UNIVERSITY OF CALIFORNIA,
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A review of Forward Osmosis application on fertigation and desalination

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Civil and Environmental Engineering

by

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Thesis Committee Members:

Professor Diego Rosso, Chair

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DEDICATION

To

My awesome family,

Diego Rosso, my talented professor

Chau N Tran, my supportive friend

Angie Zuniga, department advisor

Thank you all for being there during my master's adventure.

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ACKNOWLEDGMENTS

The notion of being an environmental engineer often has drastically different meanings when it is perceived by individuals. Personally, this concept represents both expertise and ethics: Sound engineering academic background combined with environment-centered benevolent humanism equal qualified environmental engineer.

As Environmental engineers, we prevent and resolve the contamination of air, soil, and water for public health. Environmental engineering is where public health and environmental needs meet, it includes many aspects of environmental science. During two years of study at the University of California, I have acquired both academic and practical knowledge regarding air quality, soil contamination, and water treatment/reuse. To become a qualified Environmental engineer, it is crucial for one to integrate basic environmental science and one's professional field (water treatment). The purpose of my thesis paper is to resolve the current consequential environmental contaminations using the specialized knowledge I learned at the University of California, Irvine.

Out of interest and research, I found that Nitrous oxide plays a vital role in aggravating the greenhouse effect and becoming a growing threat to public health, especially to regions that are populated and agricultural, like the state of California. Nitrous oxide is also detrimental to air quality (forming particle matters) and the atmosphere (warming troposphere). Through the Nitrous Oxides estimation Model, it is proven that the redundant Nitrogen input in the soil is a main factor of the expanding Nitrous oxide emission. As the population grows voluminously, the requirement of fertigation is accreting with food demand. Using Fertilizer drawn Forward osmosis technology to complete the fertigation water treatment can not only reduce the Nitrogen input in the fertigated water but also save a considerable amount of energy.

This review provides practical water treatment designs for N_2O air pollution, superfluous nitrogen input as soil pollution, and water shortage (water reuse using forward osmosis technology). Hopefully, it could contribute a little to the environment, and people are healthier because of environmental engineers.

Lastly, I want to thank Professor Diego Rosso for his academic guidance, support, and encouragement throughout my thesis study journey.

ABSTRACT

A review of Forward Osmosis application on fertigation and

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By

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Master of Science in Civil and Environmental Engineering

University of California, Irvine, 2022

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With the development of membrane science, reverse osmosis is at its peak in terms of innovations and developments. Its limitations, such as the high energy consumption, have been widely recognized. To eliminate said disadvantages, Forward osmosis (FO) is often viewed as a promising alternative in resource conservation, desalination, and wastewater treatment. This critical review is dedicated to exploring current applications regarding N_2O elimination methods that utilize FO. As one of the primary causes of greenhouse effects, N_2O emission in California is contributed mainly by agricultural soil (75%), where the combination of Fertilizer-drawn Forward Osmosis (FDFO) and Nanofiltration (NF) can be adopted to reduce N_2O emission by treating fertigation water to reduce over-fertilization. An empirical model of soil emission of N_2O shows a positive linear relation between the N fertilizer input and N_2O emitted. Since fertigation is extensively used in agriculture fields, when a FO system is integrated into the fertigation process, employing FDFO and Nanofiltration (NF), the minimization of N_2O emission through direct fertigation treatment

can be achieved. Also, additional benefits are removing extra nitrogen and easing water shortage by treating brackish water. The energy consumptions of FO and FDFO are addressed in the end to test the applicability of different models.

Chapter 1

1 Introduction

1.1 Agricultural Nitrous oxide emissions

As one of the six major air pollutants, nitrous oxide emission is one of the biggest contributors to the greenhouse effect. The sources of Nitrogen oxide emission are diverse. According to the federal and state ambient air quality standards in the United States, 75% of the total statewide Nitrous oxide (N_2O) emissions are from various agricultural soil management activities (Hockstad et al., 2018).

Based on the data provided by Environmental Protection Agency (EPA), Nitrous oxide is always present in the stratosphere. (IPCC, 2007) The impact of 1 pound Nitrous oxide is 300 times more detrimental than 1 pound of carbon dioxide on warming the stratosphere. (Reay et al., 2016)

As figure 1-1 shows, there are 4% of the N_2O emission from transportation, 4% from manure management, 5% from industry or chemical production, 5% from stationary combustion, and 6% from wastewater treatment. In contrast, there are more than 74% of the N_2O emission comes from agriculture soil management in the state of California, which sums up about 160,000 metric tons of N_2O emitted per year from the croplands of California. (Hockstad et al., 2018) In terms of fertilized croplands, they have higher emissions of N_2O from the soils.

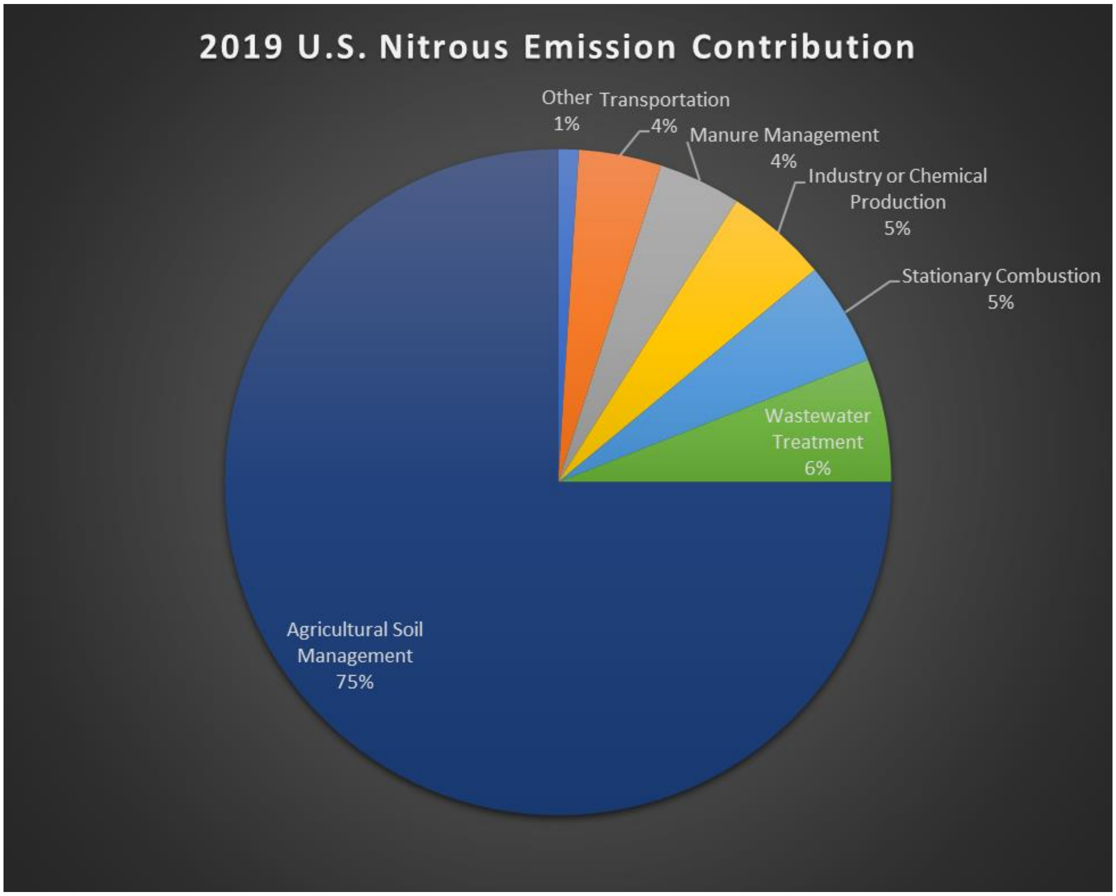

Figure1-1. 2019 U.S. Nitrous oxide Emission Contribution

(Hockstad et al., 2018)

As one of the greenhouse gasses, Nitrous oxide is also one of the driving forces to ozone depletion. (Revell et al., 2015) Nitrous oxide facilities raise the temperature of the troposphere as a ramification of the atmosphere. To be more specific, nitrous oxide enhances the greenhouse effect by capturing infrared radiation that is reflected by the planet's surface and heating the troposphere as an upshot. (Reay et al., 2012) Generally, it is released from soils to the atmosphere through the nitrification of ammonium. Nitrification of nitrogen fertilizer produces profuse nitrous oxide, which depletes the stratospheric ozone layer. With an estimate of 9 billion global population by

2050 (SDG, 2020), the demand for food would increase rapidly, which indicates the N_2O emission can have an upsurge in the future. As a state that supports 12% of U.S. food production, California has an overfertilization N_2O emission factor above 13%. (Almaraz et al., 2018) The application of an efficient Nitrous reduction treatment system needs to be widely carried out in the field of agriculture to lower N_2O emission. In the next section, viable solutions would be discussed after exploring the factors causing Nitrous oxide emission.

1.2 Research Topics & Hypothesis

According to previous research (Richter et al., 2009), fertilizer with higher Nitrogen input results in high emission of N_2O in soil. The direct fertilizer-related agricultural N_2O emission is related to the amount of nitrogen input. However, it has not been proved that either different environmental factors or nitrogen fertilizer usage in the soil would affect the N_2O emission on a greater scale. It has been discovered that the amount of N input in fertilizer/soil affects agricultural Nitrous oxide emission. (Almaraz et al., 2018) This statement indicates that low nitrogen fertilizers would not have a zero N_2O emission but a much lower N_2O emission than fertilizers with an excess of Nitrogen input. The N_2O emission could also be affected by the textures of soil, the categories of crops, various amounts of nitrogen input in fertilizer, and climate conditions including temperature and humidity. To be concise, Environmental parameters determine the mass of produced gas (N_2O emission) in microbiological processes. (Firestone et al., 1989) (Chen et al., 2007)

With existing problems of the high N_2O emission from the agricultural sector, the rationale and process of agricultural nitrous oxide production can be critical to the research. The microbiological basis of N_2O is the process of soil nitrification and denitrification. In the process of nitrification and denitrification, different soil properties and environmental conditions are found to have a direct linkage to the amount of N_2O emission production. (Firestone et al., 1989) As a result, one of the research topics of this research is, what agricultural factors are affecting Nitrous oxide emission from the soil. Assumptions of this research question are types of crops/plants, different types of soils and fertilizer, and disparate climatic conditions. The second topic towards problem-solving: what an effective way is to reduce Nitrogen oxide emission by treating fertigation. In another word, how to reduce the Nitrogen input in fertigation by applying different water treatment methods.

1.3 Possible solutions

To reduce the N_2O emission, the first task is to explore the main agricultural factors that cause the excess discharge of Nitrous oxide. Air quality is usually related to soil and water contamination. There is a high possibility that it is not only related to the soil properties and environmental conditions but also the fertigation system that has been used. Fertigation treatment is one of the most effective ways to reduce the Nitrogen input in the soil since there are more than half of farms use fertigation as the main irrigation solution instead of the traditional fertilization methods in the

United States. (ElZayat et al., 2019) Fertigation is an irrigation system that is added with fertilization. It is more convenient to target the fertigation nutrient deficiencies compares to traditional fertilization. (Kim et al, 2016) Water treatment methods can remove the excess nitrogen, potassium, phosphorus, and other deficiencies in irrigated water for direct fertigation. Choosing an efficient water treatment method to produce freshwater for direct fertigation becomes difficult due to the limited amount of energy consumption. (El Zayat et al., 2010) Among all the membrane treatment methods, forward osmosis (FO) uses the natural energy of osmotic pressure to filter water for higher quality. In another word, forward osmosis is not driven by energy-consuming hydraulic pressure, and it has extremely low energy consumption. Hence, fertilizer-drawn forward osmosis (FDFO) with nanofiltration (NF) has been studied to remove various nutrients for direct fertigation. Nanofiltration could be either applied as pre-treatment or post-treatment of FDFO as the hybrid treatment process of fertigation. Research indicates that when nanofiltration serves as post-treatment, it could reduce more than 80% of the Nitrogen input. (Chekli et al, 2016) The same treatment model (FDFO + NF) could also be used for desalination, which can remove brine for the water that contains a lower total dissolved solid than seawater. (ElZayat et al., 2019)

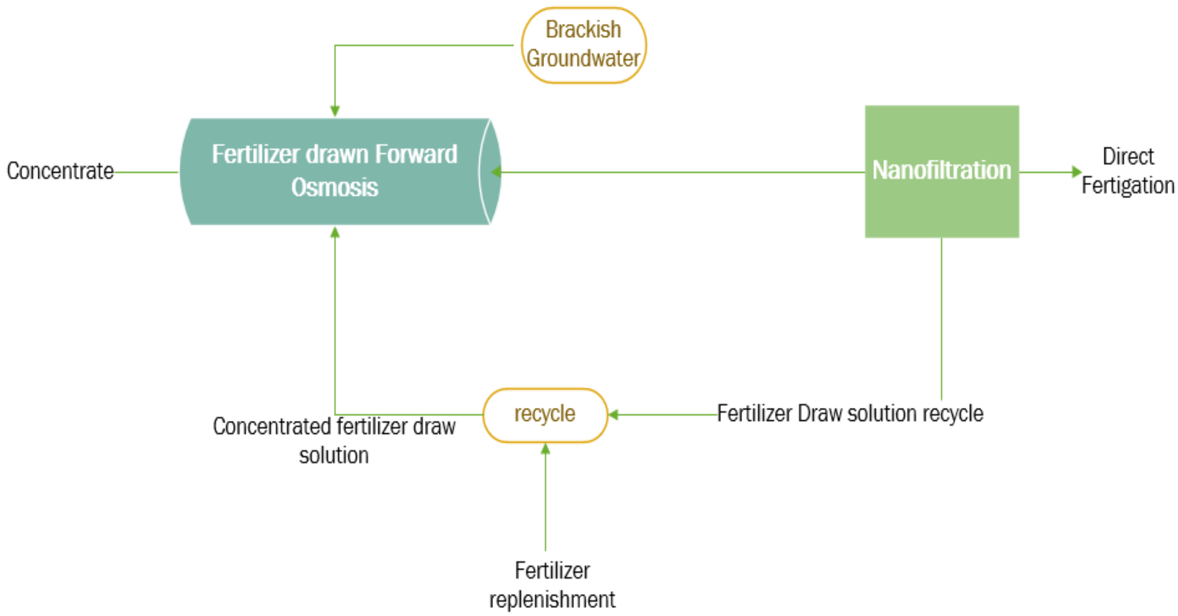

Figure 1-2. Conceptual process layout of FDFO–NF desalination process

Chapter 2

2 Background

2.1 Main factor of agricultural N_2O emission

2.1.1 N_2O emission Model Estimation

To answer the first research question, the nitrogen and non-nitrogen fertilizer usage data need to be researched, and N_2O emissions of the two different fertilizers should be compared. Nitrogen fertilizer and low-nitrogen fertilizer inputs to California agricultural soils could be tracked using the croplands data provided by the DWR of California and USDA fertilizer type. (Almaraz et al., 2018) Moreover, the amount of nitrogen input in the soil could also be tested by laboratory experiments. To estimate the N_2O emission as precisely as possible, the empirical model of soil is used to complete this estimation. (Song et al., 2020) This model can predict the N_2O emission with an 85% precision. (Yienger et al.,1995) The empirical model is a linear function that connects soil temperature, precipitation, and fertilizer categories. N_2O emission can be calculated using the following equation in the empirical model:

$$Flux = A * e^{k^{-1} * T} \text{ ....Eq-1}$$

where T= soil temperature (℃)

A=biome fitting parameter ($ngNm^{-2}S^{-1}$)

k= average dependency coefficient

This equation calculates N_2O flux using the empirical model under the condition of T is between 15-35 degrees Celsius, the value of A indicates the fertilizer rate in kg N/ha. The fertilizer rates vary depending on different types of crops in the field. With all the correct parameter inputs, this function could calculate the precise N_2O flux.

The amount of emission of N2O could be also calculated by the stable isotope method. (Ryabenko et al., 2013)

$$\delta = \left(\frac{R_{sample}}{R_{standard}} - 1\right) * 1000 \quad \text{..........................Eq-2}$$

Where R = oxygen isotopic ratios

δ = nitrogen isotope (δ15N)

$$\delta = \left(\frac{\frac{15N_{sample}}{14N_{sample}}}{\frac{15N_{air}}{14N_{air}}} - 1\right) * 1000 \quad \text{............................Eq-3}$$

Where δ=%-difference Coeff. to a widely used reference standard

$\frac{15\text{N}}{14\text{N}}$ = Ratio of two stable nitrogen isotopes

To calculate different isotopic compositions (*δ)* of various Nitrogen, the ratio of 15N isotope over 14N isotope equals to value R, 15N has a total number of 15 protons and neutrons of element Nitrogen while 14N has a total number of 14 protons and neutrons of element Nitrogen. Equation-3 is a decomposition of Equation-2, Equation-2 works for all the elements while equation-3 is specifically for Nitrogen isotopic composition. (Ryabenko et al., 2012)

$$\alpha_{eq} = K^{\frac{1}{n}} \quad \text{.........................} \quad \text{Eq-4}$$

Where K= equilibrium constant

α_{eq} =equilibrium fractionation factor

n= number of exchanged atoms

Equation-4 calculates the equilibrium fractionation factor. It affects the number of bonds in Nitrous, and it determines the states of Nitrogen (solid, vapor, or gas). Since the soil and air temperatures contribute to the change of equilibrium effect, temperature value inputs are collected in the cropland. After data collection and calculations, different N input fertilizer usage and N_2O emissions are compared to get the results.

The emissions of N_2O and NO from the soil are mostly produced by the chemical process of nitrification and denitrification. In this review, denitrification is the focus since it is an abiotic process to produce NO and N_2O. (Firestone et al., 1989) In this research, the authors collected soil samples containing various Nitrogen input fertilizers in the field and sent them to the lab for analysis. The authors tested the following properties: 1) soil Nitrogen input 2) soil porosity 3) soil organic carbon content 4) soil oxygen content 5) soil temperature 6) soil PH value. The experiment uses the control variable method to test how each property affects the N_2O emission. When a certain property is being tested, the authors remain other variables constant.

2.1.2 Agricultural factors affecting N_2O emission

According to the variables calculated in the empirical model, there could be a positive linear relation between the fertilizer input and N_2O from the soil. (Yienger,1995) As Table 2-1 shows, higher usage of Nitrogen fertilizer leads to a higher N_2O emission. (Dobbie et al., 2003) The soil that has a higher porosity also results in a higher N_2O emission indirectly. The porosity of soil is the ability to hold water and air in the soil, the porosity of clay is larger than the porosity of sand. Due to the larger porosity, clay is more likely to produce a larger amount of N_2O than sand. (Firestone et al., 1989)

	Effect on denitrification	**Effect on N2O ratio**
Increasing Nitrogen input	+	+
Increasing oxygen content	-	+
Increasing the organic carbon content	+	-
Increasing temperature	+	-
Increasing PH	+	-

Table 2-1: Effect of changes in factors on the N_2O emissions

(Lesschen et al., 2011)

Therefore, the amount of water and oxygen are critical factors to N_2O emission, and soil water content could be controlled by the soil type and evapotranspiration. (Firestone et al., 1989) Another research shows that Nitrous oxide emission from the soil is higher in spring than that in summer. (Lesschen et al., 2011) The total emission of agricultural N_2O is larger in regions that have a higher amount of precipitation compared to regions that have a lower amount of precipitation. In table 2-1, the increasing nitrogen input and soil oxygen content may boost the N_2O emission, while the increasing organic carbon could decrease the N_2O and N_2 ratio.

$$NO^{3-} \rightarrow NO^{2-} \rightarrow NO \rightarrow N_2O \rightarrow N_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq\text{-}5$$

Denitrification process equation

Bacteria could be a major effect on the N_2O emission while carbon has a considerable limitation on the N_2O emission since carbon could interfere with the denitrification process as an electron donor. Reducing the NO^{3-} (which indicates nitrogen fertilizer) could also reduce the N_2O emission since NO^{3-} and NO^{2-} are the two major N-oxide required for the process of denitrification to produce N_2O and N_2. (See equation 5) Moreover, oxygen availability could be the dominant environmental controller of Nitrous oxide emission. (Firestone et al., 1989)

Soil Factors (Increasing)	N2O emission
Soil oxygen content	Increase
Soil water content	Increase
Soil temperature	Increase ($Temperature\ range 2℃ - 37℃$)
Soil PH	Decrease (PH from 1-10)
Soil Porosity	Increase

Table 2-2: Deciding soil properties of agricultural N2O emission rise

Three of the main soil factors that affect the denitrification rate are the application of oxygen, soil water content, and temperature. (Reay et al., 2012) The compatible temperature for active nitrification should be from 2 to 50-celsius degrees. (Firestone et al., 1989)

PH could have minor effects on N_2O emission, increasing the soil acidity (in the range of PH from 1-7) and decreasing the bacteria could reduce the Nitrous oxide (N_2O) emission effectively. (Dobbie et al., 2003) However, to manage the fertilizer effectively to reduce Nitrous oxide emission, climate and seasonal conditions should be considered as well. Since the increasing sulfide could increase the N_2O and N_2 production from soil, Nitrogen-free fertilizer and sulfite-free fertilizer should be prioritized. (Reay et al., 2012) The largest amount of NH3 is from either urea applied to any crops/soils, or from ammonium sulfate applied to soil as a fertilizer. Considering the economic choice, replacing urea with ammonium nitrate could also reduce the N_2O emission in summer due to the higher temperature and higher humidity. In contrast, the substitution of ammonium nitrate for urea as fertilizer would increase the emission of Nitrous oxides (N_2O) due to the higher humidity.

2.1.3 Nitrogen input in soil

The last section has shown all the potential factors for agricultural Nitrous oxide emission, it is found that the nitrogen input has the most momentous effect on the mounting Nitrous oxide emission. As figure 2-1 shows, the area that has a higher Nitrogen fertilizer input results in a higher Nitrous oxide emission estimation. The estimation of Nitrous oxide from California soils is modified using stable isotopic modeling and the IMAGE model. (Almaraz et al., 2018) Reducing nitrogen input in the soil becomes the most crucial part of reducing nitrogen oxide emissions. Different water treatment methods could be applied to the fertigation water removing excess nutrients and reducing nitrogen for N_2O emission reduction purposes.

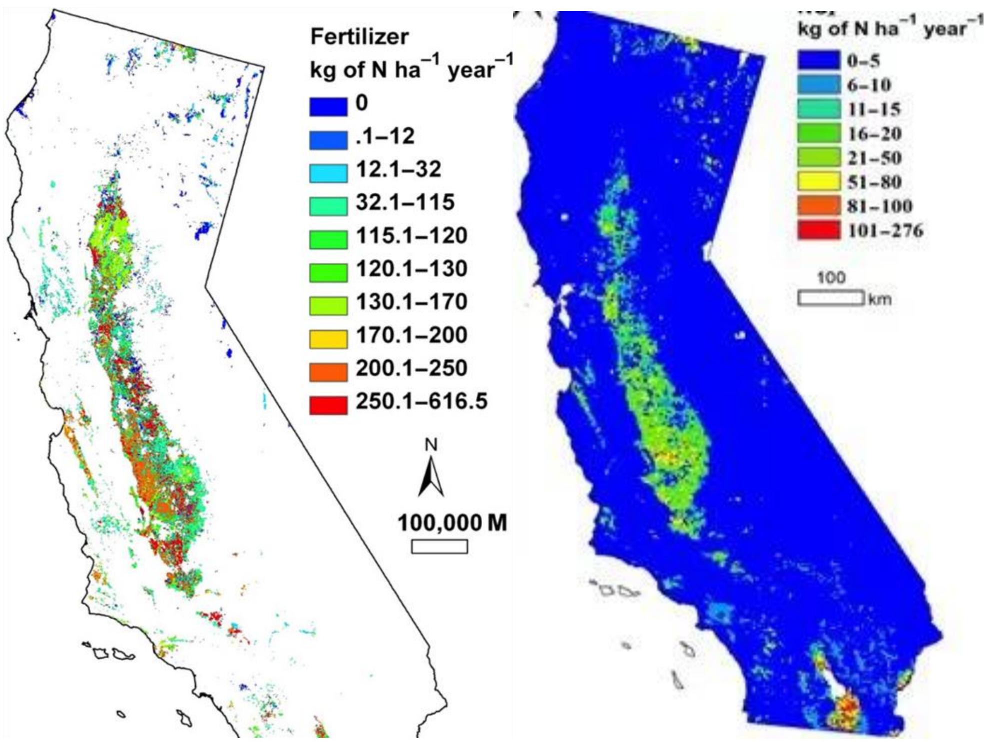

Figure 2-1. Nitrogen fertilizer soil input & estimates of N_2O emission from California soils

(Almaraz et al., 2018)

There is up to 1200g N_2O -N ha−1*d−1 when the soil is over-fertilizing, the highest record of annual N_2O emission is around 28 kg/ha. If the nitrogen input could be reduced up to 50%, the N_2O emission is estimated to be around 1.8 kg/ha. (Dobbie et al., 2003)

2.2 Solution of reducing Nitrogen input by fertigation

2.2.1 Forward Osmosis

Forward osmosis (FO) is the process where water flows from the area on the lower concentrated water chemical potential side through the selectively permeable membrane to the higher concentrated water chemical potential side area. The draw solution usually has a higher concentration while the feed solution has a relatively low concentration. Two solutions with different osmotic pressures are placed on both sides of the semi-permeable membrane, one side is a feed solution with a lower osmotic pressure, and the other is a driving solution with higher osmotic pressure (draw solution). Forward osmosis uses the osmotic pressure difference of the solution on both sides of the membrane as the driving force, so that water can spontaneously pass through the selective permeability membrane from the raw material liquid side to the driving liquid side. When the solution on the side with high osmotic pressure applies pressure (△P) that is smaller than the osmotic pressure difference (aTr), the water would still flow from the raw material hydraulic pressure to the driving fluid side. This process is called pressure damping osmosis (or Pressure-retarded osmosis, PRO). (Chekli et al., 2016) The driving force of pressure damping penetration is called osmotic pressure, so it belongs to one of the forward osmosis processes. In conclusion, FO uses natural energy in the form of osmotic pressure to transport water through the membrane while retaining the dissolved solutes on the other side.

The process of Forward Osmosis (FO) could be run with low hydraulic pressure or without any hydraulic pressure. Forward Osmosis (FO) could be used for product concentration, waste concentration, and the production of clean water. In most situations, water would be extracted from the feed solution, and the waste/concentration would be left on the surface of the membrane. Since water molecules are passing through a semi-permeable membrane, from the feed solution into the draw solution. A draw recovery system is often necessary for producing clean water and recovering the draw solution for reuse. The forward osmosis desalination process usually includes osmotic dilution of draw solution and freshwater production from diluted draw solution. There are two types of forward osmosis desalination based on the different water production methods. One applies heat sinking draw solution that broke down into volatile gases (such as SO_2 and NH_3-CO_2), these gases could also be recycled during the thermal decomposition and generate high osmotic pressure. (Long et al., 2018) The other is used as filtration or dilution of water. For instance, the combination of reverse osmosis and forward osmosis could be used for drinking water treatment or brine removal, forward osmosis could also be a fully or partly replacement of ultrafiltration (UF) under certain circumstances. (Chekli et al., 2016) Recent studies in materials science also proved that forward osmosis could be used to control drug release in the human body, it could also control the food concertation in the production phase. (Wu et al., 2017)

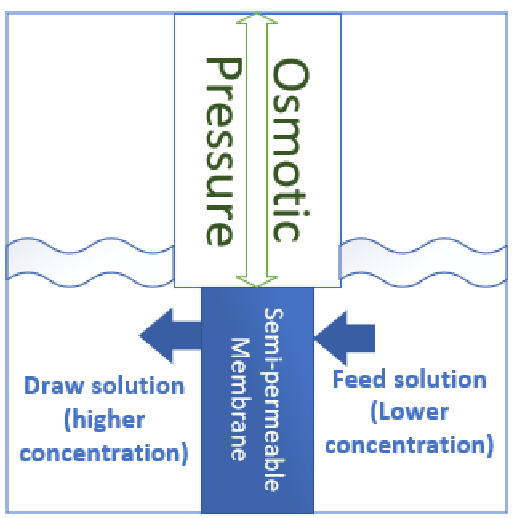

Figure 2-2. Schematic diagram of Forward Osmosis

Regarding the semi-permeable membrane used in Forward osmosis, the tubular membrane is more functional for many reasons. The tubular membrane is one of the membranes that allow solution flows bidirectionally of the membrane, it maintains high hydraulic pressure without deformation due to the self-supported feature, it is also easier to fabricate while retaining high flexibility and density. (Chekli et al., 2016)

The most common application of forward osmosis treatment methods is seawater desalination. (Iskander et al., 2017) Although there is a substantial amount of energy required to treat seawater using Forward Osmosis technology, its potential has been demonstrated through bench-scale experiments, indicating further investigations are needed to evaluate its commercial application. Seawater desalination has provided freshwater for over 6% of the world's population. (El Zayat et al., 2021) One of the commonplace models of forward osmosis seawater treatment is using a hollow fiber membrane. The key parameter in the hollow fiber membrane model is the minimum draw solution flow rate. When the flow rate increases, the energy requirement increases as well. In an ideal Forward Osmosis process, CDO (concentration of draw solution at the membrane outlet) and CFI (feed solution at the inlet) should be equal. Figure 2-3 below shows the schematic diagram of the forward osmosis membrane module. (Altaee et al. 2019)

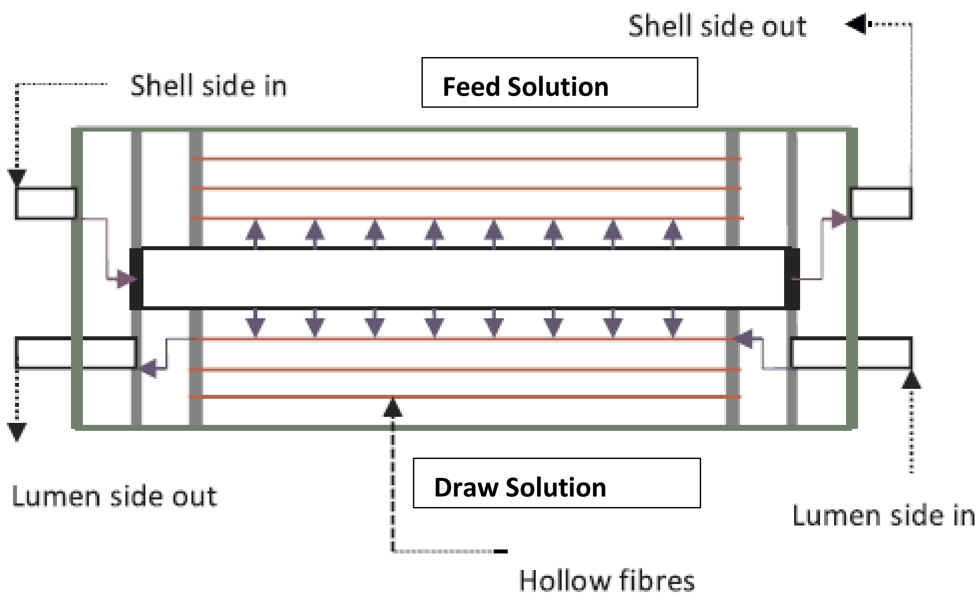

Figure 2-3. Schematic diagram of the forward osmosis membrane module (Altaee et al. 2019)

To assess the energy consumption in the FO process, the solution concentrations and flow direction of the module should be determined first. The data supports that the energy required for pumping the draw solution is less than that for pumping feed solution. To determine the effects of the direction of hydraulic pressure in the module, different modules with various concentration solutions and flow rates are designed to compare the energy efficiency. In conclusion, the results demonstrate that to reduce the energy consumption of seawater desalination, the FO module need to optimize these diameters. Also, the flow rates and concentrations of draw and feed solutions play a major role in terms of energy efficiency. The module illustrates that when a high flow rate feed solution is on the shell side and a draw solution with a low flow rate is on the lumen side, the system consumes less energy consumption. (Altaee et al., 2019)

Another vital implementation of Forward Osmosis is food concentration/enrichment. Multiple studies concluded that FO is efficient when it comes to dewatering for food production. (Wu et al., 2017) (Chekli et al., 2016) Compared to the traditional concentration method, such as pressure-driven membrane, FO requires less energy and yields less nutrition loss. Nutrition loss refers to the reduction of monomers fructose here. (Garcia-Castello et al., 2009) A closed-loop feed solution and draw solution system are built as figure 2-4 below.

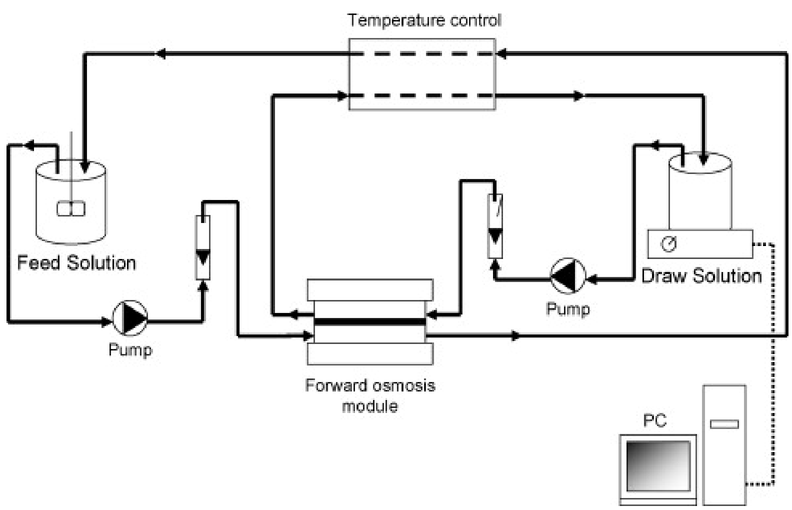

Figure 2-4. closed-loop feed solution and draw solution system (Garcia-Castello et al., 2019)

Garcia-Castello tested two membranes in the system above. A flat sheet of cellulosic membrane and an AG reverse osmosis membrane. AG membrane refers to a certain designation of membrane manufactured by Sterlitech. The result shows that the AG membrane has a higher salt rejection rate. During the procedure, once the water flux reaches a constant value, a feedstock solution is added to the tank to reach the next feed solution concentration. At the end of the experiment, the highest feed solution is 1.65M sucrose. (Mnif et al., 2015) By comparing performances of different membranes, the AG membranes yield better results when concentrating on sucrose solution due to its tucker support structure. (Garcia-Castello et al., 2009) The temperature also has a significant impact on water flux. Usually, higher temperature yields higher water fluxes. (Lambrechts et al., 2019) Compared to the concentration factor of RO, FO has a better concentration factor of 5 while it requires much less energy

2.2.2 Fertilizer-drawn forward osmosis

Fertilizer drawn forward osmosis applies the forward osmotic dilution of the fertilizer draw solutions. This technology could be used for direct agricultural irrigation. Fortunately, most of the fertilizers could be used as a draw solution for FDFO. Fertilizer drawn forward osmosis shares the same principle with forward osmosis. Freshwater as feed solution (with a lower concentration) flows through the semi-permeable membrane to the fertilizer draw solution (with a higher concentration) under the natural osmotic pressure. Additional treatments might be required to reach the water quality for different purposes.

Regarding the nitrogen removal purpose for this review, operating conditions such as feed solution concentration, feed solution water flow rate, and specific water flux can affect the effectiveness of nitrogen removal. Fertilizer-drawn forward osmosis has common applications in water recycling and fertigation applications. Nanofiltration is a viable solution for diluting the fertilizer draw solution for recycling purposes. Fertilizer-draw forward osmosis technology has used brackish water, brackish groundwater, treated coal mine water, and brine water as the feed solutions. In another word, water that has a relatively lower total dissolved solid could be feed solution for fertilizer drawn forward osmosis. Moreover, fertilizer drawn forward osmosis is also effective on biogas energy production when it is applied to an anaerobic membrane bioreactor (AnMBR) as a hybrid process. (El Zayat et al., 2019) In conclusion, fertilizer drawn forward osmosis is effective for sustainable agriculture and water reuse. Its considerable recovery rate could be used as the hydroponics part in an anaerobic membrane bioreactor (AnMBR). (Phuntsho et al., 2011)

Due to the scarcity of fresh water in arid areas, hydroponics has been used for vegetable production. In the field of hydroponics, a subset of hydroculture, crops are cultivated in a soilless environment, their roots are exposed to mineral nutrient solutions or fertilizers. Without soil culture, this type of agricultural production precludes certain aspects that are associated with traditional crops production, including soil pollution, lower fertilizer utilization efficiency, or spread of pathogens. This technology also allows the production of crops in arid, infertile, or simply too populated areas. However, economic cost aside, this technique requires both a large amount of fresh water and fertilizers compared with soil-based crops production. This could easily cause detrimental effects to the environment such as water waste and contamination, excessive nitrogen, potassium, and phosphate resulting in eutrophication. (Chekli et al., 2107) To achieve the balance between cost, efficiency, and quality, reverse osmosis and ultrafiltration are more advanced and general approaches compared to biological seawater treatments. In terms of treating seawater, the hydroponic nutrient solutions demonstrate similar performance compared with other aqueous solutions of a lower molecular weight salt. By utilizing certain membrane technologies, treated effluent has reduced the presence of pathogens and remained the ability to be better integrated into the fertigation system for direct application. The potential of the fertilizer drawn forward osmosis process was investigated for brine removal treatment and water reuse through energy-free osmotic dilution of the fertilizer for hydroponics. (Chekli et al., 2107)

2.2.3 Nanofiltration

Nanofiltration is a pressure-driven membrane process, it refers to a special membrane process that removes dissolved solutes. The membrane is with pores ranging from 1 to 10 nanometers, hence the name "nanofiltration". Nanofiltration uses a similar principle as reverse osmosis, it is a water purification process that requires pressure, and its membranes are permeable to ions. Nanofiltration is practical in removing organic substances from coagulated surface water, it is also economic and environmentally sustainable. (Hilal et al., 2004)

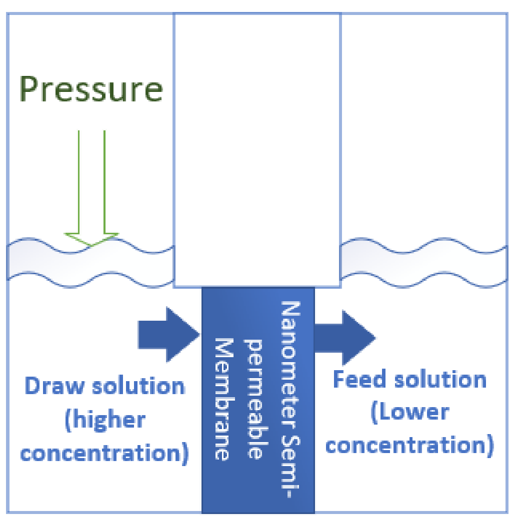

Figure 2-5. Schematic diagram of Nanofiltration

In terms of size and mass of solvents removed by nanofiltration membranes, they usually operate in the range between reverse osmosis and ultrafiltration: removing organic molecules with molecular weights from 200 to 400. Nanofiltration membranes can also effectively remove other pollutants including endotoxin/pyrogen, pesticides, antibiotics, soluble salts, etc.

Depending on the type of salt, it has various removal rates. For salts containing divalent anions, such as magnesium sulfate, the removal rate is around 90% to 98%. However, regarding salts containing monovalent anions, such as sodium chloride or calcium chloride, the removal rate is lower, which is between 20% to 80%. (Kim et al., 2013) The osmotic pressure across the membrane is typically 50-225 psi. One of the advantages of Nanofiltration is that it uses lower pressure and sustains higher water flux. Plus, it has highly selective rejection properties. Typical applications for nanofiltration membrane systems include the removal of color (e.g., wastewater color removal), total organic carbon (TOC) from surface water, reduction of total dissolved solids (TDS), and the removal of hardness or radium for well water. (Hilal et al., 2004)

Chapter 3

3 Exploration of Forward Osmosis desalination

3.1 FO evaluation for water reuse

3.1.1 Forward Osmosis desalination

In 1952, Congress passed the Saline Water Conversion Act, which is aimed at resolving the shortage of freshwater and excessive use of underground water. Two years after the act, the first desalination plant in the United States was built in 1954 at Freeport, Texas. The planet is still operative to date and is undergoing improvement. U.S. Department of Agriculture predicts to supply 10 million gallons of fresh water per day in 2040. The Claude "Bud" Lewis Carlsbad Desalination is the largest desalination plant in the U.S. The plant delivers almost 50 million gallons of fresh water to San Diego County daily. (Phuntsho et al., 2013) Due to objective conditions, desalination has prevailing existence in regions such as the Middle East, where the largest desalination plant worldwide stands in terms of freshwater production. With 17 reverse osmosis units and 8 multi-stage flashing units, the plant can produce more than 1,400,000 cubic meters of fresh water per day. (Lambrechts et al., 2019) In 1960, there were only 5 desalination plants in the world. By the mid-1970s, as the conditions of many rivers deteriorated, around 70% of the world's population could not be guaranteed sanitary and safe freshwater. (Chekli et al., 2017) As a result, water desalination has become a strategic choice commonly adopted by many countries in the world to resolve the shortage of fresh water, its effectiveness and reliability have been widely recognized.

The limitation and uneven distribution of freshwater resources have been one of the most prevailing and serious problems faced by people living in arid areas. To reduce its severity, saline water or wastewater desalination has always been a constantly researched and applied solution. In many arid regions, the desalination of seawater is evaluated as a promising solution. Despite that seawater holds around 96.5% of global water resources (Iskander et al., 2017), the global-scale application of seawater desalination is hindered by the cost, both financially and energy-wise. With the development of energy-saving technologies for seawater desalination, it is viable to use saline, such as seawater and brackish water to produce freshwater for industries and communities. Commonly used methods (e.g., reverse osmosis) require water pumping and a considerable amount of energy. As a result, forward osmosis is receiving increasing interest in this field since the FO process requires much less energy.

One of the research teams at Monash University in Australia has demonstrated a solar-assisted FO system for saline water desalination using a novel draw agent. (Li et al., 2011) The research team led by Huanting Wang and George P. Simon has investigated the potential of a thermoresponsive bilayer hydrogel-driven FO process utilizing solar energy to produce fresh water by treating saline water.

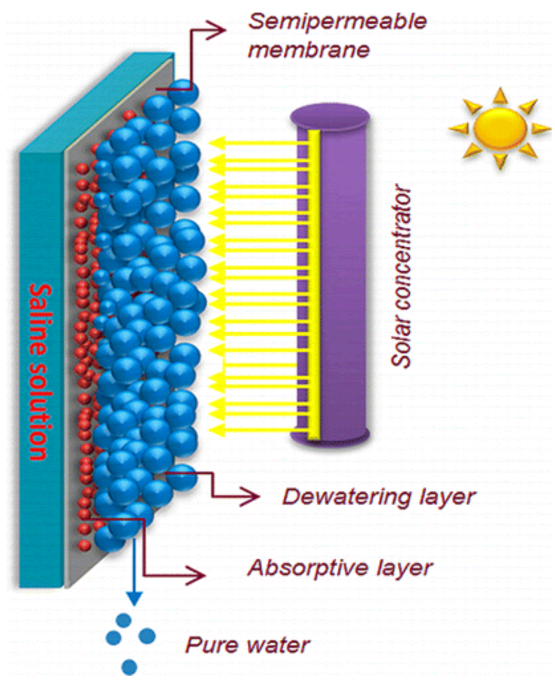

Figure 3-1. schematic diagram of the Desalting Sponge

(Li et al., 2011)

This Forward osmosis process is equipped with a new draw agent: a thermoresponsive hydrogels bilayer. Compared to one of the most used draw agents (i.e., ammonium bicarbonate), this dual-layered hydrogel is made of sodium acrylate and N-isopropyl acrylamide (NIPAM), which induces osmotic pressure differences without the need for regeneration. (Li et al., 2011) The thermoresponsive hydrogels layers generate high swelling pressure when absorbing water from high-concentrated saline. During testing, researchers used a solution of 2,000 ppm of sodium chloride, which is the standard NaCl concentration for brackish water. (Phuntsho et al., 2013) Water passes through the semipermeable membrane (the grey layer) and is drawn from saline solution to the absorptive layer (the red spheres). The hydrogel can absorb water up to 20 times larger than its regular volume. Next, the thermoresponsive hydrogel composed only of NIPAM (dewatering layer) then absorbs water from the first layer. When the dewater layer is heated to 32 °C, which is the lower critical solution temperature (LCST), the gel collapses and squeezed out the absorbed fresh water. Draw agents like ammonium bicarbonate are required to be heated up to 60 °C, then distilled at a lower temperature for regeneration. By focusing the sunlight with a Fresnel lens, the concentrated solar energy can help dewatering flux reach 25 LMH after 10 minutes, which is similar to the water flux of ammonium bicarbonate. (Li et al., 2011) Although the water flux for freshwater extraction stop is encouraging, the rate of absorbing water using hydrogel is significantly slower than other draw agents. To improve performance, the team envisioned running numerous desalting sponges in parallel, and further investigations need to be conducted. Overall, since the average salinity of seawater is 35 ppt, which is around 17 times more than the saline used in the test (McCutcheon et al., 2006), it shows a promising application in seawater desalination on a lower NaCl concentration.

3.1.2 Concentration Polarization

There are many factors affecting the efficiency of forward osmosis, such as concentration polarization, membrane fouling, reverse solute diffusion, membrane development, and draw solution design. Concentration polarization is the most important factor among all of them. Various studies conducted regarding forward osmosis, these studies share an identical focus, which is reducing concentration polarization. The existence of concentration polarization can weaken the actual osmotic pressure difference on both sides of the membrane, which is one of the limiting factors that affect the performance of forward osmosis in water flux recovery. (Iskander et. al. 2017)

Pressure retarded osmosis has been defined as osmosis through asymmetric membranes. Most forward osmosis membranes used are either an asymmetric structure membrane including an active layer/a porous support layer (i.e., selectively permeable membrane), or symmetric structure membrane (i.e., semipermeable membrane). There are two types of concentration polarizations based on the placement of the membranes: external concentration polarization (ECP) and internal concentration polarization (ICP). External concentration polarization and internal concentration polarization can be further categorized into two sub-categories: dilutive and concentrative. (McCutcheon et. al. 2006)

In general applications, forward osmosis membranes are commonly placed in a way that the active layer faces feed solution, and the support layer faces the draw solution. One of the exceptions is to use forward osmosis with the function of damping osmotic pressure. In this membrane orientation, when the solution is drawn from the feed solution and enters the active layer to the support layer, the feed solution can be diluted in the pores of the support layer and its surface, thus causing dilutive external concentration polarization and dilutive internal concentration polarization respectively. (Solvents in the feed solution are likely to pass through the permeable membrane at a slower rate, making solvents accumulate on the surface above the active layer. The result is when there is a higher surface osmotic pressure of the active layer than the osmotic pressure of feed solution, the concentrative external concentration polarization forms.

In a situation where the active layer of permeable membrane faces draw solution, and the support layer faces the feed solution, solvents of the feed solution could be trapped inside the porous support layer, also on the surface of the support layer. This leads to concentrative external concentration polarization and internal concentration polarization. (McCutcheon et. al. 2006) To be more concise, the solution that lingers in the support layer has greater osmotic pressure than that of the feed solution. When the solute from the process is transported by porous support and active layer, it can further dilute the outlier of the draw solution, causing dilutive external concentration polarization.

3.1.3 Inorganic Draw Solution

Selecting a good draw solution (DS) is crucial for the FO process. The ideal DS should have high solubility, high osmotic pressure, and stability. Non-toxicity of the draw solution has little to no effects on the performance and structure of the FO membrane. There are three categories of DS that are generally recognized: inorganic DS, organic DS, and other DS such as nanoparticles. (Achilli et al., 2010)

Currently, inorganic draw solutions are most widely used in FO technology. They usually have extremely high osmotic pressure due to the small inorganic molecular mass and high solubility, which makes them more favorable in dealing with hypersaline wastewater. However, in the reverse osmosis process, the inorganic draw solution could increase the salinity of the feed solution. The mainstream of inorganic DS is ammonium bicarbonate and sodium chloride. In 2005, McCutcheon and Elimelech et al. (2006) conducted forward osmosis experiments using ammonium bicarbonate as the draw solution and achieved ideal results; through heating, ammonia-carbon dioxide can be regenerated. Nevertheless, there can still be a certain amount of ammonia gas present in the water. As a result, in more practical applications and pilot-scale tests, ammonium bicarbonate is the most widely used draw agent. Ammonia and carbon dioxide are evaporated in the form of gas, which is effective for recovery and re-concentration. Since the ammonium bicarbonate extraction and recovery system can make full use of low-grade waste heat and reduce energy consumption, it is especially practical for places with available waste heat, such as thermal power plants, and regions with abundant solar.

3.2 FDFO evaluation for sustainable agriculture

3.2.1 Brackish Groundwater reuse in arid regions

As the population increases rapidly, the demand for irrigation raises correspondingly. Almost 70% of the global water is used to irrigate. (Lee et al., 2001) At the same time, freshwater demand is raising, water reuse treatment process and drinking water treatment process became vital technologies nowadays. Under most situations, wastewater reuse and seawater reuse are a large portion of the water reuse system. However, brackish groundwater reuse became an emergent freshwater resource recently. Brackish groundwater is often located at depths of 4,000 feet or deeper under the Earth's surface, and it has a dissolved concentration between 1,000 to 10,000 milligrams per liter (mg/L). (Stanton et al., 2017) Brackish groundwater could be used for power generation, aquaculture, industry, and public drinking water supply. There are profuse brackish groundwater resources located in the United States, including Utah, New Mexico, Arizona, Virginia, Nevada, Texas, California, Idaho, and Colorado. For instance, Texas has an estimation of 2.7 billion acre-feet of brackish groundwater; In New Mexico, 75 percent of the groundwater is too saline to use without any treatment. (USDA., 2016)

Top 3 Dissolved solids	Brackish groundwater Sample 1 (g/L)	Brackish groundwater Sample 2 (g/L)	Brackish groundwater Sample 3 (g/L)
NaCl	3.713	7.426	13

Na2SO4	1.794	3.588	6.280
MgCl2	3.947	7.895	13.820
PH	7.72	7.63	7.33

Table 3-2. Top 3 TDS compounds in different brackish water samples

Table 3-2 above shows the top three dissolved solids of the brackish groundwater (BGW) samples taken from the Murray-Darling basin located in Australia. All the information in the table shows that brackish groundwater contains a higher concentration of total dissolved solids than spring water while remaining lower total dissolved solids than the seawater. To be more specific, brackish groundwater usually contains salinity higher than 1.5 g/L. (Stanton et al., 2017)

3.2.2 FDFO fertigation model

According to what has been discussed previously, there are bountiful resources of brackish groundwater in the United States, and one of the common implements of treated brackish groundwater is direct fertigation since there are lavish nutrients in the groundwater. The combination of nanofiltration and fertilizer drawn forward osmosis (FDFO) is an ideal solution for brackish groundwater treatment. Since brackish groundwater has a relatively low total dissolved solid (TDS), it requires minor desalination and nutrient removal processes before direct fertigation. To maintain a qualified number of nutrient components in brackish groundwater for direct fertigation, researchers have compared different models combining nanofiltration and forward osmosis. The first model is fertilizer drawn forward osmosis alone without nanofiltration, the results have shown that treated water samples still contain excessive nutrients (e.g., Nitrogen, Phosphorus, and Potassium) for plant growth, which indicates that the water quality would not qualify for direct fertigation. The second model applies Nanofiltration as a pre-treatment. This model can remove most of the scaling and organic fouling species, enhancing the performance of fertilizer drawn forward osmosis. However, scaling became one of the major issues due to the excess amount of scaling ions (e.g., Mg^{2+}, Ca^{2+}). The third model applies nanofiltration as post-treatment, this system not only has the highest reduction rate of fertilizer nutrients but is also able to recycle the excess nutrients for further reuse as draw solutions. For all the models above, researchers applied an NE90 membrane with an MWCO of 220kDa. (Phuntsho et al., 2013) Generally, a1KDa MWCO refers to about 1.3 nm in membrane pore size, whereas 220KDa corresponds to a pore size of 3.84 nm.

Fertilizers	**Brackish groundwater sample 1**		**Brackish groundwater sample 2**		**Brackish groundwater sample 3**	
	N/P/K before treatment (mg/L)	N/P/K after treatment (mg/L)	N/P/K before treatment (mg/L)	N/P/K after treatment (mg/L)	N/P/K before treatment (mg/L)	N/P/K after treatment (mg/L)
SOA	162/0/0	69/0/0	1150/0/0	951/0/0	4779/0/0	1280/0/0
MAP	112/242/0	85/187/0	915/2024/0	725/1605/0	2695/596/0	929/2056/0
DAP	157/174/0	51/56/0	1369/1514/0	779//862/0	4191/4635/0	797/0/0
KCI	0/0/312	0/0/355	0/0/2256	0/0/2691	0/0/7547	0/0/2691
KH2PO4	0/248/313	0/208/261	0/2061/2602	0/1633/2054	0/6260/7904	0/1605/2019

KNO3	112/0/312	215/0/600	929/0/2595	1572/0/4378	2817/0/7867	2323/0/6472
NH4CI	112/0/0	362/0/0	916/0/0	1500/0/0	2710/0/0	1786/0/0
NaNO3	112/0/0	200/0/0	921/0/0	1185/0/0	2746/0/0	2017/0/0
Ca(NO3)2	158/0/0	360/0/0	1405/0/0	3111/0/0	4353/0/0	5241/0/0
Urea	433/0/0	2455/0/0	3437/0/0	10308/0/0	10006/0/0	17324/0/0

Table 3-1. nutrients concentrations of treated water samples

(Phuntsho et al., 2013)

Table 3-1 shows the results when nanofiltration is applied as post-treatment, this model can reduce the total dissolved solids significantly due to its highest rejections of multivalent ions. However, brackish groundwater that contains an extremely high TDS rate would require a second pass-through of the nanofiltration system before direct fertigation. (Phuntsho et al., 2016)

3.2.3 Selection of fertilizer draw solutions

Out of various fertilizers were tested, ammonium phosphate monobasic (MAP), ammonium sulfate (SOA), and mono-potassium phosphate have the highest reduction rates of nitrogen. (Kim et al., 2013) Research has shown that ammonium sulfate contains the highest water recovery rate at 76%. Potassium dihydrogen phosphate has a second ranking water flux recovery of up to 75% while ammonium phosphate monobasic shows the lowest nutrient concentration among three of them. FDFO demonstrates its potential with fertilizer draw solution, which acts as a low-energy osmotic dilution.

Researchers also proved that most fertilizers can be used as draw solutions, different combinations of various draw solutions can have numerous removal rates for a certain nutrient. (Chekli et al., 2016). For instance, the combination of KCI and $NH_4H_2PO_4$ can result in a lower concentration of N/P/K (around 0.6/1.4/1.7 g/L), which shows a higher nutrient removal rate than using KCI or $NH_4H_2PO_4$ individually as draw solution. (Phuntsho et al., 2012) Moreover, different draw solutions /fertilizers have different rejection rates of nitrogen compounds. For example, Urea has a lower rejection rate compared to ionic compounds, such as nitrate and ammonium. This phenomenon indicates that Urea may have a higher nitrogen organic removal rate after ammonification. (Lee et al., 2001)

3.3 Result and Discussion

3.3.1 Brackish groundwater for direct fertigation

It is proven that the hybrid system of fertilizer drawn forward osmosis with nanofiltration as a post-treatment has the most effective removal rates of nutrients when it comes to brackish groundwater treatment. (Phuntsho et al., 2013) When nanofiltration is applied as pre-treatment, the system has a higher removal rate on scaling precursor ions and organic fouling species treating brackish groundwater. When nanofiltration is served as post-treatment, the nitrogen removal rate is the highest compared to the FO alone without NF and NF applied as a pre-treatment. The system can also recycle excess nutrients for further reuse as draw solutions when NF is applied as a post-treatment. The water flux is analogously higher when this hybrid treatment process is orientated as pressure-retarded osmosis (PRO) instead of normal forward osmosis mode. Integration of nanofiltration with fertilizer drawn forward osmosis can reduce the nutrient concentration to meet the water quality standard for direct fertigation. It brings the nitrogen input in fertigation to a lower scale compared to the standard scale. This hybrid system can also adjust the input of different nutrients for varied types of crops/situations.

3.3.2 N_2O emission reduction result

The sources of N_2O are mainly from microbial processes in soil and oxidation of NH3 in fertilizer. This research focuses on exploring the agricultural factors and providing solutions to the issue of redundant N_2O emissions. At the same time, managing these controllable factors can reduce agricultural emissions by applying water treatment methods. Since California contributes 12% of the national food production, reducing N_2O emissions could have a consequential effect on air quality and public health. (Reay et al., 2012) Studies show that exposure to long-term N_2O would cause ebbed lung function and asthma, especially to young ages. People that live nearby farms have a higher risk of getting respiratory diseases. (Reay et al., 2012) Moreover, accession of N_2O in water is caused by the excess nutrient runoff to the river. According to this review, N_2O emissions can be reduced significantly by managing the fertigation nitrogen input appropriately. Consequently, the air quality and water quality could be improved by reducing Nitrous oxide emissions. (Chen et al., 2017)

A higher Nitrogen input fertilizer could increase the loss of certain plant species and the death of marine organisms. The excess Nitrogen that remains in the plant/crops can also cause health issues. At the same time, low-nitrogen fertilizer would not be as nutritious as nitrogen fertilizer, it might slow down the growth rates of plants and crops. Since fertigation is commonly used in agriculture, relatively low nitrogen input could have a negative impact on the efficiency of crop production. As a result, the nitrogen amount in fertigation should be controlled to a certain amount to maintain the balance.

3.3.3 Environmental Impact

Besides the dinitrogen (N2) and nitric oxide (NO) emission from soil denitrification, agricultural Nitrous oxide emission has the dominant contribution to the total greenhouse gas emission. According to previous studies, Nitrate oxide is 300 times more harmful than carbon dioxide (CO_2) towards climate change. (Reay et al., 2012) Nitrate oxides in the atmosphere contained 270 parts per billion in 1750, and it has increased to 331 parts billion in 2018. The increasing rate of Nitrate oxide in the atmosphere breaks the record every 5 years. (Reay et al., 2012) In the year 2021, the global temperature increased conspicuously, one of the reasons is the overt Nitrate oxides emission since the food demand is rising every year with the population growth. This review explores the relationship between agricultural factors of N_2O emissions and water treatment solutions. The result of this review shows that agricultural N_2O

emission is related to different factors including soil oxygen content, soil porosity, soil organic carbon content, soil temperature, PH value of soil, soil bacteria content, and Nitrogen input in soil. By adjusting these external factors, including limiting the supplement of oxygen, reducing soil water content, choosing the soil with a lower porosity (sand would be preferred than clay in this situation), increasing the soil PH values, increasing the soil organic carbon content, etc., lowering the nitrogen input to prevent over-fertilization could be the most effective solution. As a result, the agricultural N_2O emissions decrease spontaneously.

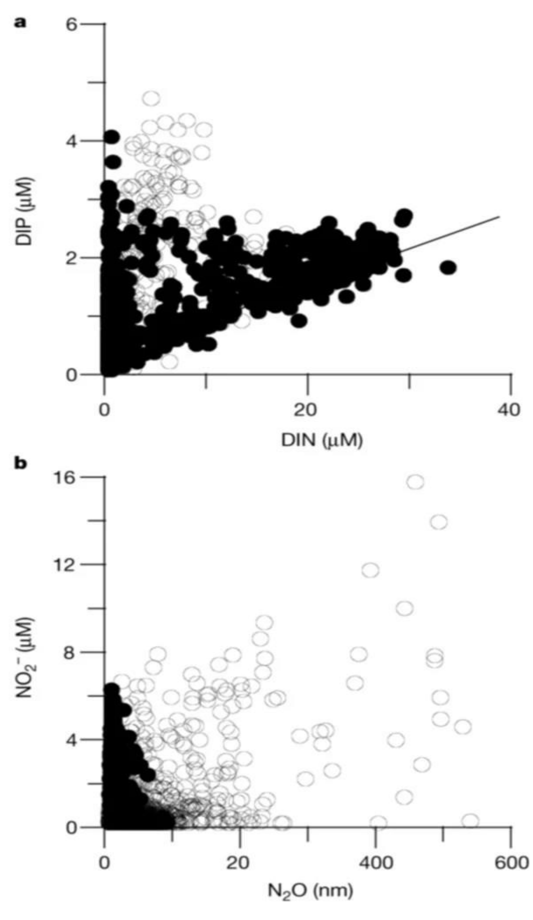

Figure3-2. Changes in nutrients and N_2O concentration in water

(Naqvi et al., 2000)

Nitrous oxide has different impacts on the atmosphere. In the stratosphere, N_2O depletes ozone levels by acting with halogen oxides. In the troposphere, N_2O is one of the paths depleting ozone. Over 3500 measurements of N_2O existences in surface water and marine troposphere, the exactitude for tropospheric, surface water, and marine measurement are 0.3%, 1.2%, and 2.2%. (Richter et al., 2009) These numbers indicate that almost two-thirds of the worldwide flux of N_2O in the atmosphere derives from sources in the northern hemisphere. Data from surface water proposes that the oceanic flux of N_2O would be less than 60 Gmol/year. Deepwater N_2O concentration is estimated using the values of salinity of water, water temperature, water oxygen content, and the water dissolved nitrogen content. (Butler et al., 1989) Raise of N_2O concentration in water is caused by anthropogenic nitrate denitrification, resulting in tremendous depletion of marine life, especially in deep water. Area with high N_2O emission has a relatively lower oxygen concentration due to the expansion of nutrients runoff from land. To diminish the negative environmental impacts, fertigation treatment could reduce the amount of nitrogen and nutrients input to the soil, prevent overfertilization, and excess nutrient runoff to the river.

3.3.4 Energy consumption & sustainability

Forward osmosis has many advantages regard saving physical footprints. High wastewater recovery rate, minimized resupply, and low energy cost can facilitate the sustainability of forward osmosis. However, forward osmosis has a lower membrane fouling propensity compared to other pressure-driven membrane processes. The research shows that it requires an average energy concentration of 1.5 $kWhm^{-3}$ to process wastewater using reverse osmosis while the highest consumption of forward osmosis is only $0.273 \pm 0.033\ kWhm^{-3}$. (Awad et al, 2019) A higher recirculation rate could increase the energy consumption since the recirculation pump energy consumption is a part of the total energy consumption. A higher draw solution concentration also leads to lower energy consumption due to the increased water flux. The lowest energy consumption by forward osmosis treatment of landfill leachate is around $0.005\ kW\ h\ m^{-3}$ when the recirculation rate is $30\ mL\ min^{-1}$ and draw solution concentration is 3-M. (Iskander et al, 2017) Forward osmosis is usually applied as pretreatment of reverse osmosis, the total energy consumption of a combination of FO and RO is lower than reverse osmosis alone. Moreover, osmotic backwashing can be compelling to restrict the membrane while reducing energy consumption at the same time. In the situation when Nanofiltration served as post-treatment combined with fertilizer draw forward osmosis can backwash the excess fertilizer replenishment and turn it into concentrated fertilizer draw solutions. The energy consumption of FDFO brackish water recovery using cellulose triacetate is affected by draw solution concentration (0.5-2M KCI), flow rates (100-400mL/min), and membrane selection. (Lambrechts et al, 2019) Membrane orientation and the flow rates have a minor effect on specific energy consumption compared to draw solution concentration. A diluted fertilizer draw solution can boost the system's performance while a higher draw solution concentration can lower the specific energy consumption. Moreover, a lower flow rate with a higher draw solution concentration can diminish the energy consumption of fertilizer draw forward osmosis to the lowest. To be more specific, the average electrical power requirement is usually less than 0.25 kWh/m^3. (Kim et al, 2017) Nanofiltration is a pressure-driven membrane process compared to forward osmosis. This additional process would increase the energy consumption of the system. However, nanofiltration is necessary for desalination and direct fertigation treatment. The minimum cost of nanofiltration treatment installation is 0.12 $\$/m^3$. (Kim et al., 2013) The energy consumption of the nanofiltration process is determined by the environmental impacts, such as recovery rate, membrane lifetime, and membrane cleaning. (Liikanen et al, 2006)

Chapter 4

4 Output and conclusions

4.1 Future implementations

Forward osmosis technology performs a 40-50% reduction in specific energy consumption compared to other alternatives. As a result, FO technology has the potential for wide adoption in drinking water treatment. Another area of application of FO usage is seawater desalination/brine removal, direct fertigation, wastewater reclamation, and wastewater minimization. Forward osmosis technology is also commonly used for food and drug processing. Without the draw solution recovery step, forward osmosis could be applied as osmotic concentration. For example, fertilizer-draw forward osmosis is widely accepted for the freshwater supply and direct fertigation. However, in terms of the evaporative desalination process, it is more practical to treat the water with a lower total dissolved solid /salinity. Forward osmosis technology can be combined with other treatment methods such as reverse osmosis, nanofiltration, or ultrafiltration for different water treatment purposes. To be more specific, forward osmosis can be an alternative pre-treatment in conventional filtration/separation system (e.g., Hybrid FO–RO system); an alternative process to conventional membrane treatment system ((e.g., UFO-MBR); a post-treatment process to recycle the volume of excess waste (e.g., RO+FO). The standalone forward osmosis process usually combines with additional post-treatment (e.g., FDFO + NF) to meet the water quality standards for different purposes.

4.2 Conclusions

Forward osmosis has been researched in the past. In this review, we focused on fertilizer drawn forward osmosis, which can not only remove brine but also reduce multiple nutrient inputs such as nitrogen, phosphorous, potassium, and so on. Since a proper draw solution can reduce the concentration polarization, the draw solution selection becomes vital for both FO and FDFO processes. Moreover, different fertilizer draws solutions have various influences on energy consumption. The nutrient concentrations of treated water are controllable using the fertilizer-drawn forward osmosis treatment method. The composition of nutrients can be adjusted in the draw solution to produce water with different ratios of nutrients, which makes fertilizer draw forward osmosis a nearly perfect treatment method for direct fertigation. For the purpose of reducing N_2O emissions, the removal rate of nitrogen in fertigation water is required to be improved using fertilizer drawn forward osmosis and nanofiltration. When nanofiltration is applied as post-treatment with fertilizer drawn forward osmosis, the nitrogen removal rate can reach up to 82.69% while using SOA as the draw solution. This number shows that treatment of fertigation can reach a higher standard of water quality attenuating nitrogen concentrations. As a result, lower nitrogen input in fertigation can significantly decrease the nitrous oxide emission from the soil for sustainable agricultural use.

Forward osmosis can be also combined with other treatment methods to resolve the freshwater shortage problem. Despite the traditional seawater desalination treatment incorporating forward osmosis and reverse osmosis, the hybrid process of reverse osmosis and fertilizer drawn forward osmosis can remove the brine from water and lower the final nutrient concentration with a higher recovery rate. Lastly, the value of water flux, recirculation rate, draw solution concentration, membrane lifetime, and membrane cleaning can all be adjusted to minimize energy consumption as much as possible. In conclusion, FO and FDFO technologies are both environmentally friendly and economically for desalination and fertigation.

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