Forward Osmosis Desalination of Brackish Groundwater in Egypt under the Framework Of Water-Energy-Food Nexus

By

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Dedication

Dedicated to my dear Father Abdelhalim for walking all this journey with me, providing all support and encouragement, and for being my best friend. I wish you could have witnessed my defense and accomplishment of your efforts. But I am sure you are watching over me as always and feeling happy now. You are truly missed.
**List of Abbreviations**

BW: Brackish water  
DI: Deionized water  
DS: Draw solution  
EC: Electric conductivity  
FS: Feed solution  
MW: Molecular weight  
RSF: Reverse solute flux  
SRSF: Specific reverse solute flux  
TDS: Total dissolved solids  
TriNex: Knowledge Triangle Platform for the Water-Energy-Food Nexus  
Cs: solute concentration (mg/L or Moles or M)  
Js : Solute flux (g.m².h⁻¹)  
Jw: Water flux (Lm⁻²h⁻¹ or LMH)  
kf: Mass transfer coefficient  
K: Resistance to solute diffusion within membrane support layer (s.m⁻¹)  
M: Molar concentration of the solution (M)  
n : Van’t Hoff factor  
P: Applied pressure (bar)  
Rs: Salt rejection (%)  
S: Structural Parameter (m)  
T: Absolute temperature (K)  
π: Osmotic pressure (atm or bar)
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Abstract

This research investigates the application of Fertilizer Drawn Forward Osmosis FDFO technique and its potential use in Egypt under the Framework of the Water-Energy-Food Nexus. Fertilizers Drawn Forward Osmosis Desalination Technique has been proven to be a great exhibition of tackling one of the sustainability challenges from Water –Energy-Food Nexus perspective. Being an energy efficient technology, it offers a technical solution to provide alternative water supply without compromising energy consumption, moreover the product water quality is adequate for agriculture and crop production.

In this work, feed solution used is real brackish groundwater extracted from a well in Sinai, Egypt. Two sets of experiments have been conducted in order to assess in selecting the proper scenario for the crop producer. The first set examined three commonly used single fertilizers in Egypt: Potassium Nitrate, Di-Ammonium Phosphate and Urea to compare between their performances. The second set examined standard hydroponic recipe, which is a mixture of nutrients, as a draw solution to fertilize crops in hydroponics systems. The nutrients mixture performance has been tested and compared to that of the individual components at the same concentrations in order to assess how mixing nutrients influence their performance.

Regarding the first set, Di-Ammonium Phosphate resulted in the best performance as draw solute among the three tested draw solutes, where it has exhibited a significant water flux equivalent to 13.8 (Liter per membrane unit area per hour $\text{LMH}^{-1}$) and always referred to as LMH, a feed ions rejection reaching 98% and acceptable concentrations of draw solute ions in the final product water. For the Second set, The Hydroponics nutrients mixture have exhibited better performance as draw solution compared to their individual macro-components. The use of the nutrient mixture as draw solute resulted in a flux of 11.7 LMH, 95% feed ions rejection compared to 9.2 LMH, 91%, and 10.03 LMH, 93% for its individual components. Mixing nutrients boosted the osmotic pressure and enhanced the driving force for fresh water permeation. Hence, it can be concluded that mixed nutrients have better performance than single fertilizers, not only for the enhanced desalination features and for water extraction performance, but also because they provide a complete set of nutrients necessary for growing crops.
Chapter I: Introduction
Chapter 1: Introduction

Currently, there is a substantial stress on natural resources due to the unsustainable consumption and immense growth in population, which represent threats to both the environmental sustainability and economic development. Consequently, it is important to adapt effective conservation measures to the utilization patterns of natural resources and eliminate any occurrence of trade-offs (Avellán et al., 2018).

The existing water deficiency in Egypt is currently exceeding 13.5 Billion annual cubic meter (BCM/yr) (Omar & Moussa, 2016). This deficiency is anticipated to elevate as a result of the constant annual Nile water quota received by the country in addition to the expanding land aridness which is one of the significant climate change impacts that the country suffers from (Wahba et al., 2018). The land aridness problem is keeping on increasing with presence of negligible rainfall specially in the north coast area, which is another major symptom of climate change that recently affected the region (Allam et al., 2003). Hence, it is crucial to develop an effective technique that can provide a sustainable alternative water supply without compromising non-renewable energy resources in addition to enhancing food production.

Desalination of brackish water using Forward Osmosis technology is an emerging field of research (Nasr & Sewilam, 2015c; Tayel et al., 2019). One of its application is Fertilizer Drawn Forward Osmosis (FDFO), which represents a potential alternative water supply for irrigation (Nasr & Sewilam, 2016; Su et al., 2012). Adapting this technique, under the framework of the Water-Energy-Food “WEF” nexus perspective, is very promising to overcome water scarcity challenges while preventing any trade-off with other sustainability pillars from occurrence. FDFO desalination technique enhances the availability of agriculture-quality water suitable for crop production with a significantly lower energy requirements compared to other desalination techniques (Manju & Sagar, 2017; Nasr & Sewilam, 2015c). Being an energy efficient technique, FDFO can be operated using renewable energy, which makes it flexible and adaptive for different distant applications (Chekli et al., 2017; Nasr & Sewilam, 2015d).

In this research, two sets of experiments have been conducted. First set represents a scenario of desalinating brackish water using the single commonly used fertilizers in Egypt and compare between their potentials as draw solutes. The second set represents a scenario of desalinating brackish water using hydroponics nutrients mixture as the draw solution, which is then compared to its individual macro-components as will be discussed in the next sections.

1.1 Research Motivation

The development of the water–energy–food (WEF) nexus in response to major global challenges has led to significant changes in the way academics and policy-makers think about our natural resources (Smajgl et al., 2016). WEF resources are inextricably linked: water and energy are used in the production and manufacture of food, while energy is required extract, treat and distribute water from source to supply, while also being used to cook, manufacture and store food produced. Food waste is increasingly being used as a means of generating
energy, and water is a critical resource in the energy production process. In 2009, former UK Chief Scientific Advisor, Sir John Beddington, addressed the inter-linked nature of resource issues in his “perfect storm” speech (Sample, 2009), indicating that a growing population and success in reducing poverty in developing countries will place considerable strain on our WEF resources by 2030. In a 2014 report, the InterAction Council identified challenges within the nexus posing a critical threat to global society alongside sectarian conflict and nuclear proliferation (Mohtar & Daher, 2016).

Egypt has considerable quantities of ground brackish water that can be efficiently utilized for growing crops (El-Kady & El-Shibini, 2001) without compromising the fixed quantities of freshwater available. This can be achieved via adapting energy-efficient desalination technology capable of producing water with a proper quality suitable either for conventional irrigation or for being applied to hydroponics systems.

Though many researches were conducted to assess the different desalination technologies and their viability in desalinating brackish ground water in Egypt, further investigation and testing are needed to examine in a bench scale the viability of desalinating real ground brackish water in Egypt under the framework of the WEF nexus using an energy efficient technology to enhance food production.

1.2 Research Objectives

Water–Energy–Food nexus (WEF Nexus) has been recently developed as an efficient perception for explaining and describing the complicated and interconnected nature of our global resource systems, on which we rely to attain different social, economic and environmental goals (Endo et al., 2017a).

Hence, this research aims at evaluating the efficiency of the Fertilizer Drawn Forward Osmosis desalination technology (FDFO) and its technical feasibility to desalinate real brackish water. This is done considering the interlinkage between the three WEF Nexus pillars. Nutrients will be evaluated to desalinate groundwater using low energy consuming technique which is the forward osmosis desalination. Then treated water will be adjusted to meet irrigation requirements to grow crops. The brackish water used is extracted from one of the potential areas using popular fertilizers in Egypt classified by macro nutrient (N, P and K) in addition to testing Hydroponics nutrients mixture as draw solutes and comparing its performance to its individual components. The objective of having two separate scenarios is to provide informative assessment that is useful for the two main agriculture techniques, the conventional soil based one and the hydroponics technique. The produced water is either a diluted solution of a single fertilizer suitable for conventional irrigation or a diluted mixture of nutrients suitable for application to hydroponics systems.
1.3 Research Steps

- Discussing the Water-Energy-Food Nexus, its perspective, objectives and importance in overcoming sustainability challenges.
- Investigating the Hydroponics system, its types, merits and drawbacks compared to conventional agriculture.
- Elaborating the Fertilizer Drawn Forward Osmosis as an energy efficient technology for desalinating brackish water for fertigation.
- Investigating the popular fertilizers used in Egypt in addition to typical nutrients mixtures recipes for hydroponics systems.
- Testing the performance of the selected fertilizers individually to desalinate real brackish water from a ground well in south Sinai.
- Testing the performance of a typical hydroponics nutrients mixture vs. the performance of its individual components.
Chapter II: Literature Review
Chapter 2: Literature Review

2.1 Review on the WEF Nexus

Water–Energy–Food nexus (WEF Nexus) has been recently developed as an efficient perception for explaining and describing the complicated and interconnected nature of our global resource systems, on which we rely to attain different social, economic and environmental goals (Endo et al., 2017b). United Nations Food and Agriculture Organization (FAO) sees it related to balancing different resource user goals and interests—while maintaining the integrity of ecosystems. Because of the interdependencies of the Water, Energy and Food, WEF evolved as a system-based approach in order to broaden the knowledge regarding sustainable methodologies for managing resources. Giving an example of agriculture and crop production, for being the largest consumer of the world’s freshwater resources. Crop production, its transportation, and processing consume nearly a quarter of the global energy supply. Fossil fuels, still a significant constituent of the global energy matrix, keep on being highly water exhaustive. In turn, the energy switch to biofuels leads to a direct trade-off between planting crops for food in competition with energy generation. Clearly, management of these critical resources requires a deeper understanding of such interactions (Abraham, 2018).

There is a rising trend around the world that, this is without a doubt, the best approach, given the complex linkages and feedbacks involved. But successfully applying nexus thinking to specific locations and challenges is not a simple challenge from every aspect. (Water–Land–Energy Nexus - Stockholm Environment Institute, 2012).

The Water energy food nexus concept has a significant advantage that it describes both the complicity and the dynamic inter-related nature of the global resource system, aims at achieving balance between different resource user goals and Interests without compromising the closed cycle and quality of the natural eco system. (Dubois et al., 2014).

Food and Energy consumption patterns on daily basis have significant impacts on freshwater consumption. Irrigation is the most significant water consuming activity for crop production. However, energy generation via fuel extraction and electricity generation is also has elevating demands on water. (Macknick et al., 2012). Figure (1) illustrates the Water Energy Food Nexus principle (Keairns et al., 2016).
At the present time, the WEF nexus has become one of the main research focus areas; with a considerable number of papers tackling it from qualitative and quantitative perceptions, discussing its importance specially in parts of the world suffering from sustainability challenges (Damerau et al., 2016). This is due to the recently realized fact that Water, Energy and Food are strongly interlinked, in addition to the increasingly resources scarcity that lead to conflicts worldwide (Ringler et al., 2013).

A number of sciences have developed methods and scenarios to support decision making under the framework of Nexus. For example, (El-Gafy, 2017) analyzed the WEF nexus in order to provide a method for decision makers while managing the crop production system in Egypt via carrying out a quantitative assessment, through this analysis, indicators for water, energy, food, mass productivity and economic productivity were suggested and based on which, water energy food nexus index (WEFIN) was conducted. (Damerau et al., 2016) examined three alteration scenarios regarding future food preferences, in addition to two potential changes in future resource preferences for electricity and transport fuels. Concluded that though there is an increase in food supply due to alteration in dietary habits to become high protein based which lead to increase in water demand, this impact is mitigated by the opposing dietary shift towards reductions in the grains and sugar consumptions. From the energy sector perspective, it was concluded that energy generation can have limited impact.
on increasing water demand based on the type of energy technology used. As an overall conclusion, the increase in water, energy and food demand can be optimized, via alterations in technologies, and dietary trends which can mitigate the negative impacts of each other. (Bogardi et al., 2012) investigated the interlinked impacts and risks of climate change, water security, urbanization and growth, and recommended managing these sustainability challenges under integrated perspective instead of tackling each risk separately. (de Fraiture et al., 2010) accomplished an integrated assessment regarding water utilized for irrigation, and found that water and food resources are sufficient, however, the consumption patterns are considered as the root cause for drastic future water shortage. In addition, (Rosegrant et al., 2009) highlighted the importance of efficient water utilization for irrigation and adapting conservation measures while optimizing food production. (Hellegers et al., 2009) analyzed the interlinkage between water, energy and food and emphasized the importance of having an integrated policy. (Allouche, 2011) discussed both water and food challenges from social point of view.

The above-mentioned researches highlighted that having an integrated framework managing water, energy and food security issues has become a crucial necessity to overcome sustainability challenges of these resources. (Hanjra & Qureshi, 2010) investigated the anticipated worldwide water security and its impact on food scarcity challenges in the near future. (Sulser et al., 2010) adapted the International Food Policy and Research Institute (IFPRI) model to investigate the anticipated increase in water demand for both Nile and Ganges Rivers based on the typical consumption of water for irrigation. These investigations resulted in a conclusion that water demand for irrigation will drastically increase from 1425 Mm$^3$/y in 2000 to 1785 Mm$^3$/y in 2050. Other researchers tackled the water-energy-food nexus from governance perspective, such as (Al-Saidi & Elagib, 2017) that highlighted the significant importance of The WEF nexus as a powerful and innovative tool.

Overall, there is no fixed concept of nexus, and the nexus is internationally interpreted as a process to link ideas and actions of different stakeholders under different sectors and levels for achieving sustainable development (Endo et al., 2017b).

2.1.1 Analyzing the current status of Nexus–Related Research Projects

WEF nexus is one of four main nexus categories that interlink different natural resources, which are: Water–Food, Water–Energy, Water–Energy–Food, and climate related Nexus.
Recently, it has been found that, the number of Water-Energy-Food nexus has one of the largest number of projects implemented worldwide compared to other Nexus categories with percentage of 30 %. Comes second after Water–Energy projects that had the highest, contributing with 32%, while climate related Nexus projects contributed with 22%, and water–food with 16%. Table 1 illustrates the different types of nexus and their respective scopes (Endo et al., 2017b).

<table>
<thead>
<tr>
<th>Water-Food Nexus</th>
<th>Water-Energy-Food Nexus</th>
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<tbody>
<tr>
<td><strong>Environment:</strong></td>
<td><strong>Environment:</strong></td>
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<tr>
<td>-Minimizing the water use via a shift to low water consuming crops.</td>
<td>-Conservation of irrigation water to reduce energy needed and carbon emissions generated during usage of groundwater.</td>
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<tr>
<td>-Assessing food importing process and virtual water calculations.</td>
<td>-Assessing potential of food waste utilization for producing energy as alternative energy source.</td>
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<tr>
<td>-Avoiding exhaustion of the residual soil moisture.</td>
<td>-Examining both the land and water needs for bioethanol production from maize.</td>
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<tr>
<td>-Promoting the efficient utilization of green water and rainwater harvest.</td>
<td>-Adapting Concentrated Solar Energy and agricultural biomass for electricity generation.</td>
</tr>
<tr>
<td><strong>Social and Governance:</strong></td>
<td><strong>Development of tunnels system for ground aquifers recovery.</strong></td>
</tr>
<tr>
<td>-Promoting –design of extension and training programs.</td>
<td><strong>Economic, Social and Governance:</strong></td>
</tr>
<tr>
<td>-Public-private partnership</td>
<td>-Hydropower investment.</td>
</tr>
<tr>
<td><strong>Economic:</strong></td>
<td>-Power market development.</td>
</tr>
<tr>
<td>Microfinance financing model.</td>
<td>-Irrigation reform.</td>
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<tr>
<td>Pro rata pricing system of electricity.</td>
<td>-regional public goods awareness building</td>
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<tr>
<td><strong>Tools:</strong></td>
<td><strong>Tools:</strong></td>
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<tr>
<td>Climate prediction model</td>
<td>-Multi-scale integrated analysis of social and ecosystem metabolism</td>
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<td></td>
<td>-SWAP model</td>
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<td>-Soil conservation service Cerrc number method.</td>
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<tr>
<td></td>
<td>-Economic calculation (land and water footprings of biofuel).</td>
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<tr>
<td></td>
<td>-Crop Model called CropSyst</td>
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<td></td>
<td>-Integrated Analytical Model.</td>
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<table>
<thead>
<tr>
<th>Water-Energy Nexus</th>
<th>Water-Energy-Food climate change Nexus</th>
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<tr>
<td><strong>Environment:</strong></td>
<td><strong>Environment:</strong></td>
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<tr>
<td>-Assessment of biofuel (micro-alges)</td>
<td>-Reduce vulnerability to climate change induced disaster and degradation taking a longer term.</td>
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<tr>
<td>-Use of abandoned mines for water storage</td>
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<tr>
<td>-Use of solar pumps and quench systems for water pumping and billing.</td>
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</table>
- Wastewater treatment plant including shale gas development from a life cycle perspective.
- Promoting well-regulated on-site treatment technologies.

**Social and Governance:**
- Improvement of accurate, fine-scale, site-specific data.
- Stakeholder engagement.

**Economic:**
- Multiple market management approaches.
- Tariffs and investments.
- Further investigation on life cycle of products
- Assessment scenario of carbon and water prices.

**Tools:** Websites

- Analyzing specific data such as 280 aquifers including precipitations and temperature in Mexico.

**Social and Governance:**
- Setting strategies for development with climate protection impacts and capacity building of communities in developing countries.
- Utilizing meteorology and historical data to correlate and emphasize the relationship between climate change and poverty nexus developing countries.
- Addressing the issues of energy use and GHG emissions to associate with water management.

**Tools:** Normalized Deficit Index NDI and Normalized Deficit Cumulated NDC.

### 2.1.2 Nexus Regions

Nexus concept has become popular worldwide. However, each region adapts different types of Nexus Projects to overcome their specific local challenges. Various Nexus projects are spread differently in regions based on each region’s needs as can be observed from Figure 2. The regions illustrated in the figure below are categorized into Asia, Europe, Oceania, North America, South America, Middle East and Africa. In this taxonomy, the Middle East is represented as a separate region from Asia due to a significant number of on-going nexus projects. While counting projects per region, if a nexus project is implemented internationally, it has been counted as a project that being implemented in all regions. During this investigation, it has been detected that six projects were implemented on international basis: two projects for water–food, one project each for water–energy and water–energy and food, and two for climate-related projects. North America and Oceania has a tendency to focus on specific nexus types, which are water–energy (46%) and climate related (43%), while Africa has more focus on Water-Energy-Food Nexus and less focus on water–energy (7%). Rest of the regions has relatively balanced interest in each nexus type (Fig. 2) (Endo et al., 2017b).
2.1.3 Examples on Water-Energy-Food Nexus Initiatives

Eventually, as previously discussed, WEF nexus has gained an increasing popularity. That was reflected on the form of carrying out large number of events and conferences on international level to enhance awareness regarding this important perspective. This arose importance was also reflected on tackling energy security issues in integrated approach (Rees, 2013). Starting in 2012, during the summit of Rio 20, the nexus thinking was highlighted as an integrated perspective to tackle water, energy and food problems (Weitz et al., 2014). In addition, the German Government and international organizations have become main sponsors for carrying out Nexus events and projects starting with Bonn 2011 WEF Nexus Event (Weitz et al., 2014), such nexus events at German universities are continuously being held on annual basis since 2014 till 2019.

As a consequence of the growing importance of the WEF nexus, number of applications and projects applying WEF nexus has also been growing. As an example, in central Asia, the increasing demands of the population and the need for development obliged the optimal use and adaptive management of the watershed resources. Accordingly, comprehensive measures have been adapted to reach sustainable development goals. This objective has been achieved by the application of interdisciplinary and professional approaches through establishing dynamic and optimal balance in supply and demand resources.

In this project, the integrated WEF Nexus approach has been applied for planning 14 crops planted in the tested region, irrigated farms, and rain-fed farms, between 2006 and 2014, and
targeting water-energy-food nexus index (WEFNI) maximization. The connections among the water, energy, and food were then evaluated through determining the amount of consumption, mass productivity, and economic productivity of water and energy. The results can be used as an effective tool for designating proper soil and water resource management strategies in the region (Sadeghi et al., 2020).

Another WEF nexus project has been recently implemented in UK. It presents a new methodology for assessing the environmental sustainability in the food-energy-water nexus on a life cycle basis. The environmental impacts, estimated through life cycle assessment, are used to determine a total impact on the nexus by assigning each life cycle impact to one of the three nexus aspects. These are then normalized, weighted and aggregated to rank the options for each aspect and determine an overall nexus impact. The outputs of the assessment has been visualized to enable structured and transparent interpretation of results. The methodology is illustrated by considering resource recovery from household food waste within the context of a circular economy.

The impact on the nexus of four treatment options has been quantified: anaerobic digestion, in-vessel composting, incineration and landfilling. Anaerobic digestion is environmentally the most sustainable option with the lowest overall impact on the nexus. Incineration is the second best option but has a greater impact on the health aspect than landfilling. Landfilling has the greatest influence on the water aspect and the second highest overall impact on the nexus. In-vessel composting is the worst option overall, despite being favored over incineration and landfilling in circular-economy waste hierarchies. This demonstrates that circular does not necessarily mean environmentally sustainable. The proposed methodology can be used to guide businesses and policy makers in interpreting a wide range of environmental impacts of products, technologies and human activities within the food-energy-water-nexus (Slorach et al., 2020).

2.1.4 Nexus keywords:

The number of articles published related to the different categories of Nexus has been drastically increasing during the last years. Various keywords were indicated in these articles, water and energy had the highest number of keywords as per indicated in figure 3 below. This was concluded upon considering a sample of 38 nexus projects worldwide and clustering the
keywords based on their relation to Water such as desalination, brackish water, water treatment. Energy such as solar systems, renewables, off grid energy generation. Food such as crops, agriculture etc. This increase in number of keywords in recent publications is an indication of the increasing importance that the Nexus approach is gaining overtime due to its ability to analyze and treat the interlinked sustainability of resources (Endo et al., 2017b).

As per the WEF nexus event held in Germany in 2011, Water, Food, Energy and Climate Nexus event was carried out in the United States of America in 2014, during the event, the ‘Nexus Academic-Practitioner Network’ was established. Afterwards, Nexus meetings and conferences started to be carried out on annual basis, tackling the sustainability issues worldwide (Leck et al., 2015).

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-Energy-Food-Climate Nexus Event.</td>
<td>2009</td>
</tr>
<tr>
<td>Addressing the interlinkage between the four sustainability issues. Location: United Kingdom.</td>
<td></td>
</tr>
<tr>
<td>Event</td>
<td>Year</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>The Water-Energy-Food Nexus discussion during the Global Economy Forum Tackling the economic impacts and risks resulting from Water, Energy and Food scarcity.</td>
<td>2011</td>
</tr>
<tr>
<td>Publishing articles defining the principles of the Nexus concept as Background Paper for the Bonn 2011 conference published: ‘Understanding the Nexus’, coordinated and led by the Stockholm Environment Institute (SEI)</td>
<td>2011</td>
</tr>
<tr>
<td>Planet Under Pressure International Conference ‘Interconnected risks and solutions for a planet under pressure’</td>
<td>March 2012</td>
</tr>
<tr>
<td>Future Earth launched in June 2012 at the UN Conference on Sustainable Development (Rio + 20)—importance of nexus thinking recognized from outset.</td>
<td>June 2012</td>
</tr>
<tr>
<td>-Nexus 2014: Water, Food, Climate and Energy Conference was held at the Water Institute at the University of North Carolina (UNC) at Chapel Hill.</td>
<td>5-8 March 2014</td>
</tr>
<tr>
<td>Academic and Practitioners network for the Water Energy Food and Climate Nexus launched at Nexus 2014 Conference.</td>
<td>2014</td>
</tr>
<tr>
<td>Event</td>
<td>Date</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>Nexus Declaration delivered to the UN Secretary General on (for input to formulation of Sustainable Development Goals (SDGs))</td>
<td>26 March 2014</td>
</tr>
<tr>
<td>Nexus Network launched in the UK—funded by Economic and Social Research Council (ESRC) 2014</td>
<td>2014</td>
</tr>
</tbody>
</table>

To summarize, Nexus has been spreading in a very broad range supported by international organizations, universities in addition to policy makers upon realizing its importance as an integrated tool for tackling water energy, and food in an interdisciplinary manner (Howarth & Monasterolo, 2016).

2.1.5 The WEF Nexus initiative in Egypt: The TriNex Project:

In December 2013, it was the first time for the Water-Energy-Food Nexus to be introduced in the country. The Knowledge Triangle Platform for the Water-Energy-Food Nexus (TriNex) has been established. This platform represents a multidisciplinary project with main objective of adapting the multidisciplinary research concept tackling the sustainability challenges of water-energy and food in Egypt from integrated perspective. The American University in Cairo has been one of the main project partners through the Center for Sustainable Development (“The Knowledge Triangle Platform for the Water-Energy-Food Nexus,” 2013).

The project has been focusing on building capacities of Egyptian researches through workshops, Summer University for PhD students and hands on trainings to ensure the complete understating of the water, energy and food nexus concept. Meanwhile, a series of integrated researches are carried out to provide solutions for the sustainability issues in Egypt (The Knowledge Triangle Platform for the Water-Energy-Food Nexus, 2013).
2.2. Desalination and the WEF Nexus
2.2.1: Energy Requirements for desalination techniques

The prerequisites of energy are significant for desalination process necessary for separating minerals from water with high salinity (Manju & Sagar, 2017). The actual minimum amount of energy essential for separation is significantly larger than the theoretical amount obtained by calculation. This amount is equivalent to the Free Energy subtraction of inward saline water and outward saline water streams. Arrangement of a desalination system and its installation plays an important role in determination of the actual energy consumption needed for treating saline and brackish water into salt concentrate and low salinity water. This fact has been proven by an equation created based on the second law of thermodynamics (Cerci et al., 2003). For instance, the calculated energy consumption needed to desalinate seawater with approximate salinity of 35000 ppm is ~ 0.9 kWh/m$^3$, however, desalination units utilize a significantly higher energy that can exceed 25 times of the calculated value, and it differs based on the technology used, table (3) summarizes Energy Consumed per Desalination Technology (Subramani & Jacangelo, 2015).

<table>
<thead>
<tr>
<th>Design Capacity (m$^3$/day)</th>
<th>Multi-Stage Flash</th>
<th>Multiple Effect Distillation</th>
<th>Thermal Vapor Compression</th>
<th>Mechanical Vapor Compression</th>
<th>Reverse Osmosis</th>
<th>Electro-Dialysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>60,000</td>
<td>5</td>
<td>2</td>
<td>1.7</td>
<td>10</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>10,000</td>
<td>2</td>
<td>1.7</td>
<td>10</td>
<td>4</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>20,000</td>
<td>1.7</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>20,000</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>50,000</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>
Desalination technologies rely on two basic sorts of energy, heat energy and electrical energy. Vapor Compression, Reverse Osmosis and Electro Dialysis depend primarily on electricity to operate. On the other hand, Multi-Stage Flash Distillation, Multiple-Effect Distillation and Thermal Vapor Compression depend primarily on heat energy and secondarily on electrical energy for water circulation; table (4) illustrates Features of Main Desalination Types. Therefore, due to the intense reliance on energy for desalination, it is crucial to adapt transition of the operation energy matrix utilized and switch to utilization of renewables. Such as wind, geothermal and solar systems instead of nonrenewable and fossil fuels such as oil, coal or gas in order to mitigate climate change by eliminating the high carbon dioxide they generate and make the desalination process more sustainable. (Manju & Sagar, 2017).
Table 4: Features of Main Desalination Types (Al-Karaghouli & Kazmerski, 2013)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Specific Heat Energy (MJ/m³)</th>
<th>Specific Corresponding Electrical Energy (kWh/m³)</th>
<th>Specific Electrical Energy (kWh/m³)</th>
<th>Overall Specific Energy (kWh/m³)</th>
<th>Final Product Salinity (ppm)</th>
<th>Specific Cost per unit product ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Stage Flash</td>
<td>235</td>
<td>20</td>
<td>4</td>
<td>24</td>
<td>&lt;10</td>
<td>1.2</td>
</tr>
<tr>
<td>Multiple Effect Distillation</td>
<td>188</td>
<td>16</td>
<td>2.2</td>
<td>18</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>Mechanical Vapor Compression</td>
<td>None</td>
<td>None</td>
<td>10</td>
<td>10</td>
<td>&lt;10</td>
<td>4.5</td>
</tr>
<tr>
<td>Thermal Vapor Compression</td>
<td>227</td>
<td>14.5</td>
<td>1.7</td>
<td>16.3</td>
<td>&lt;10</td>
<td>0.91</td>
</tr>
<tr>
<td>Seawater Reverse Osmosis</td>
<td>None</td>
<td>None</td>
<td>5</td>
<td>5</td>
<td>450</td>
<td>1</td>
</tr>
<tr>
<td>Brackish Water Reverse Osmosis</td>
<td>None</td>
<td>None</td>
<td>2</td>
<td>2</td>
<td>350</td>
<td>0.8</td>
</tr>
<tr>
<td>ED</td>
<td>None</td>
<td>None</td>
<td>2.8</td>
<td>2.8</td>
<td>330</td>
<td>0.8</td>
</tr>
<tr>
<td>Solar Concentrated Solar Power/ Multiple Effect Distillation</td>
<td>188</td>
<td>16</td>
<td>2.25</td>
<td>18</td>
<td>&lt;10</td>
<td>2.6</td>
</tr>
<tr>
<td>Solar Photovoltaic/Reverse Osmosis</td>
<td>None</td>
<td>None</td>
<td>2.8</td>
<td>2.8</td>
<td>325</td>
<td>0.8</td>
</tr>
<tr>
<td>Solar Photovoltaic/Electro dialysis</td>
<td>None</td>
<td>None</td>
<td>2.8</td>
<td>2.8</td>
<td>325</td>
<td>11</td>
</tr>
<tr>
<td>Wind/ Reverse Osmosis</td>
<td>None</td>
<td>None</td>
<td>5</td>
<td>5</td>
<td>450</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>2</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Wind/Mechanical Vapor Compression</td>
<td>None</td>
<td>None</td>
<td>9.5</td>
<td>9.5</td>
<td>&lt;10</td>
<td>6.5</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>------</td>
<td>------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Geothermal Energy / Multiple Effect Distillation</td>
<td>188</td>
<td>16</td>
<td>16</td>
<td>18</td>
<td>&lt;10</td>
<td>2.4</td>
</tr>
</tbody>
</table>

2.2.2 Limitations of adapting renewable energy to the conventional techniques

It is of great importance to adapt renewable energy sources to operate desalination in order to overcome its negative ecological influence in terms of excessive energy consumption, from figure (4) below, due to the high energy consumption, energy is the main pillar in terms of desalination system cost. However, this adaptation of renewable energy sources has high impact on desalination cost compared to the utilization of conventional non-renewable resources.

[Figure 4 Distribution of Desalination Costs (Burn et al., 2015)]
Though this economic impact, it can be considered as a compensation for the positive environmental impacts resulting from this switch, mainly the conservation of the nonrenewable resources and reduction of the carbon footprint per each m$^3$ of desalinated water (Al-Karaghouli & Kazmerski, 2013). As a consequence of this economic constrain, the renewable energy driven systems are feasible only in remote areas where there is no access to the subsidized non-renewable electricity grid, if the land has good potential for sun and wind installations in addition to the existence of sever clean water access problem. On the other hand, due to the continuous development of new desalination technologies and the remarkable expansion of this market, it is foreseen that costs will be more feasible in near future. (Al-Karaghouli & Kazmerski, 2013).

2.2.3 Desalination and Food Production

The Global water needs are significantly proportional to inhabitants increase, urbanized expansions, and sprawl in addition to energy-food sustainability roadmaps. Moreover, global trading, alternations consumption trends and population distribution have a considerable influence on nutritional diversification and food intake rates. As per illustrated in figure (5) Agriculture consumes average of 70% of total global freshwater extractions, this can reach a percentage reaching a value of 90% distributed various locations in emerging regions, which leads to the conclusion that irrigation activities are the highest water consumption area (Pellegrini et al., 2016). Agriculture has vital role in international food availability. Plants generated from conventional irrigation activities represent 40% of plants produced worldwide from cultivation of 20% of land area worldwide (FAO, 2016).
Based on the above discussions in previous chapters, desalination will be an important technique to provide alternative sustainable water supply to conserve the large amounts of water consumed in food production. Desalination is largely expanding worldwide and in MENA region to compensate for the aridness and increasing water shortage resulting from climate change and population growth. Figure (6) below illustrates a comparison of the cumulative produced water from desalination in MENA Region between two years of 2010 and 2016 (Sewilam & Nasr, 2017).
The majority of the previously discussed desalination types are still not economically feasible for producing water for agriculture, this is attributed to the considerable energy consumption and the good water quality generated that can be used as potable water instead of conventional irrigation. Hence, it is of great importance to assess on case-by-case basis the main parameters that influence the cost of saline water desalination for agriculture. Based on the assessment, results can significantly differ from one desalination technique from the other, water composition and salinity and the available energy sources.

Forward Osmosis Technology, as will be discussed in detail in chapter 6, unlike other desalination technologies, has minimal energy demands. This is due to its unique mechanism that differs from other types that rely on application of mechanical pressure or heat energy to desalinate sea or brackish water into freshwater and brine. Forward Osmosis relies on the concentration gradient between the feed solution and the draw solution as a driving force for the desalination process, resulting in making it the least energy consuming type and a good candidate for desalinating water for agriculture specially the Fertilizer-Drawn Forward Osmosis as will be discussed in section 2.4.
2.2.4. The Nexus Approach as a Tool for Environmental Conservation

Resources optimization is considered as a significant challenge due to the presence of heavy consuming activities such as conventional agriculture and irrigation techniques. Such heavy consumers lead to the increase of sustainability risks and natural disasters such as depletion of water ground wells, global warming and desertification. Lack of experience of managing resources and consider their interlinkage have been always key elements of sustainability problems specially in developing countries. For instance, various dams have been built in different locations across Africa (Barreteau et al., 2014) with different objectives such as water storage and energy generation, however, due to shortage in experienced labor and adequate planning in terms of water, energy and land use (Afzal et al., 2016).

Worldwide, despite the significant importance of proper distribution and efficient management of resources, many countries are not capable of conducting improvements of their water and energy use management systems, this is mainly attributed to economic constraints (Farolfi et al., 2006).

As a result, processes that are supply-oriented have to definitely leave sufficient space of handling of demand, enhancement of efficient use approaches, improved distribution of different resources, building capacity and governance sound approaches (Farolfi et al., 2006).

Global water sources and their individual share represent fixed quantity that keeps decreasing by population growth. According to recent statistics implemented by the International Commission on Irrigation and Drainage, water is one of the extremely limited resources to the extent that it is foreseen that its reserve will be decreased by more than 60 percent in thirty years from now. Consequently, in the field of agriculture, it is crucial to switch from the conventional irrigation techniques that are extremely inefficient in terms of water use to the new water conservation-oriented techniques such as drip irrigation whenever is accepted regarding economic and social feasibility (Avellán et al., 2018).

From the abovementioned challenges faced, regarding resource management and their conservation, it can be concluded that such sustainability problems need to be tackled from different perspective (Vlotman & Ballard, 2014). A perspective that put integrity and interlinkage between natural resources and sustainability patterns into consideration during planning and solving one of the resources shortages. This is crucial to prevent tradeoff that
may occur between water, energy and food sustainability (Ringler et al., 2013). Hence, the water–energy–food (WEF) plays a significant role in tackling sustainability issues with a holistic approach (Hoff, 2011).

2.2.5 Promotion of reliance on non-freshwater resources as water supply

Non-freshwater resources are the ones with quality not adequate for direct use whether for irrigation or drinking. Either this can be due to high salinity such as seawater, saline or brackish wells or contaminated wastewater from industrial effluents from oil, textile or food industry, conventional planting wastewater that is contaminated with pollutants from soil. Utilization of the non-freshwater for agriculture and food production after being adequately treated or diluted to meet the standards for irrigation represents great potential and an example for the nexus thinking specially in countries or regions that are suffering from fixed water quota and fast population growth such as the majority of MENA region countries like Egypt. This approach will be of great help to conserve the huge amount of water consumed on agriculture by treating its runoff water or mixing it with low salinity water to meet crop standard minerals intake.

This approach of non-freshwater reuse has wide acceptance and great opportunity for implementation in communities where water scarcity is a major problem and there is wide agriculture activities at the same time. In such circumstances, this wastewater reuse minimizes the waste effluents being discharged to freshwater surfaces and hence protects from contamination with excess minerals and the subsequent Eutrophication.

However, it is crucial prerequisite to enhance people awareness and provide them with proper training to build their capacities to be able to treat and use the non-freshwater in addition to get the knowledge of the adequate plants that can cope with high salinity water such as palms and olive.

More than 70% of waste effluents are not properly discharged or subjected to treatment worldwide (WWAP, 2014). The main generator of these wastes are developing countries with significant consumption and production of wastewater. The utilization of such wastewater that is rich in minerals and organics essential for healthy growth of crops in addition of the resulting reduction of dependency on inorganic fertilizers. Such practices are currently
spreading specially in central African countries with sever freshwater scarcity challenges (Wahba et al., 2018).

Agronomists in the above-mentioned regions can have a profitable and water efficient crop production opportunity. For this utilization of wastewater will result in higher speed of plants growth, resulting in having more harvests per year and higher rates of food production (Zbyszewski & Corcoran, 2011). The main issue that needs to be highly taken into consideration is the insurance of compliance with the official norms and standards of wastewater indicators in order to protect both farmers and the communities that will use these crops from pathogens and infections coming from the used wastewater (Mannan et al., 2018). For other regions that generates considerable amounts of wastewater and having ground wells with declining levels, treated wastewater can be used to compensate for the losses in the wells level.

In addition to adaptation of wastewater reuse, treatment and usage of water with high salinity whether from sea or brackish wells are also of great potential to achieve conservation of freshwater consumption and provide an alternative sustainable water resource for agriculture and food production. However, such practices still have their limitations that need to be overcome which is the generation of very high salinity brine which needs further treatment or dilution before being discharged in order to avoid Eutrophication of water surfaces (Avellán et al., 2018).

2.3. Hydroponics Systems

The definition of Hydroponics systems can be summarized as an alternative technique for producing crops replacing conventional agriculture by planting without soil, relying only on mixing water with nutrients necessary for plants to grow sustainably. For Hydroponics systems, in order to compensate for the lack of soil, supporting media such as sand or gravel is utilized to place the plants on (Rufí-Salís et al., 2020).

In hydroponics systems, while starting up the system, minerals must be supplied to the system in the form of a liquid containing mixture of nutrients that is easy to be absorbed by plant roots. This mechanism is dissimilar from the traditional soil-based cultivation, where the nutrients needed are already present in the soil and penetrate directly to the roots of the crops. For the case of hydroponics, minerals are applied in a liquid state close to the roots so
the plant can captivate it. Figure 7 illustrates the differences between the traditional agriculture and the hydroponics systems (Treftz & Omaye, 2016).

![Figure 7 Differences between hydroponically and soil-grown plants (Treftz & Omaye, 2016).](image)

Apart from the different advantages of Hydroponics that will be discussed in the coming sections, utilization of hydroponics systems for food production has an indirect benefit is that it helps people to get introduced to the environmental benefits and also the negative impacts of the soil based agriculture (Gruda & Schnitzler, 2006).

The following sections are discussing the different types of Hydroponics systems in addition to their benefits and limitations.

**2.3.1 Types of Hydroponics Systems**

**2.3.1.1 Drip System**

This type is the most commonly used hydroponics system. The methodology of operation behind the hydroponic drip system is relatively simple which makes it extremely easy to be utilized, and makes it very popular amongst other types, figure 8 represents and illustration of the system setting. Vital minerals and nutrients are added to a tank of water to create a nutrient reservoir which is kept insulated from the plants. The water is then pumped up an assembly of tubes, and is released to the plants individually.
The pump can be adjusted via a timer, and eliminates the need for any conventional manual irrigation, and enabling to decide an accurate frequency for the irrigation series to implement. A valve can be placed at the end of each tube in the network to allow more, or less, water to reach a specific plant during each watering cycle. This implies that a range of different plants species can be put into the same system and tailor the watering cycle to cater to the different plants’ individual needs. Drip systems can be divided into two categories: The recovery drip system and The non-recovery drip system (Chen et al., 2020).

The first category which is the recovery drip, the name illustrates the system characteristics, and highlights the system ability to whether the water recycles itself or not. In such hydroponic recovery drip system, any excess nutrient solution will be collected again into the nutrient reservoir, where it can be re-utilized. This makes the system much more efficient; consequently, a relatively low amount of maintenance is needed (Bharti et al., 2019).

For this type of installation, the nutrients solution inside the reservoir will necessarily need to be checked on regular basis, as due to the fact that plants captivate the nutrients this will begin to alter the composition of the nutrients remaining in the solution.

2.3.1.2 Ebb and Flow System (Flood and Drain System)

The ebb and flow hydroponics system (as known as a flood and drain system) is another very commonly used type of hydroponics. It works in a way similar to the drip system, however, it
is characterized by further simplicity compared to it. That simplicity makes it easy to be utilized by beginners and farmers that still need to gain experience.

![Image of an ebb and flow hydroponics system](image)

Figure 9 Ebb and Flow Hydroponics System (Datko, 2016)

Similar to the drip system, an ebb and flow system also relies on the utilization of a nutrient reservoir, keeping the water in a separate tank to the plants, which are placed in a grow tray as shown in figure 9 above. A timer is set to regularly control a distribution pump which is erected in the nutrient reservoir. During operation, the pump will submerge the grow tray with the nutrient solution, provides the plants with the nutrients crucial for their healthy growth.

When the growth tray is completely submerged, the system will automatically turn itself off, and the extra flow will start to circulate back to the nutrient reservoir. This constant sequence of submerging the growth tray with the nutrients solution, then enabling it to discharge, is the reason behind naming this system. Because the overflow returns back into the nutrient reservoir, the system requires very low maintenance, and almost self-reliant.

As in the case of the drip system, the pump timer can be manually adjusted for plants nourishing as regularly as needed per each type of plant. However, on the contrast to the drip system, this system does not support the control of nutrients that is being fed to each crop individually, the entire group of crops will be submerged with water and minerals at the same level.
Because of the uncomplicatedness of ebb and flow Hydroponic type, it is considered to be relatively flexible to be installed everywhere even in residential places. In addition to being simple in terms of installation, it is also relatively cheap and affordable, hence providing an economic technique for planting crops.

2.3.1.3 Nutrient Film Technique (NFT)

Unlike the above type that is being used in residential areas, this Hydroponics category is typically used for business scale crop production for growing plants that have various harvest cycles per year. It is called Nutrient Film Technique, NFT as an abbreviation and illustrated in figure 10 below.

![Nutrient Film Technique (NFT)](Datko, 2016)

This category is considered to be different from the other two types discussed above. In this one no time adjustment needed to control the time of water flow through the system. As a replacement to that the water is constantly flowing through the tank. Level of the growth compartment is constructed with inclination to allow smooth discharge of water and nutrients to be recollected again to the minerals tank (Aggarwal et al., 2020).

As a replacement of scheduled automated irrigation of crops, fertilized water is allowed to continuously trickle through the planted crops. The previously mentioned inclination in the
designed structure is to permit the water to trip without touching the bottom of the tank to guarantee that water will not submerge the growing tray and deteriorate the plant due to being exposed to excess minerals and nutrients. Further flow control through this inclination to also guarantee the presence of the adequate minerals concentrations needed by the growing crops (Datko, 2016).

Due to the lack of time control in this Hydroponic category, the maintenance requirements and errors possibility is almost none. The system is ready to operate by just adding fertilized water and enable it to be pumped across the crops (Vidhya & Valarmathi, 2019). This type of hydroponics installation has the ability to operate for considerable durations without being stopped, therefore it is strongly required to test its aeration level to prevent any anaerobic deterioration inside the system (Chen et al., 2020).

2.3.2. Merits of Hydroponics Produced Plants Over Conventionally Cultivated

2.3.2.1 Ecological benefits

One of the major environmental benefits of hydroponics systems is that it can be installed in lands that are not suitable for agriculture such as desert areas. This represents a great opportunity for food production in non-arable lands and in regions apart from natural fresh water resources (Grewal et al., 2011). In addition, hydroponics is user friendly system, for it doesn’t need experienced farmers to operate (FAO, 2013). Moreover, Hydroponics prevents the soil and ground water contamination with fertilizers resulting from runoff that occurs during conventional agriculture (Rufí-Salís et al., 2020).

2.3.2.2 Economic benefits

Hydroponics represents positive economic opportunity to grow crops. Adapting such systems enables planting several crops at high yields during the same time of the year. In addition, healthier crops can be obtained by tailoring the nutrients mixtures utilized in addition to the full control on the system parameters such as nutrients concentrations, temperature and light (Gruda & Schnitzler, 2006).

Several universities in the United States have implemented case studies to assess the economic aspects of hydroponics systems and set comparison between the different designs of single and double bay house types (Trefitz & Omaye, 2016). During conduction of the case studies, several crops have been tested such as lattice, tomatoes and other crops (Coolong et al., 2004). Based on these tests, it was proven that Hydroponics are more economic for garden
crops such as lattice, cucumber and tomatoes compared to other crops in terms of energy consumption and labor needs (Coolong et al., 2004) (Rufí-Salis et al., 2020).

Nevertheless, such finding is still under research and development to overcome the economic challenges for different crops and it is foreseen to be significantly improved in near future (Treftz & Omaye, 2016).

Currently, different variables are being studied to determine a full image of all economic components of hydroponics systems with different designs. The main recent focus of economic assessments is the type of media used, based on these assessments it was concluded that cost differs based on the type of media installed in the hydroponic system (Bushey et al., 2006). Other case studies assessed other significant costs while growing garden crops such as lettuce, it was found that skilled workers and energy consumption are the main pillars in terms of hydroponics crops costs that can exceed 80 per cent of the total cost (Aggarwal et al., 2020) (Coolong et al., 2004).

Another case study investigating the performance of cylinder-based hydroponics system type concluded that the ROI of such hydroponics system is almost 40 times higher than that of equivalent conventional soil agriculture system, moreover, it was found that it results in reduction in manpower cost by more than 20 percent (Treftz & Omaye, 2016). Another important factor while assessing the benefit of hydroponics is the system area, it has been found that the higher the area the higher the profit, for instance, a 1500 square meter farm can have profit margin of 4 percent while a 4000 square meter farm can has a profit increase reaches more than 15 percent (Treftz & Omaye, 2016). Moreover, hydroponics has a significant advantage that it can be theoretically installed at location because it is independent from soil fertility. Such advantage can enable farmers to produce crops nearby their villages and cities (Treftz & Omaye, 2016). This will significantly impact transportation cost of produced crops which result in reduction of food prices with the subsequent reduction in carbon footprint resulting from reducing fossil fuel consumed in transportation (Vidhya & Valarmath, 2019).

Moreover, such approach is greatly accepted by society who prefers to obtain crops from nearby producer to ensure the good quality and freshness of the food. This results in higher economic benefits to the farmers as more than 60 percent of the crop price will be returned to the farmers compared to less than 45 percent if crops were sold in a far location from where they have been grown (Treftz & Omaye, 2016).
2.3.3 Limitations of Hydroponics Systems

Installation of hydroponics systems still have challenges to overcome. First, is the capital expenses per unit area, this is still significantly higher than conventional agriculture by an average of 15 times (Aggarwal et al., 2020). Second, it is a crucial prerequisite for hydroponics systems to have highly experienced labor in terms of how hydroponics systems function, the key parameters and settings that need adjustment for proper operation in addition to the key performance indicators such as water acidity, minerals concentrations and temperature to follow up to ensure sustainable and efficient control (Rosegrant et al., 2009). Third, it is the energy cost and more importantly its availability. Despite the fact that hydroponics systems are flexible to be installed in non-fertile lands, they are strongly reliant on energy for operation and illumination. This dependency results in making the system inadequate to operate in low income countries that usually lack energy stability which can affect the growing plants. Nevertheless, the development of renewable energy generation and utilization can minimize both challenges; the cost and the availability (Treftz & Omaye, 2016).

Fourth challenge, is the safety of crops produced by hydroponics systems. Both community and food authorities are always concerned about food safety and quality. Though Growing crops inside the hydroponic system may protect crops from many contaminations compared to those planted by soil based agriculture, risk of contaminants existence can also occur in hydroponics systems (Aggarwal et al., 2020). Water based diseases and organisms can easily attack the crops, this is based on detection of harmful organisms on crops, cleaning tools and inside the hydroponics basins and puddles. Consequently, in order to overcome the contamination challenges in Hydroponics systems, development of Best Practice policies and guidelines are crucial in order to protect crops from harmful bacterial and fungal attacks (Bharti et al., 2019)(Treftz & Omaye, 2016). Research on hydroponics is considered to be relatively new field, considering the vital advantage of having the ability to completely control their operational indicators. Hence, it is important to continue studying the optimum conditions and operation methodology for each crop instead of reliance on practices that are trial and error based (Treftz & Omaye, 2016).
2.3.4 Hydroponics vs. Conventional Agriculture

Hydroponics agriculture techniques have growing popularity due to their features and advantages that led to making them a good alternative to regular agriculture. Regular agriculture has a large number of drawbacks such as excessive water use that exceeds 65 percent of freshwater, land contamination resulting from fertilizers and herbicides in addition to soil erosion. On the other hand, hydroponics systems have been proven to be efficient in terms of water and energy consumption. Moreover, they have remarkable advantage of being flexible in terms of types of crops to be planted or the location to be installed at. This flexibility is a result of the ability of fully control the key parameters necessary to grow a specific plant such as temperature, nutrients concentration, water circulation and illumination. In addition, such systems are independent of soil fertility, hence they are basically can be installed anywhere, avoiding excessive land use that reaches 40 per cent of available lands and soil exhaustion of traditional agriculture. Another additional merit of the hydroponics is the high crop productivity compared to the conventional soil-based technique which makes it able to fulfill the increasingly food needs due to the growing population worldwide (Barbosa et al., 2015).

Table (5) below illustrates the advantages and limitations of hydroponic systems compared to soil-based culture (Seungjun Lee & Lee, 2015).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Hydroponics</th>
<th>Conventional Agriculture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecological Impact</td>
<td>Independent of land with no impact on crop quality.</td>
<td>Has significant limitation in case of land aridness, contamination with various pollutants and also lack of fertility.</td>
</tr>
<tr>
<td></td>
<td>Simple Minerals Adjustment and provision of optimum conditions for each crop regardless the season and external weather conditions.</td>
<td>Constrained by weather and light hours, hence affecting the flexibility of cultivating crops outside their typical growth season.</td>
</tr>
<tr>
<td></td>
<td>The flexibility to be installed almost anywhere even inside buildings.</td>
<td></td>
</tr>
<tr>
<td><strong>Work Needed</strong></td>
<td>Very limited labor needed, systems can be automatically controlled.</td>
<td>Large number of labor needed for implementing the conventional farming activities.</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>Cleanliness</strong></td>
<td>Full control over cleanliness conditions simple dismantle and erection that guarantee the good conditions in each part of the system.</td>
<td>Maintain soil and crops in clean and healthy conditions is challenging.</td>
</tr>
<tr>
<td><strong>Infections</strong></td>
<td>Hydroponics systems provide protection of the crops from infections and plants diseases that can be transferred through soil.</td>
<td>It is a challenge to prevent infections and diseases within the soil, insecticides are necessary for infections control.</td>
</tr>
<tr>
<td><strong>Resource Efficiency</strong></td>
<td>Resources especially water are being utilized in very sustainable approach. Nutrients solutions can be reutilized, renewable energy sources can be used to operate the system.</td>
<td>Conventional agriculture is the highest water consumer among all activities; in addition, water used for irrigation cannot be reused due to the potential of land contamination with excess minerals.</td>
</tr>
<tr>
<td><strong>Minerals needed by crops</strong></td>
<td>Minerals can be supplied to plants with high accuracy that guarantees the fulfillment of crops needs using the minimum quantities of nutrients which makes it extremely economic.</td>
<td>Uneven distribution to crops (partial deficiency); often use of excessive amount of nutrient; high variation, hard to control pH and amount of nutrient</td>
</tr>
<tr>
<td><strong>Plants Health</strong></td>
<td>Constant quantities of crops can be contained. Crops are</td>
<td>Quantities of crops produced cannot be controlled due their high exposure to risks such as insects and</td>
</tr>
</tbody>
</table>
having all features of the adequate and healthy plants. diseases that may end up disposal of the planted crop. In addition, crops features are not always healthy as they depend on soil fertility and existence of the minerals needed for their growth.

2.3.5 Hydroponics Nutrients and Standard Recipes

For vegetative crops, most nutrient-solution recipes do not adjust the ratio of nutrients while they grow. Whereas, in fruiting crops the ratio may be adjusted to alter the shift between vegetative and reproductive growth. The majority of nutrients recipes are made-from-scratch recipes that require mixing of several individual compounds. Large commercial operations often follow the made-from-scratch method because of the ability to adjust individual compounds and because it can be more cost effective to purchase the individual compounds in bulk (S. Mattson & Peters, 2014a).

Most hydroponic recipes are using two or three tanks. This is necessary to avoid precipitate formation or sludge creation that will occur when specific nutrients are mixed in the concentrated form. In particular, calcium can combine with phosphates and sulfates to form insoluble precipitates. To form successful nutrients recipes it is crucial to select high quality nutrients with very high purity and 100% water soluble (S. Mattson & Peters, 2014a).

2.4 Overview on Forward Osmosis Desalination

This desalination technology can be classified as one of the membrane-based categories where either saline or brackish water can be treated in to fresh water and brine using a membrane with a selective permeability for salts ions. Forward desalination system consists of Feed Solution Compartment where saline or brackish water is placed, and Draw Solution Compartment where a highly soluble draw solute is dissolved in distilled water. Both Feed and Draw Solutions are in contact with a semi permeable membrane through which freshwater molecules are being transported from the Feed Solution to the Draw Solution resulting in gradual dilution of the draw solution and corresponding concentration of the feed solution.
Final products of Forward Osmosis is a diluted draw solute and concentrated brine. (Cath et al., 2006a). Figure (11) illustrates the mechanism of Forward Osmosis versus reverse osmosis technique (Howflux, 2016).

![Figure 3 Forward Osmosis Mechanism (Howflux, 2016)](image)

As per Figure (11) there is a solution penetrates the membrane from one compartment to the other. For the case of Forward Osmosis, the solution is the fresh water molecules and they flow from the feed solution compartment (usually contains saline or brackish water). In this technique, there is no pressure difference as there is no applied mechanical pressure on any of the compartments as the driving force is the concentration gradient of draw solution between the two compartments and its osmotic pressure. For the case of Pressure Retarded Osmosis, Fresh water molecules are transported from to the high salinity solution compartment. The high salinity solution compartment is under hydraulic pressure. Regarding the Reverse Osmosis Technique, fresh water molecules are transported from the high salinity compartment to the low salinity compartment upon application of high hydraulic pressure (Cath et al., 2006b).

This relatively new technology of Forward Osmosis represents a remarkable potential for several uses due to its very low energy consumption compared to other membrane-based desalination technologies. Potential uses are such as in pharmaceutical and nutritional products industries. Moreover, during the past few years, Forward Osmosis became very promising in the field of desalinating saline and brackish water (McCutcheon et al., 2005).

Forward Osmosis exhibits a large number of advantages; it is characterized by significantly low energy consumption resulting from no application of hydraulic pressure as it depends only on the osmotic pressure difference between the draw and feed solutions. Figure (12)
summarizes the main merits of the Forward Osmosis technology while being used for different aspects. As previously mentioned, Forward Osmosis presents a very positive example of energy efficient desalination techniques, which increases its economic feasibility compared to others. The Forward Osmosis technology can be effectively optimized by proper selection of draw solutes with high osmotic potential, proper water solubility and can be easily recovered without passing through a complex process (Elimelech & Phillip, 2011). Such characteristic feature makes it very promising in the view of the global energy conservation approach. Moreover, Forward Osmosis has very low fouling rates due to the absence of applied hydraulic pressure, which enables the membrane to have higher durability and lower maintenance rates resulting in reduction in operating cost (Achilli et al., 2010) and easy to regenerate (Sangyoup Lee et al., 2010). Full control on the process is achievable via hydrodynamic adjustment (Sangyoup Lee et al., 2010). Furthermore, Forward Osmosis is characterized by high selectivity, ability to reject impurities and unwanted ions and prevents them from penetrating the membrane into the draw solution compartment (Cartinella et al., 2006) (Achilli et al., 2010). In addition, Forward Osmosis has a positive feature of providing significant water flux resulting from the driving force of the concentration differences and the subsequent osmotic pressure gradient throughout the Forward Osmosis set up (McCutcheon et al., 2005).

2.4.1 Fertilizer Driven Forward Osmosis Desalination FDFO

The Fertilizer Drawn Forward Osmosis is one of Forward Osmosis types where the draw solute is a single or a mixture of fertilizers. This type of desalination is suitable for treating both saline
and brackish water in order to produce water with adequate quality for irrigating crops (Nasr & Sewilam, 2015b; Phuntsho, Shon, Majeed, et al., 2012a). During this process, a continuous dilution occurs to the highly concentrated fertilizer solution due to the transport of fresh water molecules from the saline or brackish water compartment, this dilution continues until osmotic pressure gradient across the draw and feed solutions reaches the equilibrium. The produced treated water mixed with fertilizers that can be utilized for conventional agriculture or—in case of nutrients mixture—can be applied to hydroponics systems. This type of forward osmosis has a unique advantage compared to other forward osmosis desalination uses, which is eliminating the need to recover the draw solute from the treated water. This results in a considerable reduction of energy consumption required for recovery. Based on the final produced mixture concentration, it can be directly applied to the crops or may need additional dilution before being utilized.

This special Forward Osmosis Technique has several environmental benefits in terms of energy savings and achieving sustainable water resource for food production. Forward Osmosis exhibits the interlinkage between Water- Energy-Food and represents a great example for the WEF nexus, however, this technique still needs further research to get a full picture of its merits and drawbacks and how to mitigate a common Forward Osmosis drawback such as the need of further dilution (Phuntsho et al., 2011). Being one of the FO types, it functions with the same mechanism; the fertilizer solution used as draw solution is put in contact with the brackish or saline water used as feed solution through a semi-permeable membrane. The two solutions are pumped in countercurrent flow pattern to mitigate the concentration polarization phenomenon that hinders the steady flow of molecules across the membrane. Due to the osmotic pressure and concentration gradient resulting from the difference in osmotic pressure values between the draw and feed solutes, fresh water molecules penetrate the membrane from the feed solution with lower fertilizers concentration to the draw solution with higher fertilizers concentrations. The produced diluted fertilizers solution will then need to be tested to assess the adequacy of its minerals content with irrigation standards, if it is suitable, it can be directly applied, in case of inadequacy, further dilution will be needed before usage (McCutcheon et al., 2005).

As previously discussed, Forward osmosis (FO), is an osmotically driven desalination process utilized in number of industrial and medical applications (Cath et al., 2006a). This technology
is characterized by the low energy consumption compared to the conventional reverse osmosis techniques (McCutcheon et al., 2005).

Unlike Reverse Osmosis that operates with differential of hydraulic pressure, Forward Osmosis operates using the differential of osmotic pressure symbolized by \(\Delta \pi\) as a driving force to transfer water molecules across the semi-permeable membrane with the previously mentioned subsequent dilution of the draw solution and concentration of the feed solution. Water flux through the semi permeable membrane can be determined using equation (2.1) below:

\[
J_w = A (\sigma \pi - \Delta P) \quad (2.1)
\]

In this equation, \(J_w\) (L.m\(^{-2}\).h\(^{-1}\)) stands for water flux, \(A\) (L.m\(^{-2}\).h\(^{-1}\).bar\(^{-1}\)) represents the membrane permeability constant, \(\sigma\) illustrates the reflection coefficient while \(P\) is the hydraulic pressure (bar) applied which is equal to zero for the case of FO.

As a consequence of no application of hydraulic pressure, i.e. \(\Delta P\) is zero, and an assumption of \(\sigma\) to be equivalent to unity, a rephrase of equation (2.1) can be made as the following:

\[
J_w = A \Delta \pi = A [\pi_{DS} - \pi_{FS}] \quad (2.2)
\]

While, \(\pi_{DS}\) (bar) Stands for bulk osmotic pressure of the DS

\(\pi_{FS}\) (bar) Stands for bulk osmotic pressure of the FS

Being non-ideal membranes, Polymer-based membrane are not capable of achieving complete elimination of solute penetration. Consequently, there is always a potential of solute transport through the membrane from the two sides. Figure 13 describes the concentration gradient which is the driving force for solute penetration through the membrane (Phuntsho et al., 2011).

From the figure, draw solute is able to transfer from the solute side of the membrane to the feed water solute due to the difference in concentration of solute at the two sides of the membrane. \(CF\) represents the concentration of the draw solute at the feed solution side which is approximately zero, \(tS\) is the width of the support part of the membrane, \(tA\) is the width of active layer of the membrane, \(CiS\) and \(CiA\) symbolize the concentration of the draw solute and the support part and active part sides (Elimelech & Phillip, 2011). Hence, Reverse Solute Flux which is usually symbolized as \((Js or RSF)\) can be described as draw solutes penetration taking place in the counter direction of fresh water flux.
Reverse Solute Flux (RSF) is a critical parameter while assessing forward osmosis desalination process. High RSF indicates significance of the quantities of draw solute lost during desalination and a subsequent economic loss. This is due to the irreversible reduction of draw solute concentration that will require compensation to restore its original concentration in the draw solution compartment (Cath et al., 2006a). Moreover, RSF can result in contamination of feed water and the water reservoir that will receive the discharged brine, this will happen specially when the draw solute contains phosphorus or nitrogenous salts due to the tendency to cause water eutrophication (Kim et al., 2017). RSF is considered a damaging indicator due to negative impact on feed and draw solutes concentrations which consequently affects the osmotic gradient and the driving force needed to operate. In addition, it can have a significant impact on membrane fouling and lifetime due to the possible reactions between the draw and feed salts (Cath et al., 2006a). Hence, it is of crucial importance to assess RSF for forward osmosis (Nasr & Sewilam, 2015b).

RSF through a semi-permeable membrane is a function of the concentration difference between Feed and Draw solutions [i.e. \( J_s \propto f(\Delta C) \)] (Nasr & Sewilam, 2015b) and hence it can be determined from the equation (2.3) below:

![Figure 5 Chemical Concentration Gradient that drives Forward Water and Reverse Solute Flux (Elimelech et al., 2011)]
\[
RSF = \frac{J_s}{V_i - \Delta V} \times Cs \quad (2.3)
\]

Where:  
\( V_i \): Stands for the primary volume of FS  
\( \Delta V \): Stands for the water volume transferred from FS to the DS.  
\( Cs \): Stands for the concentration of the draw solute in the FS after experiment completion.

The RSF value is not indicative for the fresh water quantity transported via the membrane. Therefore, it is important to include another indicator to represent the relation between the water amount transported and the losses in the draw solute occurred. This has been achieved by calculating the Specific Reverse Solute Flux (SRSF). This represents the ratio between the quantity of draw solute lost and the fresh water extracted volume (Cath et al., 2006a). SRSF can be determined using the equation below:

\[
SRSF = \frac{J_s}{J_w} \quad (2.4)
\]

A low SRSF value indicates high membrane selectivity and efficient forward osmosis process and vice versa (Zhao et al., 2012). SRSF is also indicative for the selectivity level of the membrane active part; however, it does not rely on the concentration of the draw solute nor the support structure of the membrane (Hancock & Cath, 2009; Phillip et al., 2010).

Forward rejection of the feed solute ion is the opposite feature of the reverse solute flux, and it can be calculated as per the equation 2.5 below:

\[
Rs(\%) = \frac{(C_i - C_p)}{C_i} \times 100 \quad (2.5)
\]

Where: \( C_i \) stands for the initial concentration of the ion in FS.  
\( C_p \) stands for the final concentration of the ion in permeate,  
This is equivalent to \( C_{p,D}(V_i + \Delta V)/\Delta V \), where \( C_{p,D} \) represents the measured ion concentration in the draw solution (Nasr & Sewilam, 2015b).

### 2.4.2 Draw solutions

Draw solution and its concentration, composition and physical properties play vital role in the performance of the Forward Osmosis desalination process. Its concentration functions as the driving force to extract water from the feed solution. Consequently, selection of adequate draw solution is of great importance for an efficient forward osmosis desalination process.
Figure (14) summarizes the selection criteria for draw solution. The first main selection feature is the high osmotic pressure; draw solution must have osmotic pressure higher than that of the feed solution in order to develop the driving force necessary for desalination. To determine the osmotic pressure of a solute with a specific concentration, a simulation software can be used to predict the value before conducting the experiments. The software used for the experiments in this research is named OLI stream Analyzer (OLI Systems Inc., 2019). It is a software that predicts the osmotic pressure of the proposed draw solutions at different concentrations and temperatures using thermodynamics modeling based on previously published experimental data.

The Second feature of draw solution selection is to be possible to be recovered from the treated water after the desalination process and re-concentrated to be reused again. In the past, highly concentrated NaCl solution such as dead sea water and Salt Lake water have been used as draw solution, this is because it is very soluble in water and adequate for easy re-concentration process. Re-concentration process can be done using a secondary treatment using Reverse Osmosis technique. In addition to the previously mentioned features, diffusivity of draw solute molecules through the semipermeable membrane is also of great importance. For instance, if the FO application demands high rejection, it is recommended to utilize solutes with multivalent ions to prevent contamination of feed solution with draw solute ions (Cath et al., 2006a).
Over the past years, different types of chemical compounds other than NaCl solutions have been tested, such as water and gaseous mixtures that used to desalinate seawater, table (6) illustrates various types of DS. The most commonly used ones were Sulfur dioxide and aliphatic alcohols, adding to that other mixtures such as aluminum sulfate, glucose solution and mixture solution of glucose and fructose (Hoover et al., 2011).
<table>
<thead>
<tr>
<th>Year</th>
<th>Draw solute / solution</th>
<th>Recovery method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964</td>
<td>Ammonia and carbon dioxide</td>
<td>Heating</td>
<td>(Neef, 1964)</td>
</tr>
<tr>
<td>1965</td>
<td>volatile solutes (e.g. SO₂)</td>
<td>Heating or air stripping</td>
<td>(Balasch, 1965)</td>
</tr>
<tr>
<td>1965</td>
<td>Mixture of H₂O and another gas (SO₂) Distillation or liquid (aliphatic alcohols)</td>
<td></td>
<td>(Giew, 1965)</td>
</tr>
<tr>
<td>1972</td>
<td>Al₂SO₄</td>
<td>Precipitation by doping Ca(OH)₂</td>
<td>(Frank, 1972)</td>
</tr>
<tr>
<td>1975</td>
<td>glucose</td>
<td>None</td>
<td>(Krauth &amp; Davis, 1975)</td>
</tr>
<tr>
<td>1976</td>
<td>glucose-Fructose</td>
<td>None</td>
<td>(Kessler &amp; Moody, 1976)</td>
</tr>
<tr>
<td>1980</td>
<td>Fructose</td>
<td>None</td>
<td>(Stacho, 1980)</td>
</tr>
<tr>
<td>1992</td>
<td>glucose</td>
<td>Low pressure RO</td>
<td>(Yael, 1992)</td>
</tr>
<tr>
<td>1997</td>
<td>MgCl₂</td>
<td>None</td>
<td>(Loeb, Tittelman, Kornfeld, &amp; Freiman, 1997)</td>
</tr>
<tr>
<td>2002</td>
<td>KNO₃ &amp; SO₂</td>
<td>SO₂ was recycled through standard means</td>
<td>(R. L. McGinnis, 2002)</td>
</tr>
<tr>
<td>2005-2007</td>
<td>NH₃ &amp; CO₂ (NH₄HCO₃) or NH₄OH-Moderate heating (~60 °C) NH₄HCO₃</td>
<td></td>
<td>(McCUTCHEON et al., 2005, 2006)</td>
</tr>
<tr>
<td>2007</td>
<td>Magnetic nanoparticles</td>
<td>Captured by a canister separator</td>
<td>(Adham, Oppenheimer, Liu, &amp; Kumar, 2007)</td>
</tr>
<tr>
<td>2007</td>
<td>Dendrimers</td>
<td>Adjusting pH or UF</td>
<td>(Adham et al., 2007)</td>
</tr>
<tr>
<td>2007</td>
<td>Albumin</td>
<td>Denatured and solidified</td>
<td>(Adham et al., 2007)</td>
</tr>
<tr>
<td>2008</td>
<td>Salt, ethanol</td>
<td>Pervaporation-based separations</td>
<td>(McCormick, Pellegreno, Mantovani, &amp; Sarti, 2006)</td>
</tr>
<tr>
<td>2010</td>
<td>2-Methylimidazole based solutes</td>
<td>Membrane Distillation</td>
<td>(Yen, N. Su, Wang, &amp; Chung, 2010)</td>
</tr>
<tr>
<td>2010</td>
<td>Magnetic nanoparticles</td>
<td>Recycled by external magnetic field</td>
<td>(Ge, Su, Chung, &amp; Amy, 2011; Ling, Wang, &amp; Chung, 2010)</td>
</tr>
<tr>
<td>2011</td>
<td>Stimuli-responsive polymer hydrogels</td>
<td>Deswelling of the polymer hydrogels</td>
<td>(Li, Zhang, Yao, Zeng, et al., 2011; Li, Zhang, Yao, Simon, &amp; Wang, 2011)</td>
</tr>
<tr>
<td>2011</td>
<td>Hydrophilic nanospheres</td>
<td>UF</td>
<td>(Ling &amp; Chung, 2011)</td>
</tr>
<tr>
<td>2011</td>
<td>Fertilizers</td>
<td>None</td>
<td>(Phuntsho, Shon, Hong, Lee, &amp; Vigneshwaran, 2011)</td>
</tr>
<tr>
<td>2011</td>
<td>fatty acid-polyethylene glycol</td>
<td>Thermal method</td>
<td>(Linda &amp; Iyer, 2011)</td>
</tr>
<tr>
<td>2012</td>
<td>Sucrose</td>
<td>NF</td>
<td>(Su, Chung, Heimer, &amp; Wit, 2012)</td>
</tr>
<tr>
<td>2012</td>
<td>Polyelectrolytes</td>
<td>UF</td>
<td>(Ge, Su, Amy, &amp; Chung, 2012)</td>
</tr>
<tr>
<td>2012</td>
<td>Thermo-sensitive solute (DerivativesNot studied of Acyl-TAEA)</td>
<td></td>
<td>(Noh et al., 2012)</td>
</tr>
<tr>
<td>2012</td>
<td>urea, ethylene glycol, and glucose</td>
<td>Not studied</td>
<td>(Yong, Philip, &amp; Elmsliech, 2012)</td>
</tr>
<tr>
<td>2012</td>
<td>Organic salts</td>
<td>RO</td>
<td>(Bowdren, Achilli, &amp; Childress, 2012)</td>
</tr>
<tr>
<td>2012</td>
<td>hexaamine phosphazene salts</td>
<td>Not studied</td>
<td>(Stone, Wilson, Harrup, &amp; Stewart, 2013)</td>
</tr>
<tr>
<td>2014</td>
<td>Hydro Acid Complexes</td>
<td>Recycled</td>
<td>(Go et al., 2014)</td>
</tr>
</tbody>
</table>
Another FO technique has been previously used that relies on temperature-dependency of certain substances solubility. In this technique draw solutes recovery is done by cooling down the diluted draw solution to precipitate the solute mixture and recover it for reuse. McGinnis made a recommendation to utilize a number of draw solutes mixtures with proven efficiency and easy recovery due to the previously mentioned temperature-based solubility feature. As examples on such draw solutes are, Potassium Nitrate (KNO₃) and Sulfur Dioxide blends, Carbon dioxide and ammonia gases mixtures have also proven high efficiency as draw solute due to their ability to form thermally based removable salts which are easy to recover. This methodology resulted in formation of an efficient draw solution that is very useful to desalinate saline water and minimizing brines generation due to its significantly high osmotic pressure that exceeds 200 atm (McCutcheon et al., 2005). More recent draw solutions are nanotechnology based, such as using nano particles of iron which can be recovered from the product via magnetic field utilization (Cath et al., 2006a). Inorganic fertilizers have been recently excellent candidates for forward osmosis due to their high osmotic potential compared to saline and brackish water, specially when the product water which is a mixture of fresh water and diluted fertilizers are used for irrigating crops. In this case no further recovery in needed for the Fertilizer Drawn Forward Osmosis (FDFO).

2.5. Commonly Used Fertilizers in Egypt

Egypt has a broad history of utilization of inorganic fertilizers. Inorganic fertilizers were used in the form of Chilean nitrates since 1902 (FAO, 2005a). The most popular fertilizers are the Nitrogen based ones (N-Fertilizers) as shown in the figure below, in the second rank comes the Phosphorus based fertilizers (P-Fertilizers) and then comes the least popular category which is Potassium based (K-Fertilizers) this is attributed to lack of availability of natural resources into produce it in Egypt. Figure (15) illustrates the annual Fertilizer Consumption in Egypt per Hectare of Arable Land Production covering the period 2002 -2015 (World Bank, 2015).
The most popular nitrogenous fertilizer is Urea with the highest production rate among the other N-fertilizers with production rate of 5,146,788 tons per year (El-Gebaly, 2015b) compared to the production rate of Ammonium Nitrate 621,908 tons per year and the Ammonium Sulfate with production rate of 116,636 tons per year as illustrated in figure (16).
Regarding the phosphate-based fertilizers (P-Fertilizers), Di-Ammonium Phosphate (DAP) is considered one of the potential P-Fertilizer in Egypt which has been expanded by a production rate of 1,065,000 tons in 2017 (El-Gebaly, 2015a). Potassium-based fertilizers are not widely produced or utilized in Egypt, this is attributed to lack of natural raw materials necessary for production. However, in case specific crops that utilize potassium for growth are needed to be planted, Potassium Nitrate is considered the most preferable for fertilizing as it is more compatible with irrigation using water with relatively high salinity as it minimizes plant chloride uptake. Besides, the potassium element in potassium nitrate has several positive impacts on crop features and quality specifications. Potassium positively affects fruit size resulting in larger dimensions and increased uniformity, gives Fruit better appearance and minimizes blemishes and unusual markings of mechanical injuries or any sign of disease. In addition, Potassium increases crop nutritional value as it makes it has higher content of protein, oil, vitamin C, etc. In addition, it provides better Organoleptic features, enhanced flavor and aroma and Longer shelf life. Adequate processing quality for industry(PNA, 2016).
In this research, Urea, Di-Ammonium Phosphate and Potassium Nitrate have been tested as draw solutes to desalinate real brackish water from one of the potential locations in Egypt, in addition to a standard mixture of fertilizers that is used as hydroponics nutrients and its individual components as will be discussed in the next chapter.
Chapter III: Analyzing the performance of Urea, KNO$_3$ DAP and Hydroponics Mixture as DS
Chapter 3: Analyzing the performance of Urea, KNO₃, DAP and Hydroponics Mixture as DS

3.1 Materials and Methods

Laboratory scale experiments were conducted using the Fluxometer illustrated in Figure (17). It consists mainly of two weigh scales connected to a data logger for continuous FS, DS weight measurements. In addition to double-headed pump providing water flow rate of 0.22 l/min, Stenner Model 170DMP5 as shown in figure (19-a). All experiments were conducted at constant temperature of 25° C. Temperature was maintained using heat exchanger, Polyscience, model 9106 A illustrated in (figure 19-b). All experiments have been conducted in WEF Nexus lab, Center for Applied Research on the Environment and Sustainability (CARES), The American University in Cairo. Full experimental setting is illustrated in figure (20).

Figure 9 Fluxometer Set Diagram (Porifera Inc., 2015)
The initial volume of Draw and Feed Solutions is one liter each, the increase in DS volume and reduction in FS volume were continuously real time monitored and registered on three minutes interval until the equilibrium between the osmotic pressures of the draw and feed solutions has been reached. Average flux has been then calculated based on the changes in volume between DS and FS.

Mass transfer was conducted through commercial membrane named Porifera with a membrane area of $1.257 \times 10^{-3} \text{ m}^2$. Figure (18) shows the membrane cell and scales connected to the data logger for continuous FS, DS weight measurements.

![Figure 10 Cell used for FO](image)

![Figure 11 a, Double Headed Pump, 19 b heat exchanger - Center for Applied Research on the Environment and Sustainability (CARES).](image)
Two set of experiments testing two scenarios were conducted. First scenario assesses the performance of commonly used fertilizers in Egypt (FAO, 2005b) to desalinate brackish water from ground well in Sinai, representing the main nutrients, Urea representing Nitrogen, Di-Ammonium Phosphate (DAP) representing Phosphorus and Potassium Nitrate representing Potassium. The Second Scenario investigates a standard hydroponics mixture for nutrients versus the performance of its macro components as a potential DS. The reason of conducting such comparison in the second scenario is to investigate the changes in occur to single nutrients after being mixed. The performance in both scenarios was assessed based on water flux, draw solute concentration in final product water and Rejection of Feed ions ($Na^+$ and $Cl^-$). Figure 21 summarizes the two scenarios.
3.3 Conducted Experiments

3.3.1 Draw and Feed Solutions

A number of 12 experiments were conducted in a duration of 6 hours each using real brackish groundwater extracted from Sinai-Egypt, testing Potassium Nitrate (KNO₃) Di-Ammonium Phosphate (DAP), Urea at concentrations equal to 1, 2, 3 M. All used chemicals are reagent grade provided by Sigma-Aldrich, Australia. In addition, hydroponics standard mixture against its individual components was examined. Before starting the experiments and during processing, membrane has been visually inspected for scaling that can affect membrane performance. Experiments are illustrated in the table below:

Table 7: List of Conducted Experiments

<table>
<thead>
<tr>
<th>Sr.</th>
<th>Draw Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Potassium Nitrate KNO₃ (1M)</td>
</tr>
<tr>
<td>2</td>
<td>Potassium Nitrate KNO₃ (2M)</td>
</tr>
<tr>
<td>3</td>
<td>Potassium Nitrate KNO₃ (3M)</td>
</tr>
<tr>
<td>4</td>
<td>Di-Ammonium Phosphate (1M)</td>
</tr>
<tr>
<td>5</td>
<td>Di-Ammonium Phosphate (2M)</td>
</tr>
<tr>
<td>6</td>
<td>Di-Ammonium Phosphate (3M)</td>
</tr>
<tr>
<td>7</td>
<td>Urea (1M)</td>
</tr>
<tr>
<td>8</td>
<td>Urea (2M)</td>
</tr>
<tr>
<td>9</td>
<td>Urea (3M)</td>
</tr>
<tr>
<td>10</td>
<td>Hydroponics Mixture</td>
</tr>
<tr>
<td>11</td>
<td>Hydroponics Mix- KNO₃ as individual component.</td>
</tr>
<tr>
<td>12</td>
<td>Hydroponics Mix-Ca(NO₃)₂ as individual component.</td>
</tr>
</tbody>
</table>

A Number of 24 samples were collected from both the Draw and Feed Solutions, draw solution samples were analyzed to determine the feed solute ions via analyzing N, P, K ions concentrations using Photometer NOVA 60 Spectroquant.

Equation (2.6) was utilized to calculate water flux Jw (in Lm⁻²h⁻¹):
\[ J_w = \Delta V \times \text{membrane area} \times \text{time} \quad (2.6) \]

\[ J_w = \text{Pure water Flux (LMH).} \]

\[ \Delta V: \text{difference in draw solution volume before and after the experiment (l).} \]

**Feed Solution:**

The feed solution used is real brackish water from south Sinai area with estimated osmotic pressure of 2.44 atm (Lenntech, 2017) which is significantly lower than Seawater which is estimated to have osmotic pressure of 55.5 atm (OLI Systems Inc., 2019) and has the following chemical composition:

Table 8: Real Brackish Water Composition Extracted from El-Tor-Sinai (Nasr & Sewilam, 2016 a)

<table>
<thead>
<tr>
<th>Raw GW sample characteristics in El Tor, South Sinai (Nasr &amp; Sewilam, 2016a)</th>
<th>Ion Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na(^+)</td>
<td>700 mg/l</td>
</tr>
<tr>
<td>Cl(^-)</td>
<td>1041 mg/l</td>
</tr>
<tr>
<td>NH(^4+)</td>
<td>2 mg/l</td>
</tr>
<tr>
<td>SO(_4^{2-})</td>
<td>2225 mg/l</td>
</tr>
<tr>
<td>Ca(^{2+})</td>
<td>565 mg/l</td>
</tr>
<tr>
<td>Mg(^{2+})</td>
<td>215 mg/l</td>
</tr>
<tr>
<td>K(^+)</td>
<td>42 mg/l</td>
</tr>
<tr>
<td>Fe(^{3+})</td>
<td>0.04 mg/l</td>
</tr>
<tr>
<td>Mn(^{2+})</td>
<td>0.02 mg/l</td>
</tr>
<tr>
<td>NO(_3^-)</td>
<td>30 mg/l</td>
</tr>
<tr>
<td>HCO(_3^-)</td>
<td>17 mg/l</td>
</tr>
<tr>
<td>CO(_3^{2-})</td>
<td>0 mg/l</td>
</tr>
<tr>
<td>EC</td>
<td>7.32 mS/cm</td>
</tr>
<tr>
<td>TDS</td>
<td>4 g/l</td>
</tr>
<tr>
<td>pH</td>
<td>6.5</td>
</tr>
</tbody>
</table>
From the above analysis, this groundwater has Sodium Adsorption Ratio is 33.9 which is extremely high ratio than crops can withstand, resulting in making it toxic to the plants if used for irrigation (Suarez et al., 2008). The lower the osmotic pressure of the feed water the higher will be the driving force for a specific draw solution resulting in high water extraction and more efficient fertilizer drawn forward osmosis process.

### 3.3.2 Scenario I: Individual Assessment of KNO\textsubscript{3}, DAP and Urea and performance as representatives of, N,P,K nutrients commonly used fertilizers in Egypt

Before conducting the experiments, all key physical and chemical properties of the three candidate fertilizers have been collected for initial assessment of their potential as draw solutes, table (9) illustrates the physical and chemical properties of the three fertilizers.

#### Table 9: Physical and Chemical Properties of the Three Tested Fertilizers

<table>
<thead>
<tr>
<th>Fertilizer</th>
<th>KNO\textsubscript{3}</th>
<th>DAP</th>
<th>Urea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Weight</td>
<td>101.102 g/mol</td>
<td>132.056 g/mol</td>
<td>60.056 g/mol</td>
</tr>
<tr>
<td>pH</td>
<td>7</td>
<td>8</td>
<td>7.2 (10% solution)</td>
</tr>
<tr>
<td>Molecular Formula</td>
<td>KNO\textsubscript{3}</td>
<td>(NH\textsubscript{4})\textsubscript{2}HPO\textsubscript{4}</td>
<td>NH\textsubscript{3}CONH\textsubscript{2}</td>
</tr>
<tr>
<td>Osmotic Pressure at 2M</td>
<td>64.85</td>
<td>94.95</td>
<td>46.08</td>
</tr>
<tr>
<td>Physical Description</td>
<td>Colorless-To-White Crystalline powder.</td>
<td>Crystals or crystalline powder.</td>
<td>Solid odorless white crystals or pellets.</td>
</tr>
<tr>
<td>Water Solubility</td>
<td>38.3 g/100 g water at 25 deg C</td>
<td>69.5 g/100 g water at 25 deg C</td>
<td>545000 mg/L (at 25 °C)</td>
</tr>
<tr>
<td>Ionic Strength</td>
<td>0.0336</td>
<td>0.1</td>
<td>1.72 E-3</td>
</tr>
<tr>
<td>Electric conductivity</td>
<td>14.9247</td>
<td>21.47</td>
<td>4.96 E-3</td>
</tr>
</tbody>
</table>
Osmotic potential of each of these fertilizers was simulated at different concentrations using (OLI Systems Inc., 2019) and illustrated in the figure below:

![Figure 15 Osmotic Potential Simulation of Urea, DAP and Potassium Nitrate](image)

3.3.3 Scenario II: Assessing the performance of Macro components of Hydroponics Nutrient Mixture vs. the performance of the individual components at the same concentrations:

For the hydroponics mixture the solution was prepared using DI water and a mixture with specific weights of each component of the nutrients’ recipe.

The following is a selected hydroponics recipe named Jack’s Hydro-FeEd (16-4-17), for growing various types of vegetables such as potatoes, lettuce and tomatoes. It consists of two tanks, A and B, each has mixture of nutrients to be dissolved in water separately to avoid precipitation then the two compartments will be mixed together and diluted to be applied to the hydroponics system (S. Mattson & Peters, 2014b). The table below indicates the composition of each mixture in addition to their osmotic potential compared to the Osmotic potential of the brackish water (Lenntech, 2017; OLI Systems Inc., 2019).
Table 10: Composition of Hydroponics Nutrients Mixture Tested

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Quantity</th>
<th>Nutrient</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca(NO$_3$)$_2$·3H$_2$O</td>
<td>184.0 g</td>
<td>KH$_2$PO$_4$</td>
<td>51.5 g</td>
</tr>
<tr>
<td>NH$_4$NO$_3$</td>
<td>14.4 g</td>
<td>MgSO$_4$·7H$_2$O</td>
<td>93.1 g</td>
</tr>
<tr>
<td>KNO$_3$</td>
<td>167.3 g</td>
<td>MnSO$_4$·H$_2$O</td>
<td>0.290 g</td>
</tr>
<tr>
<td>10% Iron-DTPASprint 330 or Sequestrene 330</td>
<td>3.8 g</td>
<td>H$_3$BO$_3$</td>
<td>0.352 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Na$_2$MoO$_4$·2H$_2$O</td>
<td>0.023 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZnSO$_4$·7H$_2$O</td>
<td>0.217 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CuSO$_4$·5H$_2$O</td>
<td>0.035 g</td>
</tr>
<tr>
<td>Osmotic Pressure</td>
<td>127.36</td>
<td>Osmotic Pressure</td>
<td>53.7836</td>
</tr>
<tr>
<td>Osmotic Pressure Tank A + Tank B (1:1) mixture</td>
<td>129.727</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brackish Water (Salinity 3000 ppm)</td>
<td>2.42 atm (Lenntech, 2017)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As per the table above, due to the low concentrations of tank B and its subsequent low osmotic potential, it can be concluded that tank A has the dominant osmotic impact of the mixture and tank B has negligible impact. In addition, to avoid any precipitation that may occur due to mixing tank A and Tank B to test them as draw solution, Macro Nutrients of Tank A were used alone for conducting the experiments which are Ca(NO$_3$)$_2$ and KNO$_3$. The performance of this mixture was assessed compared to the individual performance of Ca(NO$_3$)$_2$ and KNO$_3$ individually using the same concentrations in the Hydroponics Mixture which are 1.12M and 1.655 M respectively. The objective of this comparison is to assess the influence of mixing the nutrients on the performance of each single fertilizer used.
Chapter IV: Results and Discussion
Chapter 4: Results and Discussion

4.1 Results of Scenario I

4.1.1 Assessing Performance in terms of flux

1. KNO₃:

Potassium Nitrate flux was determined at three different concentrations of 1, 2, and 3 M. As shown in figure 23, the average flux increased with the increase of DS concentration, where the average flux was 5.71 LMH at 1 M and then it increased to 7.85 LMH then slightly elevated to reach 8.12 LMH at 3 M. This increase is attributed to the corresponding increase in osmotic pressure upon increase the DS concentration. However, the increase of flux at 3M was not significant compared to the increase resulted from raising concentration from 1 M to 2 M. This can be attributed to the increase in concentration polarization occurring due to increasing solute concentrations. It can be noticed that the change in water flux was stable starting from the second hour of the experiment (Majeed, 2016).

![Figure 163 Water Flux –KNO₃ as DS](image)

2. Urea:

Upon Testing Urea, relatively low flux compared to Potassium Nitrate was obtained; Average flux was only 2.56 LMH at 1M DS, 3.53 LMH at 2 M and increased to 4.39 LMH at 3 M as per illustrated in figure 24. The reason of this low flux is the relatively low osmotic pressure of
Urea that resulted in lowering the driving force based on osmotic pressure difference between the draw and the feed solutes. This low osmotic potential of Urea is attributed to the few number of species formed upon dissociation in water.

![Figure 17 Water Flux Using Urea as DS](image)

3. **Di-Ammonium Phosphate DAP**

During the experiments, water flux was varying and did not reach the plateau phase till the 5th hour, though these experiments were repeated several times to cross check the behavior of DAP as DS, similar results were obtained every time. From the graph below, it can be concluded that DAP has highest flux compared to Potassium Nitrate and Urea, resulting in average flux of 5.37 LMH at 1 M concentration, 7.42 at 2 M and 9.53 LMH at 3M concentration as shown in figure 25. This is attributed to the fact that DAP has the highest osmotic pressure compared to the other tested draw solutions.
Figure 18 Water Flux Using DAP as DS

Figure 26 below illustrates a comparison between the flux obtained at different molarities of the three tested fertilizers. Di-Ammonium Phosphate has the highest water flux among the three fertilizers, which is attributed to having the highest osmotic potential compared to Potassium Nitrate and Urea. Urea exhibited the lowest flux rates due to its relatively low osmotic potential and few species formed.

Figure 19 Comparison of Flux Rate between DAP, KNO3 and Urea
4.1.2 Assessing Performance in terms of draw solute concentration in final product water

Draw solutes ions in the final water product were analyzed using NOVA 60 Spectroquant and results are illustrated in table 11. Based on these concentrations, which are higher than crops tolerance and can result in damage of plants, the required dilution factors prior being utilized for direct fertigation are estimated.

As an Example of the maximum allowable NPK concentrations for crops, potatoes can be a good one due to its high tolerance of nutrients concentration in soil. The NPK concentrations for potatoes are 0.15, 0.12 and 0.19, respectively and summarized in table 10 (Carrie et al., 2012). Thus, individual fertilizers tested as draw solutes to desalinate the selected brackish water sample will need further dilution. The dilution factor will exceed 10, as per table 11, Urea showed the highest solute concentration in product water, which is a result of the relatively low osmotic pressure and the subsequent low water flux that caused limited dilution of the draw solution. Both KNO₃ and DAP exhibited lower solute concentrations, which is attributed to the relatively high flux that caused solute dilution. Solute concentration was inversely proportional to the original solute concentration, which is matching with the increasing water flux.

<table>
<thead>
<tr>
<th>Table 11: Maximum Allowable N, P, K Intake Concentration for Potatoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen Concentration (g/l)</td>
</tr>
<tr>
<td>0.150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 12: N,P,K Concentration in the Final Produced Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draw Solution</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>KNO₃ 1M</td>
</tr>
<tr>
<td>KNO₃ 2 M</td>
</tr>
<tr>
<td>KNO₃ 3 M</td>
</tr>
<tr>
<td>Urea 1M</td>
</tr>
<tr>
<td>Urea 2 M</td>
</tr>
<tr>
<td>Urea 3 M</td>
</tr>
<tr>
<td>DAP 1 M</td>
</tr>
<tr>
<td>DAP 2 M</td>
</tr>
<tr>
<td>DAP 3 M</td>
</tr>
</tbody>
</table>
4.1.3 Assessing Performance in terms of Forward Rejection

Ion rejection values of Na\(^+\) and Cl\(^-\) ions of both KNO\(_3\) and DAP were remarkably higher than in the case of Urea. It had rejection ranged between 74\% and 82\% as illustrated in figure 27. This figure is comparing the performance of the three types of tested fertilizers at 1, 2 and 3 M concentrations. The increase in rejection is proportional to the increase in osmotic pressure difference between the Feed and Draw solutions that depends on the type and concentration of the draw solute used. Hence, this low feed ions rejection of Urea is attributed to its low osmotic potential compared to the other two fertilizers used. Moreover, there is another significant reason, which is the membrane surface charge. Investigating the behavior of DAP and KNO\(_3\), Na\(^+\) rejection tends to increase with Draw solution increases. Meanwhile, this resulted in decrease in Cl\(^-\) rejection. This can be justified with alteration of the membrane surface charge which is basically negative. Due to the decrease in pH and the formation of H\(^+\) ions with the DS concentration increase, H\(^+\) are attracted to the negative surface and alter its charge. This resulting in changing in surface overall charge to positive. This enhances the rejection of Na\(^+\) and negatively affect Cl\(^-\) ions that become attracted to the new positive charge formed on the membrane surface (Nasr & Sewilam, 2016 a).

On the other hand, investigating Urea behavior, unlike KNO\(_3\) and DAP, increasing Urea concentration increases the pH and subsequent OH\(^-\) which doesn’t alter the surface charge of the membrane resulting in decrease Na\(^+\) ions rejection and enhancement of Cl\(^-\) Rejection.

Figure 20 Forward Rejection of Feed Na+ and Cl- ions at Different DS types and Concentrations
4.2 Results of Scenario II: The hydroponics mixture and its individual components

4.2.1 Assessing Performance in terms of Water Flux
A typical hydroponics mixture was assessed and compared to its two macro components individually, which are Calcium Nitrate and Potassium Nitrate. From the figure below, it can be realized that the flux of the mixture is significantly higher than that of the individual components. The average flux of hydroponics mixture is 11.7 LMH compared to calcium nitrate which has the lowest value of 9.1476 LMH and potassium nitrate with flux rate of 10.03 LMH. The increase in both osmotic pressure and water flux in the hydroponics nutrient mixture can be due to the alteration in the ions species generated as a result of this blend. The higher the number of species formed, the higher the osmotic pressure with a subsequent increase in water flux (Phuntsho, Shon, Majeed, et al., 2012b)

![Water Flux of the Hydroponics Mix vs. its individual Macro Components](image)

4.2.2. Assessing Performance in terms of draw solute concentration in final product water
Draw Solutes Ions were analyzed for the selected hydroponics mixture in addition to its individual components in order to compare their dilution requirements. Giving the example of the maximum allowable N, P, K for crops, selecting potatoes as one of the crops with relatively high tolerance of nutrients concentration in soil, the concentrations are as follow:

<table>
<thead>
<tr>
<th>Nitrogen Concentration (g/l)</th>
<th>Potassium Concentration (g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.150</td>
<td>0.190</td>
</tr>
</tbody>
</table>

Table 13 Maximum Allowable N, K Intake Concentrations for Potatoes
From the tables below, it can be concluded that solutes ions concentrations were significantly decreased in case of the hydroponics mixture compared to its individual components. This resulted in lowering the dilution requirements to be ranging from 3 to 5 times instead of 20 times as in the case of scenario I. This drastic change in solutes behavior in case of being utilized as mixture can be attributed to change in species formation and in ions diffusivity, especially that this nutrients mixture had common nitrate ions that can alter the behavior of draw solute due to the common ion effect. The common ion effect can be defined as a phenomenon that takes place if a solution is added to another solution and both have the same ion. This addition results in decreasing solubility of this common ion with subsequent precipitation upon mixing (Li et al., 2017).

Table 14 Draw Solutes Concentration in the Final Water Product-Hydroponics

<table>
<thead>
<tr>
<th>Draw Solution</th>
<th>N Concentration (g/l)</th>
<th>K Concentration(g/l)</th>
<th>Dilution Factor Needed /Macro Nutrient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydroponic Mixture</td>
<td>0.8</td>
<td>0.62</td>
<td>5.3</td>
</tr>
<tr>
<td>Ca(NO$_3$)$_2$ 1.12M</td>
<td>3.1</td>
<td>------</td>
<td>20.6</td>
</tr>
<tr>
<td>KNO$_3$ 1.655M</td>
<td>3.4</td>
<td>2.43</td>
<td>22.6</td>
</tr>
</tbody>
</table>

4.2.3 Assessing Performance in terms of Forward Rejection of Feed Na$^+$ and Cl$^-$ ions for Hydroponics Mixture vs. its components

Feed Na$^+$ and Cl$^-$ ions rejection has been assessed for the hydroponics mixture compared to its individual macro-components. Rejection percentage results are summarized in figure 29 below. Calcium Nitrate showed higher rejection % compared to Potassium Nitrate that had rejection of 91% for Na$^+$ and 88% for Cl$^-$. The Hydroponics mixture exhibited the highest feed ions rejection compared to its individual components with 95% for Na$^+$ and 93% for Cl$^-$. Both observations are attributed to the increase in the driving force resulted from the increase in osmotic pressure difference which is matching with the fact that the hydroponics mixture has the highest osmotic potential followed by that of Calcium Nitrate then the component with the least osmotic potential which is the Potassium Nitrate. In addition, this phenomenon can be attributed to the membrane surface charge. pH of the three DSs are acidic, with formation of H$^+$ ions that are attracted to the negative charges on the membrane surface with subsequent alteration of these negative to positive charges that repel the Na$^+$ ions resulting in enhancement of its rejection, while attract the negative chloride ions Cl$^-$ and reduce their rejection.
Figure 29 Forward Rejection of FS Na+ and Cl- ions for Hydroponics Mix vs. its Components
Chapter V: Conclusion and Recommendations
Chapter 5: Conclusion and Recommendations

The first Scenario compared the performance of individual fertilizers representing the core macro-pollutants for crops nutrition N, P, K represented in commonly used fertilizers in Egypt, which are Urea, Di-Ammonium Phosphate and Potassium Nitrate respectively. DAP showed the highest water flux rate compared to the other two single fertilizers reaching 13.8 LMH, a feed ions rejection reaching 98% and acceptable concentrations of draw solute ions in the final product. On the other hand, Urea exhibited poor performance as a DS with a water flux as low as 2.2 LMH, low feed ions rejection equivalent to 78%, in addition to high DS solute in the final water product of 4.3 g/l, which agrees with (Phuntsho, Shon, Hong, et al., 2012) findings. Hence, Urea solely is not a recommended draw solute for this application. In the Second scenario, Macronutrients of Hydroponics standard recipe were tested compared to its individual macro components at the same concentrations. Water flux of hydroponics mixture reached 14.35 LMH compared to potassium nitrate, which had the lowest value of 9.1 LMH and calcium nitrate with flux equivalent to 12.15 LMH. Final concentrations of draw solute ions in the final product was also tested. Nutrients mixture results exhibited a significant improvement in terms of the needed dilution to meet the crops fertigation requirement compared to the individual recipe components. For example, for Nitrogen concentrations, dilution factor needed dropped from 22.6 to 5.3 when the hydroponics mixture was utilized.

Based on the conducted research and its conclusion, for single fertilizers, it is crucial to select a draw solute with high molecular weight and larger number of species formation due to their vital impact on the performance during the desalination process. On the other hand, fertilizer blending is recommended over the individual nutrients. Not Only due to the ability of the mixture to meet the plant nutritional requirements without the need of further addition of more fertilizers, but also due to the higher osmotic potential of the mixture and its ability to mitigate a major Forward Osmosis limitation, which is the need of product water dilution. However, it is advised to conduct a preliminary simulation to test the osmotic potential for each hydroponic recipe before testing to predict its adequacy as a draw solution and study its ingredients before blending to prevent salts precipitation due to the common ion effect. Regarding testing other hydroponics mixtures, creating nutrients recipes tailored to fit the
Egyptian crops nutritional requirements can be very useful as an adaptation measure for climate change to boost crops productivity without compromising energy sustainability nor freshwater consumption in addition to overcome the challenge of the increasing land aridness.

In summary, adapting forward osmosis desalination to produce diluted hydroponics nutrients mixtures for food production is a promising plan to tackle Water, Energy and Food challenges in Egypt. However, further research is needed to develop the FDFO technique in order to overcome its limitation regarding the after-treatment dilution requirements. Moreover, it is crucial to consider the interlinkage of the three WEF Nexus pillars while conducting further research in order to avoid tradeoffs that may occur if treated from water treatment perspective individually.
Chapter VI: Bibliography
Chapter 6: Bibliography


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