$	Zinc sulfate	287.6	Zn^{2+}, SO_4^{2-}	1:3	Inexpensive	—
$ZnCl_2$	Zinc chloride	136.3	Zn^{2+}, $2Cl^-$	1:1.5	Inexpensive	—
$(NH_4)_6Mo_7O_{24}$	Ammonium molybdate	1163.8	NH_4^+, Mo^{6+}	1:2.3 Highly soluble	Moderately expensive	—
Na_2MoO_4	Sodium molybdate	205.92	$2Na^+$, Mo^{6+}	Highly soluble	Moderately expensive	—
[a]ZnEDTA	Zinc chelate	431.6	Zn^{2+}	Highly soluble	Expensive	—
[a]MnEDTA	Manganese chelate	381.2	Mn^{2+}	Highly soluble	Expensive	—

[a] These more soluble compounds should be used for preparing nutrient solutions.

TABLE 3.6
Composition of Nutrient Solutions (ppm)

References		pH	Ca	Mg	Na	K	N as NH_4^+	N as NO_3^-	P as PO_4^{3-}	S as SO_4^{2-}	Cl	Fe	Mn	Cu	Zn	B	Mo
Knopp (1865)		—	244	24	—	168	—	206	57	32	—	[b]na	—	—	—	—	—
Shive (1915)		—	208	484	—	562	—	148	448	640	—	[b]na	—	—	—	—	—
Hoagland (1919)		6.8	200	99	12	284	—	158	44	125	18	[b]na	—	—	—	—	—
Jones & Shive (1921)		—	292	172	—	102	39	204	65	227	—	0.8	—	—	—	—	—
Rothamsted		6.2	116	48	—	593	—	139	117	157	17	8	0.25	—	—	0.2	—
Hoagland & Snyder (1933, 1938)		—	200	48	—	234	—	210	31	64	—	[b]na	0.1	0.014	0.01	0.1	0.016
Hoagland & Arnon (1938)		—	160	48	—	234	14	196	31	64	—	0.6	0.5	0.02	0.05	0.5	0.01
Long Ashton Soln		5.5–6.0	134–300	36	30	130–295	—	140–284	41	48	3.5	5.6 or 2.8	0.55	0.064	0.065	0.5	0.05
Eaton (1931)		—	240	72	—	117	—	168	93	96	—	0.8	0.5	—	—	1	—
Shive & Robbins (1942)		—	60	53	92	117	—	56	46	70	107	[b]na	0.15	—	0.15	0.1	—
Robbins (1946)		—	200	48	—	195	—	196	31	64	—	0.5	0.25	0.02	0.25	0.25	0.01
White (1943)		4.8	50	72	70	65	—	47	4	140	31	1.0	1.67	0.005	0.59	0.26	0.001
Dudos (1957)		5–6	136	72	—	234	—	210	27	32	—	3	0.25	0.15	0.25	0.4	2.5
Tumanov (1960)		6–7	300 to 500	50	—	150	—	100 to 150	80–100	64	4	2	0.5	0.05	0.1	0.5	0.02
A. J. Abbott		6.5	210	50	—	200	—	150	60	147	—	5.6	0.55	0.064	0.065	0.5	0.05
E. B. Kidson		5.5	340	54	35	234	—	208	57	114	7.5	2	0.25	0.05	0.05	0.5	0.1
Purdue	A	—	200	96	—	390	28	70	63	607	—	2.0	0.3	0.02	0.05	0.5	—
(1948)	B	—	200	96	—	390	28	140	63	447	—	1.0	0.3	0.02	0.05	0.5	—
	C	—	120	96	—	390	14	224	63	64	—	1.0	0.3	0.02	0.05	0.5	—
Schwartz (Israel)		—	124	43	—	312	—	98	93	160	—	—	—	—	—	—	—
Schwartz (California)		—	160	48	—	234	15	196	31	64	—	—	—	—	—	—	—
Schwartz (New Jersey)		—	180	55	—	90	20	126	71	96	—	—	—	—	—	—	—
Schwartz (South Africa)		—	320	50	—	300	—	200	65	—	—	—	—	—	—	—	—
CDA	A	—	131	22	—	209	33	93	36.7	29.5	188	1.7	0.8	0.035	0.094	0.46	0.027
Saanichton	B	—	146	22	—	209	33	135	36.7	29.5	108	1.7	0.8	0.035	0.094	0.46	0.027
B.C. Canada	C	—	146	22	—	209	33	177	36.7	29.5	—	1.7	0.8	0.035	0.094	0.46	0.027

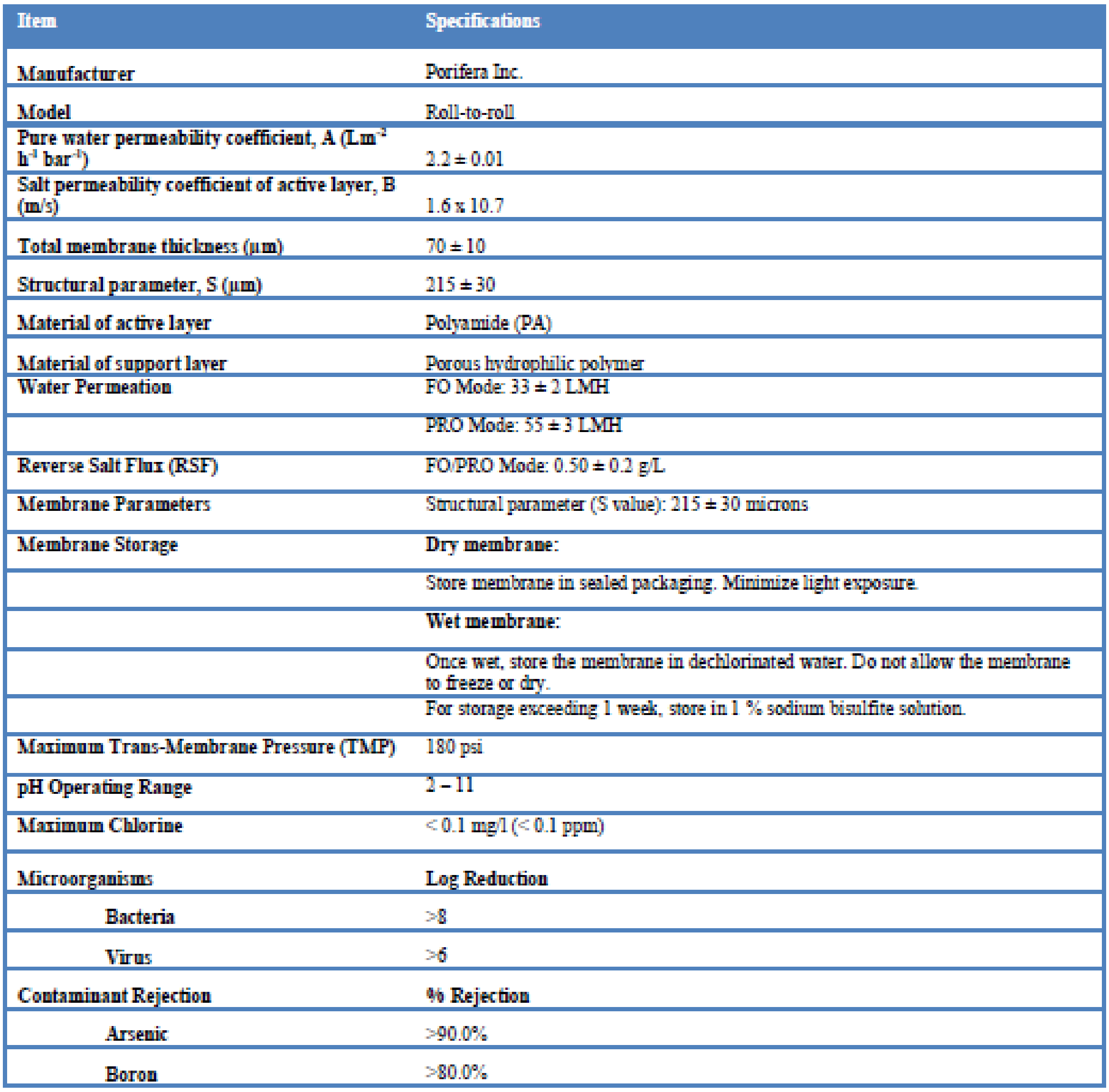
Dr. Pilgrim	C	—	272	54	—	400	—	143.4	93	237.5	—	—	—	—	—	—	—
Elizabeth	B	—	204	41	—	300	—	107.6	70	178	—	—	—	—	—	—	—
N.C., USA	A	—	136	27	—	200	—	71.7	46.5	119	—	—	—	—	—	—	—
Dr. H.M. Resh	C	—	197	44	—	400	30	145	65	197.5	—	2	0.5	0.03	0.05	0.5	0.02
Univ. of B.C	B	—	148	33	—	300	20	110	55	144.3	—	2	0.5	0.03	0.05	0.5	0.02
Vancouver Canada (1971)	A	—	98	22	—	200	10	80	40	83.2	—	2	0.5	0.03	0.05	0.5	0.02
Dr. H.M. Resh Tropical – Dry		—	250	36	—	200	53	177	60	129	—	5	0.5	0.03	0.05	0.5	0.02
Tropical – Wet Lettuce (1984)		—	150	50	—	150	32	115	50	52	—	5	0.5	0.03	0.05	0.5	0.02
Dr. H.M. Resh Lettuce Florida (1989) Calif. (1993)		—	200	40	—	210	25	165	50	113	—	5	0.5	0.1	0.1	0.5	0.05
Dr. H.M. Resh Cucumbers	I	—	100	20	—	175	3	128	27	26	—	2	0.8	0.07	0.1	0.3	0.03
Florida	II	—	220	40	—	350	7	267	55	53	—	3	0.8	0.07	0.1	0.3	0.03
(1990)	III	—	200	45	—	400	7	255	55	82	—	2	0.8	0.1	0.33	0.4	0.05
Dr. H.M. Resh Lettuce Anguilla, B.W.I. (2011)		—	200	50	[a]50–80	210	—	185 to 195	50	66	[c]65 to 253	5	0.5	0.15	0.15	0.3	0.05
Dr. H.M. Resh Tomato	A	—	240	50	—	201	—	169	49	119	—	2.5	0.58	0.15	0.4	0.3	0.03
Anguilla, B.W.I.	B	—	200	60	—	351	—	137	49	196	—	2.5	0.58	0.15	0.4	0.3	0.03
(2011)	C	—	214	50	—	379	—	177	49	145	—	2.5	0.58 to 0.6	0.15	0.3	0.3	0.05
Sonneveld & Straver Tomato	I	—	240	48	—	195	7	224	46.5	64	—	2.3	0.6	0.05	0.4	0.3	0.05
Netherlands	II	—	190	60	—	351	—	189	46.5	128	—	2.3	0.6	0.05	0.7	0.3	0.05
(1992)	III	—	170	48	—	341	18	192	38.7	120	—	2.3	0.6	0.05	0.3	0.3	0.05
Sonneveld & Straver Cucumber	I	—	185	33	—	270	18	190	39	90	—	2.3	0.6	0.05	0.4	0.4	0.05
Netherlands	II	—	210	33	—	345	18	246	39	65	—	2.3	0.6	0.05	0.4	0.4	0.05
(1992)	III	—	170	36	—	293	18	213	39	44	—	2.3	0.6	0.05	0.4	0.3	0.05

[a] Add three times weekly.

[b] na, information not available or indicated trace or as required.

[c] These were sodium and chloride levels in the raw water from sea water desalinated by reverse osmosis. These level variations were present in all formulations used in Anguilla, for lettuce, herbs, tomatoes, cucumbers, and peppers for the period 1999 through 2011.

Membrane



Item	Specifications
Manufacturer	Porifera Inc.
Model	Roll-to-roll
Pure water permeability coefficient, A (Lm^{-2} h^{-1} bar^{-1})	2.2 ± 0.01
Salt permeability coefficient of active layer, B (m/s)	1.6 x 10.7
Total membrane thickness (µm)	70 ± 10
Structural parameter, S (µm)	215 ± 30
Material of active layer	Polyamide (PA)
Material of support layer	Porous hydrophilic polymer
Water Permeation	FO Mode: 33 ± 2 LMH
	PRO Mode: 55 ± 3 LMH
Reverse Salt Flux (RSF)	FO/PRO Mode: 0.50 ± 0.2 g/L
Membrane Parameters	Structural parameter (S value): 215 ± 30 microns
Membrane Storage	**Dry membrane:**
	Store membrane in sealed packaging. Minimize light exposure.
	Wet membrane:
	Once wet, store the membrane in dechlorinated water. Do not allow the membrane to freeze or dry.
	For storage exceeding 1 week, store in 1 % sodium bisulfite solution.
Maximum Trans-Membrane Pressure (TMP)	180 psi
pH Operating Range	2 – 11
Maximum Chlorine	< 0.1 mg/l (< 0.1 ppm)
Microorganisms	**Log Reduction**
Bacteria	>8
Virus	>6
Contaminant Rejection	**% Rejection**
Arsenic	>90.0%
Boron	>80.0%