A NOVEL MULTI-FLOOR HEXAGONAL DESIGN FOR THE COMMERCIAL HYDROPONIC PRODUCTION OF THE LOOSE-LEAF LETTUCE OSCARDE (ASTERACEAE LACTUCA SATIVA L.)

A GRADUATION PROJECT REPORT SUBMITTED TO THE DEPARTMENT OF BIOENGINEERING
OF
NEAR EAST UNIVERSITY

By

AHMAD SABRI AMMAR

In Partial Fulfillment of the Requirements for
The Degree of Bachelor of Science
in
Bioengineering Department

NICOSIA, 2017

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DECLARATION

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name:

Signature:

Date:

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ABSTRACT

Tremendous amount of research has been conducted in the field of hydroponic systems. Recent research has given rise to new production techniques that are more efficient and self-sustainable than contemporary agricultural plant production practices which leave a negative footprint on the environment. Henceforth, hydroponic systems are emerging as a new technology that could potentially suffice the deficit in agricultural production and supersede conventional agriculture as the primary producer of vegetables. Hydroponic production is becoming an attractive frontier for investors and plethora of studies revealed the benefits of hydroponic systems. The major advantage of hydroponic systems is the tight control over plants' growth environment. That is, to reach the optimum production capacity, several parameters should be vigilantly controlled and monitored. In this report, the production of Lettuce Oscarde was divided into two stages, the germination and transplantation stages. The Germination of lettuce will incorporate the use of Nutrient Film Technique whereas the production of lettuce will incorporate the novel multi-floor hexagonal design. One Module involved in the production stage will resemble a hexagonal prism. The honeycomb-like structure of the stacked hexagonal prisms will conserve space and increase production. An overview of a production facility with the capacity to germinate as much as 223,200,000 seeds and produce as much as 168,407,424 plants was described.

Keywords: Agriculture; Hydroponics; Lettuce Oscarde; Nutrient Film Technique; Hexagonal Prism Modules; Germination Chamber; Production Chamber; Transplantation; Nutrient Solution

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LIST OF ABBREVIATIONS AND SYMBOLS

LED	Light Emitting Diode
FFT	Fog Feed Technique
RMT	Root Mist Technique
PVC	Poly Vinyl Chloride
NFT	Nutrient Film Technique
pH	Potential of Hydrogen
EC	Electrical Conductivity
ppm	Parts Per Million
UV	Ultra-Violet
PPF	Photosynthetic Photon Flux
PAR	Photosynthetically Active Radiation
EES	Energy Storage System
L	Liter
Kg	Kilograms
lb.	Pound Weight
ha	Hectares
KJ	Kilo-Joules
DO	Dissolved Oxygen
g	Grams
mol	Moles
s	Seconds

cm Centimeter

m Meter

m^2 Meter Squared

m^3 Meter Cubed

ft^2 Feet Squared

S Siemens

dS Deci-Siemens

µS Micro-Siemens

KW Kilo-Watts

MW Mega-Watts

KWh Kilo-Watts Hour

GWh Giga-Watts Hour

CO2 Carbon Dioxide

H+ Hydrogen

OH- Hydroxide

NH3 Ammonia

NH4+ Ammonium

KOH Potassium Hydroxide

H3PO4 Phosphoric Acid

NO3- Nitrate

SO2 Sulfur Di-Oxide

SO3 Sulfur Tri-Oxide

NO2 Nitrogen Di-Oxide

NH_4O_3	Nitric Oxide or Nitrogen Monoxide
$Ca(NO_3)_2 * 4H_2O$	Calcium Nitrate Tetrahydrate
KNO_3	Potassium Nitrate
KH_2PO_4	Monopotassium Phosphate
$MnSO_4 * 5H_2O$	Manganese Sulfate Monohydrate
$MgSO_4 * 7H_2O$	Magnesium Sulfate Heptahydrate
$CuSO_4 * 5H_2O$	Copper Sulfate Pentahydrate
H_3BO_3	Boric Acid
$Mo_7O_{24} * 4H_2O$	Hepta-Molybdate Tetrahydrate
$ZnSO_4 * 7H_2O$	Zinc Sulfate Heptahydrate
NaFe EDTA	Ferric Sodium Ethylenediaminetetraacetate

CHAPTER 1

GENERAL INTRODUCTION

Ecosystems compose an essential component in the wellbeing of living organisms. Ecosystems are identified whenever any kind of interactions between either living organisms amongst themselves, or between the nonliving component of the environment such as air, water, or soil, and group of living organisms (Tansley et al., 1934; Chapin et al., 2002). Either of these interactions between the biotic and abiotic components are underpinned by the sheer size of their networks which are linked via the different energy flow reactions and nutrients cycling processes (Chapin et al., 2002; Odum, 1971). These ecosystems are recognized as beneficial and sustainable provisioners of fresh water, food, feed, fiber, and biodiversity (Killebrew et al., 2010).

In addition, impartial governance and healthy ecosystems are requisites to the processes governing the provision of sufficient agricultural sustenance to feed the world's population. However, contemporary agricultural-economic models are resulting in massive inequities due to the marginalization of small producers and are aggravating the impacts on the environment due to the implementation of unsustainable agricultural policies (Mugundhan, 2011).

As such, emerging economies are suffering from chronic under-investment in their agricultural sectors affected by the biased belief that to provide good food, ecosystems have to be in good shape (Mugundhan, 2011). Eventually, emerging economies, which have been experiencing unprecedented improvement of the socio-economic conditions of their populations for the past few decades, are ought to cope with the increasing demand and rapid transition of their populations in adapting diversified healthier diets high in protein content, vitamins, and minerals, due to their increased income, enhanced purchase power and the proliferation of scientific literacy (Banerjee et al., 2013; Gracia-Mier et al., 2013).

In modern days, an increase in the demand and consumption of fruits and vegetables has been noticed by the scientific community, due to the extensive research reinforcing the inverse relationship between following a healthy and nutritious diet, and the risk of developing one of the many types of chronic diseases and neurological disorders (Murphy et al., 2011). The source of health benefits of fruits and vegetables can be attributed to the presence of bioactive compounds such as beta-carotene, polyphenols, anthocyanins, and many other antioxidants (Murphy et al., 2011).

However, while realizing that populations with stable life conditions are shifting toward healthy diets, the world is expected to experience an increase of 2 billion humans by the year 2050. A notable portion of this new population are going to inhabit cities and urban areas. Hence, this increase will result in the growth of food demand and require a 70% upsurge in agricultural productivity. This migratory movement from rural areas to cities will fuel the loss of cultivated land surrounding these cities due to an acceleration in expansion construction projects, that will provide essential services for its inhabitants (Touliatos et al., 2016).

A milestone in the development of human civilization was the development of plant domestication techniques and protection methods to counter the adverse effects of biotic and abiotic stress factors (FAO, 2013; Gracia-Mier et al., 2013). Therefore, conventional agriculture has been in use for thousands of years and it has been historically defined as the practice of growing crops in soil, in the open air, with irrigation, and the perpetual application of nutrients, pesticides, and herbicides (Barbosa et al., 2015). In Europe for instance, agriculture comprise the largest sector of land use (Walls, 2006).

Yet, the perfusion of intensive conventional and industrialized agricultural practices gave rise to profound repercussions on the environment. Furthermore, the spectrum of negative impacts on the environment encompass the harmful emissions to air and water, inefficient use of water, large land requirements, pollution due to extensive use of pesticides and high concentrations of nutrients, loss of biodiversity, and soil degradation accompanied by the soil's erosion (Barbosa et al., 2015; Walls, 2006). Subsequently, these negative effects leave perilous impact not only on the environment itself, but also on plants, animals, and humans. For instance, the exposure of farmers to soil satiated with fertilizers and pesticides could result in irreversible damage to their health. Also, these practices could result in chemical contamination of the plants which when degraded by bacteria, animals, or humans, can cause poisonings, induce cancerous mutations, and accelerate bacterial antibiotics' resistance (Killebrew et al., 2010).

Consequently, arable agricultural land is slowly evolving into a scarce resource due to land degradation, loss of soil fertility, land-use intensification, climate change, the increase in world population, and the migration of populations from rural to urban areas. Likewise, the demand on agricultural products is in continuous rise, yet enormous resources are already devoted to conventional agricultural techniques, particularly 38.6% of the ice-free land and 70% of withdrawn fresh water.

In the light of the aforementioned information, to sustainably feed the world’s growing population, countries are in dire need for new innovative methods for growing food which uses resources such as land, water, and energy efficiently (Killebrew et al., 2010; Touliatos et al., 2016).

Several vital environmental factors such as light, temperature, geography, cultivars, drought resistance, humidity, atmospheric Carbon Dioxide, and nutritional availability are correlated with the outlining of fruits’ and vegetables’ qualities (Murphy et al., 2011). Greenhouse technologies such as hydroponics allow for a greater control over plant growth conditions and growth media conditions (Murphy et al., 2011; Alatorre-Cobos et al., 2014). Therefore, when cultivation difficulties can be surmounted and the manipulation of phenotypic variation in bioactive compounds can be achieved, the quality of fruits and vegetables can be improved (Murphy et al., 2011; Mugundhan, 2011).

Hydroponics is one of the different soilless plant growing methods such as aquaponics, aeroponics, and fogponics, and describes the soilless cultivation methods of obtaining ornamental and edible plants grown in a liquid nutrient solution (Mugundhan, 2011; Treftz et al., 2015). This implies that either container nurseries or greenhouses can be utilized to grow a wide range of vegetation. Correspondingly, gravel, vermiculite, perlite, and Rockwool are all examples of solid substrates, they are also called growing media, that can be used in lieu of soil (Hershey, 1994). Then, plants are going to be nurtured on the growing medium which act as an inert material to support the plants while the nutrient solution flows down the tubes passing around the roots (Wahome et al., 2011).

Moreover, this method has been gaining attention worldwide from both public and private sectors due to its sustainability and beneficial impacts on the environment (Treftz et al., 2015; Treftz and Omaye, 2015). The applications of hydroponics are versatile and can generate food in various environments ranging from small installments in backyards to highly sophisticated commercial or scientific enterprise the Arctic regions, roof tops, deserts, and space stations (Murphy et al., 2011; Mugundhan, 2011). Nevertheless, climatic conditions and the status of the socio-economic environment are two determinants of the degree of sophistication and technology used in hydroponic systems (FAO, 2013).

Although it is a common practice nowadays to grow the numerous commercial and specialty crops hydroponically, some species will grow better than others (Murphy et al., 2011; Wahome et al., 2011). For instance, hydroponics can be ideal for the cultivation of leafy vegetables such as lettuce and herbs, fruit vegetables like tomato and cucumber, and some ornamental plants (Murphy et al., 2011; Wahome et al., 2011).

Hydroponic agriculture exhibits a plethora of benefits over conventional agricultural methods leaving less negative and severe impacts on the environment (Murphy et al., 2011). An important factor in obtaining higher experimental reproducibility and consistent yield is the standardization of growth conditions such as lightning, humidity, temperature, nutrient media composition (Alatorre-Cobos et al., 2014). Eventually, this allows for the invention of hydroponics systems with greater control over the environment supporting perpetual all-year round production (Murphy et al., 2011). Subsequently, the need for low labor force, higher yields, efficient water use, selective monitoring of the distribution and delivery of nutrient solution, independence of soil quality, minimal use of pesticides, and growing food closer to customers are among the few advantages of hydroponic systems (Dinpanah and Zand, 2013; Murphy et al., 2011; Treftz and Omaye, 2015). Finally, compared to conventional agriculture, researchers have indicated that hydroponically grown fruits and vegetables have high nutritional value and possess more desirable sensory attributes (Treftz and Omaye, 2015).

CHAPTER 2

INDUSTRIAL AGRICULTURE

2.1. Overview of Industrial Agriculture

The main goals of industrialized agriculture are to increase the efficiency and decrease the costs of producing food (Ferre, 2008). The increase in global population dictated that an increase in global food production is imperative for the continuation of contemporary lifestyle of modern citizens (Gracia-Mier et al., 2013). Henceforth, this challenge induced a huge agricultural transformation to change the way food is produced, stored, processed, distributed, and accessed (Gracia-Mier et al., 2013; Godfray et al., 2010). Such developments resulted in an unprecedented agricultural production boom in the 18th and 19th centuries with the advent of the Industrial Revolution (Godfray et al., 2010). An agricultural revolution has been documented in Europe and North America from the beginning of the 20th century onwards due to scientific progress in inventing new agricultural technologies (Ferre, 2008; Godfray et al., 2010).

Advances in farming machinery, artificial fertilizers, pesticides, herbicides, irrigation systems, and genetically modified crops have aided companies and individual to increase their yields. Between the years 1971 and 2005, these technologies have achieved an outstanding 61% increase in food production (Ferre, 2008).

Global world population is in constant increase and in continuous migration toward urban cities. Therefore, by 2050, 60% more food will be required to sustain the 6 Billion inhabitants of urban mega-cities. This explosion of citizen urban agglomerates can result in disastrous consequences if global agricultural production didn’t increase (Banerjee et al., 2013).

2.2. Disadvantages of Some Cultivation Techniques

Although industrialized agriculture has been noticeably increasing the global production of food for the past 100 years, there is a plethora of scientific evidence implicating modern industrial techniques in leaving a negative footprint on the environment’s ecological diversity, animals’ health, and humans’ wellbeing (Ferre, 2008; Gracia-Mier et al., 2013).

With regards to the diversity of ecological environments, to cope with the increased demand on agricultural products, more land in Europe had to be devoted for cultivation. Hence, agricultural land in modern Europe spans 10 times more land than that of urban areas and cover as much as twice as forestry areas. Also, trends in Europe to adopt more industrialized agriculture by the incorporation of rural landscapes into the intensive massive cultivation operations has proved to negatively impact the environment (Walls, 2006). Harmful intensive cropping trends including monoculture, continuous cropping, conventional tillage, and intensive hillside cultivation, and industrial crops processing have been employed on large scales worldwide, but particularly in developing countries (Killebrew et al., 2010).

2.2.1. Monoculture

Monoculture technique is defined as the process of cultivating a single crop species possessing similar growing and maintenance requirements in the same field (see figure 2.1.). Although this technique allows farmers to increase their annual crop yields, when farmers selectively choose which crops' species will be raised they are controlling the biodiversity of their field. Henceforth, the decrease in biodiversity render fields grown with monoculture technique susceptible to widespread outbreaks of insect infestation, diseases, and plant viruses (Killebrew et al., 2010; Gracia-Mier et al., 2013). The use of monoculture is also correlated with the decrease in the populations of farmland birds (Walls, 2006).

Figure 2. 1: Four harvesters working in conjunction in Brazil while cultivating one crop type from the field. From "BAF supports investment in Latin America Agriculture," (World Finance, World Finance, 15 Jan. 2014; Web; 1 Dec. 2016).

2.2.2. Continuous Cropping

Continuous cropping is the practice of increasing yields by adjusting the timing of growing plants. This allows farmers to grow two or three times on the same field. The resulting effect is the decline in soil fertility due to nutrient mining. For example, to make up for nutrient deficiency, farmers tend to increase their use of fertilizers (Killebrew et al., 2010).

2.2.3. Conventional Tillage

A common practice is to plow the soil promoting the loosening of soil structure, drainage, aeration, and turning under crop residues (see figure 2.2.). However, this practice reduces soil organic matter leading to increased erosion and contributing to CO2 emissions (Killebrew et al., 2010).

Figure 2. 2: A field that is being tilled by using a chisel plow. From "CONSIDERING CARBON NEUTRAL: TILLAGE OPTIONS," by Troy (America's Farmers, America's Farmers, n.d.; Web; 1 Dec. 2016).

2.2.4. Intensive Hillside Cultivation

Since arable land is finite, farmers in some areas around the world are increasingly cultivating hillsides to cope with the increase demand (see figure 2.3.). However, hillsides are lands sensitives to erratic soil composition. Slopes steeper than ten to 30 percent may not provide proper soil and water maintenance. For instance, rainfall can result in the erosion of soil when it carries away nutrients down the hillside slope.

Eventually, redistributing the nutrients and rendering upward sloping soils less fertile than lower ones (Killebrew et al., 2010).

Figure 2. 3: Cultivating Rice on hillsides on the Island of Bali in Indonesia. From "Rice Dreams: Southeast Asia's Stunning Terraces," by John Oates (ASEAN Tourism, ASEAN Tourism, 16 Feb. 2010; Web; 1 Dec. 2016).

2.3. Effects of Industrial Agricultural Practices

2.3.1. Decline in Soil Fertility

Frequent degradation of soils coupled with the numerous irreversible losses of soils are due to unsustainable agricultural practices. Soil sealing, superfluous use of pesticides and fertilizers, acidification, salinization, compaction loss of mineral nutrients, and loss organic carbon are all factors that hampers the productivity of plants (Walls, 2006).

2.3.2. Increased Greenhouse Gases Emissions

Certain scientists claim that man-made greenhouse emissions due to industrial agriculture comprise 14% of the global emissions. Land conversion from forestry into arable areas contribute to a further 18% of the global emissions (Godfray et al., 2010). Furthermore, agricultural practices are responsible for 8% of the overall global greenhouse gases emissions (see figure 2.4.). Interestingly, in the US, agricultural practices used in cultivation is responsible for 48.5% of the total greenhouse gas emissions (see figure 2.5.).

A huge portion of emitted greenhouse gases is caused by the decomposition of organic matter in the soil. Particularly, soil and organic matter are responsible for 13.1 % of the total greenhouse gases emissions in the agricultural sector in the US (see figure 2.5.). This occurs when the soil is degraded releasing trapped CO_2 into the atmosphere (Walls, 2006).

Practices such as the usage of nitrogen-rich fertilizers and liming of arable land, are other minor sources for greenhouse emissions (Walls, 2006). Both, synthetic and organic fertilizers contribute to 35.4% of overall greenhouse emissions in the agricultural sector in the US (see figure 2.5.).

Besides, many industrial crops processing technologies contribute to CO2 because they require the intensive usage of fossil fuel dependent machinery (Killebrew et al., 2010; Walls, 2006). Greenhouse gases result in the deterioration of air quality, ozone layer depletion, and acid rain (Killebrew et al., 2010).

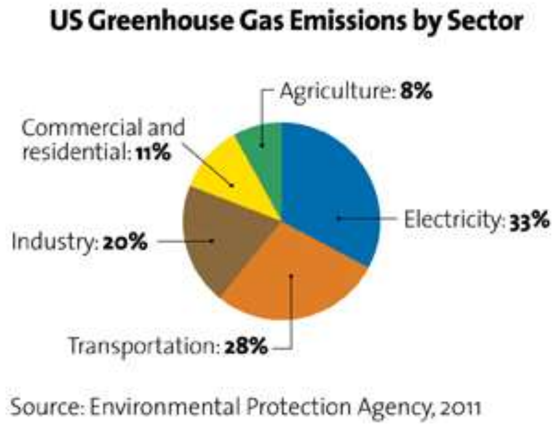

Figure 2. 5: Greenhouse gas emissions by sector in the US. Agriculture contribute to 8% of total greenhouse gas emissions. From "One Weird Trick to Fix Farms Forever," by Tom Philpott (Mother Jones, Mother Jones, 9 Sep. 2013; Web; 1 Dec. 2016).

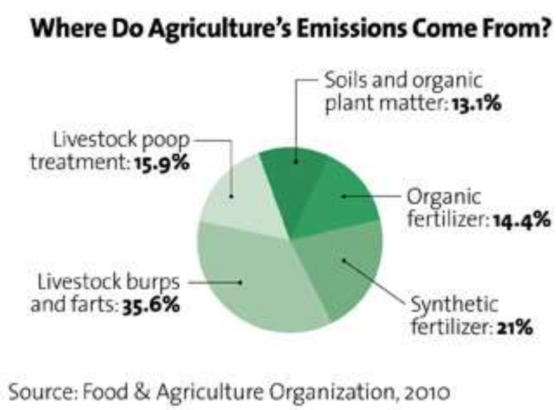

Figure 2. 4: The major contributors to greenhouse gas emissions in the agricultural sector in the US. Practices used in cultivation is responsible for 48.5% of the total greenhouse gas emissions. From "One Weird Trick to Fix Farms Forever," by Tom Philpott (Mother Jo *Jones*, Mother Jones, 9 Sep. 2013; Web; 1 Dec. 2016).

2.3.3. Loss of Biodiversity

Industrialized food production which encompasses agricultural products result in the loss of biodiversity. This occurs through the land conversion of rainforests and grasslands into agricultural landscapes which begets the disruption of land-based ecosystems (Ferre, 2008).

Moreover, with the introduction of genetic engineering, the maintenance of genetic diversity in agricultural field has been lost. Maize, wheat, and rice have been developed to be based on few elite varieties that are responsive to new environmental conditions. Thus, the replacement of locally grown seed varieties with genetically modified ones doesn't only infer the loss of useful alleles found in local varieties, but also laden breeding programs (Killebrew et al., 2010; Ferre, 2008).

Also, the scientific community has serious concerns pertinent to the hitherto unknown consequences of genetic modification on the environment due to the lack of sufficient research in that field. Particularly, the exchange of genetic material between wild plant varieties and transgenic crops (Killebrew et al., 2010).

2.3.4. Deterioration of Human Health

Numerous studies documenting the safety risks and health diseases associated with the use pesticides on both farmers and consumers have been published. Consumers can be susceptible to dangerous health problems which include reduced sperm count and male sterility, birth defects, precocious puberty, acute and chronic neurotoxicity, immunological abnormalities, and reproductive disorders (Ferre, 2008; Gracia-Mier et al., 2013). Likewise, significant number of farmers mostly in developed countries are continually exposed to pesticides resulting in severe poisonings (Ferre, 2008).

2.4. Limitations and Drawbacks

2.4.1. Finite Arable Land

Arable land is limited to 11% of total land area. Statistically, by 2040, an increase of only 2% in agricultural land can be achieved (Banerjee et al., 2013). Due to the scarcity of arable land, demand for food has been met by the increase of crop production per unit area. This was performed by the application of intensive agricultural techniques that uses synthetic chemical fertilizers (Gracia-Mier et al., 2013).

2.4.2. Scarcity of Water

In addition, water is a scarce resource and modern industrial agriculture is considered to be the single largest consumer of fresh water demanding 70% of the total global supply (Banerjee et al., 2013; Christie, 2010). Subsequently, the preservation and conservation of freshwater along with the development of new cheaper technologies to desalinate sea water are ought to be the primary concern in sustainable agricultural planning (Christie, 2010).

2.4.3. Use of Pesticides

Large quantities of yields are lost to the wide spreading of plant pathogens, pests, and weeds (Gracia-Mier et al., 2013). In addition, through the practice of excessive pesticide usage, industrial agriculture promotes the emergence of infectious diseases and bacterial pathogens that are antibiotic resistant (Ferre, 2008). Another disadvantage of using pesticides is their persistence in the ecosystems. Residues of insecticides such as DDT were detected in the United States even after 20 years of their ban (Killebrew et al., 2010).

2.4.4. Use of Fertilizers

The intensive use of fertilizers is increasing all over the world to meet the colossal demand of soils in cropping agriculture for a continuous nutrient supply (Gracia-Mier et al., 2013; Christie, 2010). Albeit fertilizers rich in synthetic micronutrients maximized yields per unit area, over the past half-century, they adversely affected the qualities of soil, air, and water (Killebrew et al., 2010; Gracia-Mier et al., 2013). Nitrate leaching and ammonium based fertilizers contribute to the decline in soil fertility due to the acidification of soil (Killebrew et al., 2010).

Moreover, as much as 44% of irrigation water is lost as a result of the inefficient use of irrigation systems. Agricultural runoff carries excessive quantities of phosphorous and nitrogen resulting in the eutrophication of water bodies (Christie, 2010). Henceforth, contaminating them by reducing oxygen levels and destabilizing marine ecological systems (Killebrew et al., 2010; Christie, 2010).

2.4.5. Mismanagement of Irrigation Systems

A major drawback of industrial agriculture is the inadequate supervision of irrigation systems occasionally leading to over-irrigation. Therefore, causing salinization of the soil and waterlogging which make water absorption form the soil a difficult task for the plants. Salinization not only increase the concentration of solid substrates in the soil but also prevents roots from obtaining enough oxygen (Killebrew et al., 2010).

CHAPTER 3

HYDROPONIC AGRICULTURE

3.1. Overview of Hydroponic Agriculture

Several factors including the consistent increase in global food demand by urban populations, the need to limit greenhouse emissions, minimize soil degradation, and conserve fresh water sources, and protect biodiversity has dictated the start of a gradual process to diversify and divert away from modern industrial cultivation methods (Banerjee et al., 2013; Gracia-Mier et al., 2013). Likewise, developed technologies are ought to have neutral or positive impact on the environment (Banerjee et al., 2013). Henceforth, food production systems including those employed in agriculture must become fully sustainable by using renewable inputs. This also implies that they should use resources at rates that do not exceed earth's capacity to replenish them (Godfray et al., 2010).

In the past few years, hydroponic agriculture has been gaining more momentum in modern agricultural industry due to its beneficial impacts on the environment (Lee and Lee, 2015). It is simply defined as a soilless plant growing and cultivation technology (Lee and Lee, 2015; Ronay and Dumitru, 215).

The term Hydroponics was first coined by Dr. W.F. Gericke in 1963 and the word can be dissected into two fragments with the first being 'hydro' which means water and the second being 'ponos' which means labor (Mugundhan, 2011). However, one of the early attempts to grow plants in water culture (spring water, rain water, Thames River water, and Hyde Park conduit water) was first recorded by the English Physician John Woodward in the year 1699. This was an effort by John to test Helmont's theory that plant matter is formed entirely from water (Hershey, 1994).

Primitive forms of hydroponics can also be traced back to the hanging gardens of Babylon and the floating gardening rafts of the Aztecs as well as the Chinese's (Mugundhan, 2011; Abdullah, 2016). Furthermore, the first attempt to produce vegetation on an industrial scale was during the Second World War when the US army hydroponically grew lettuce and tomato for troops stationed on the infertile islands of the Pacific (Wahome et al., 2011). Hydroponic plant systems have been in used not only in education, personal gardening, and research but also in commercial farming (Lee and Lee, 2015; Wahome et al., 2011).

Tomato and pepper were among the first plants to be hydroponically cultivated for commercial use (Wahome et al., 2011).

3.2. Growing Techniques

With new advances in technology, material science, and equipment manufacturing, a variety of systems using different operating mechanisms have been developed. One advantage of hydroponics is that it is easily customizable. Hence, experts have been developing different systems which selectively provide optimum growth conditions for particular plants (Lee and Lee, 2015).

The gravel flow sub-irrigation system, ebb and flow system, drip irrigation system, nutrient film technique, aeroponic system, deep flow system, aerated flow system, wick hydroponic system, grow bag technique, rock wool technique, aquaponics, and vertical farming technique are among the newly developed technologies in the science of hydroponics (Mugundhan, 2011; Lee and Lee, 2015).

Although there is ample of research literature documenting the advantages of all the aforementioned techniques, hydroponic systems which employs nutrient enriched media are among the simplest to develop, use, and commercialize (Abdullah, 2016).

When researchers select a hydroponic technique that will be used in the cultivation of a specific plant species, they consider a variety of factors. The decision of researchers is bounded by factors related to the availability of space and resources, productivity's expectations, availability of an adequate growth medium, produce quality expectations, and what are the desirable sensory attributes (Sardare and Admane, 2013).

Generally, hydroponic systems fall into two categories (Lee and Lee, 2015). The first category involves Closed System Techniques. In these systems, nutrient solution and supporting media are recycled or reused for an unspecified length of time (Christie, 2010; Lee and Lee, 2015). Subsequently, demanding up to 20 to 40% less water and nutrients, reducing water run-off and waste. Yet, disadvantage of Closed System Techniques extends from their demand for continuous monitoring to maintain the continuous supply of fresh water and constant concentration levels of nutrients to the intricate infrastructure of reservoirs and pumping systems (Christie, 2010).

The second category involves Open System Techniques or the run-to-waste systems (Christie, 2010; Lee and Lee, 2015). In these systems, neither nutrient solution nor supporting media are recycled or reused (Lee and Lee, 2015). Subsequently, eliminating the need for routine maintenance of nutrient solutions and reducing the dangers of an infectious outbreak. However, one major drawback of Open System Techniques is that they consume large quantities of nutrients and water (Christie, 2010).

3.2.1. Vertical Farming Systems

Vertical Farming is a farming technique that produces plants on commercial scales by placing different or same plant species in growing shelves on top of each other in stacked growth rooms. By stacking plants in the vertical dimension, this technology uses land efficiently and offer an opportunity to cultivate plants in high-rise buildings (see figure 3.1.) (Touliatos et al., 2016). Increased productivity and higher yields per unit area can be achieved in vertical farming systems compared to conventional ground based horizontally-oriented systems (Touliatos et al., 2016).

Figure 3. 1: A multi-level aeroponic growth system is an application of vertical farming. Extending the production of hydroponic plants vertically can considerably increase the yields. From "Vertical Farms Lets Growers Apply the Right Amounts of Automation, IoT," by Jim Nash (*robotics business review,* robotics business review, 7 Jul. 2016; Web; 1 Dec. 2016).

3.2.2. Wick Hydroponic System

One of the simplest hydroponic setups is the wick hydroponic system (Mugundhan, 2011). It is a passive and self-feeding system in that it lacks any moving parts (Mugundhan, 2011; Lee and Lee, 2015). In this module, nutrient enriched water solution is supplied slowly from a reservoir with a wick or any fibrous material into the growing medium (Mugundhan, 2011; Abdullah, 2016). The wick or fibrous material uses capillary action to absorb and transport water to the root area (see figure 3.2.) (Lee and Lee, 2015).

Two critical downsides of the wick hydroponic system are manifested with the slow supply of nutrient solution and the limited application of the setup to small-scale and personal gardening activities (Mugundhan, 2011; Lee and Lee, 2015).

These limitations arise from the need of commercially grown plants to large quantities of water which the wick hydroponic system cannot provide (Lee and Lee, 2015).

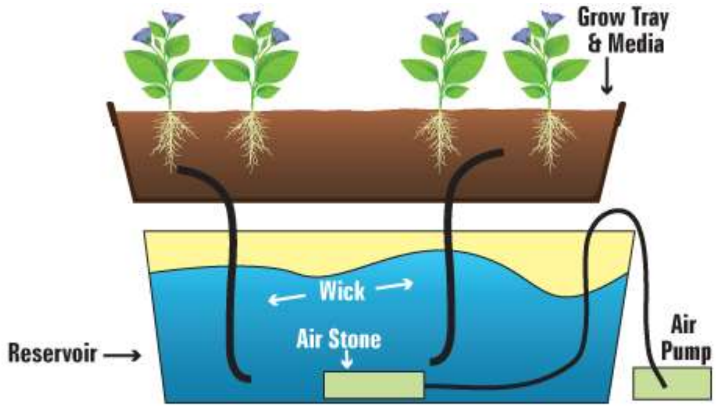

Figure 3. 2: The Wick Hydroponic System. From "Why Hydroponics…," (Hummert International, Hummert International, Oct. 2013; Web; 1 Dec. 2016).

3.2.3. Nutrient Film Technique

Developed in 1966 by Allen Cooper and his colleagues, it was considered the most revolutionary stride in hydroponic technology since the 1930s (Christie, 2010). Moreover, it is the most widely used hydroponic growing technique (Christie, 2010). This system consists of a slightly sloping channel with shallow depth where plants' roots are left dangling in the nutrient solution while plants are suspended above in plastic trays (Mugundhan, 2011; Christie, 2010; Abdullah, 2016). At first, the nutrient solution is introduced from a reservoir circulating throughout the system. Excess nutrient solution is collected and reused (see figure 3.3.) (Lee and Lee, 2015). It is important to note that since growth won't be affected by the availability of growing media, growers can decide to either not use a growing media support or use a Rockwool growing cube (Mugundhan, 2011; Abdullah, 2016).

An advantage of this technique is the maintenance of a constant continuous flow of nutrients throughout the system without the need for a timer (Mugundhan, 2011; Abdullah, 2016). Also, oxygen enrichment of nutrient solution can be controlled by regulating the flow of water and depth of the sloping channels (Lee and Lee, 2015). Moreover, nutrient film technique utilizes a less complex watering system which passively circulates water (Christie, 2010). Due to the smallness of the physical parameter of nutrient film technique, space is efficiently exploited allowing for growers to stack this technique in vertical configurations (Abdullah, 2016).

Nonetheless, the initially high capital costs, the need for skilled employees with deep knowledge of the system, and the increased risk of contracting diseases and fungal infections are major disadvantages for using nutrient film technique (Christie, 2010; Chapin et al., 2002). Moreover, several complications such as oxygen depletion of circulating nutrient solutions by earlier plants earlier in the system and the slow flow rates resulting from excessive root growth in the channels can be eliminated with more research and suitable system management and design (Christie, 2010).

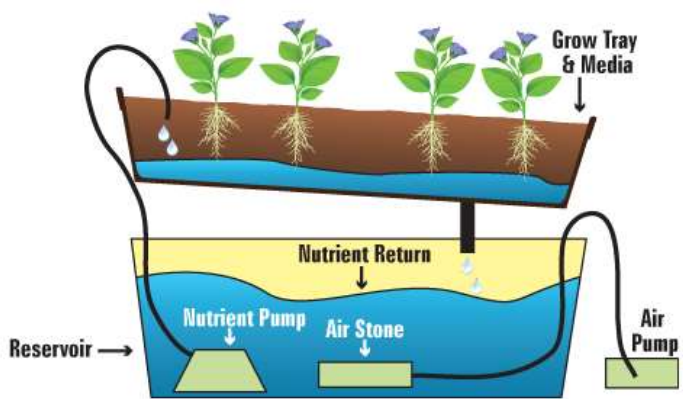

Figure 3. 4: The Nutrient Film Technique Hydroponic System. From "Why Hydroponics…," (Hummert International, Hummert International, Oct. 2013; Web; 1 Dec. 2016).

3.2.4. Ebb and Flow Hydroponic System

The Ebb and Flow system was amongst the first commercially available innovative and complicated hydroponic systems. It is sometimes called as the Flood and Drain system because it uses a flood and drain watering mechanism that systematically and intermittently flood the growth trays. The system operates by pumping nutrient enriched water from the reservoir into the growth trays, accumulating there for a predetermined period of time. At regular intervals, the growth trays are flooded which results in draining back the water solution into the reservoir via a tubing system (Mugundhan, 2011).

On one hand, the ease of handling individual plants grown in separate containers and the availability of a wide collection of media that can be used around root area are two primary strengths of this hydroponic system (Mugundhan, 2011).

On the other hand, the need for extensive monitoring of available water in the system is a major disadvantage of this system. Moreover, the increased risk of plants contracting root diseases and the growth of algae and molds require the usage of sterilization and filtration steps which can elevate operational costs (Lee and Lee, 2015).

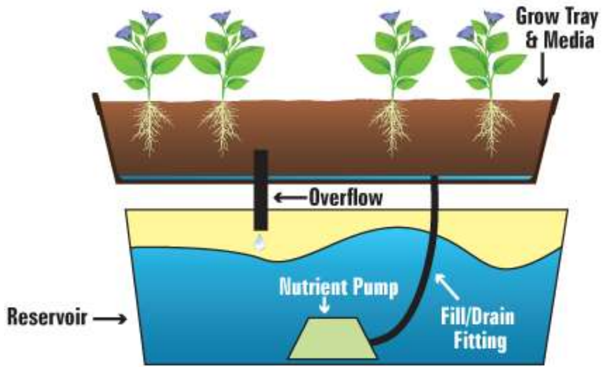

Figure 3. 5: The Ebb and Flow Hydroponic System. From "Why Hydroponics…," (Hummert International, Hummert International, Oct. 2013; Web; 1 Dec. 2016).

3.2.5. Drip Irrigation Hydroponic System

It is a popular commercial growing system that has been in common use by growers lately (Mugundhan, 2011). The system operates by pumping nutrient solution from a reservoir into the base of each growth tray with the aid of drippers at constant intervals of time (see figure 3.5.) (Mugundhan, 2011; Lee and Lee, 2015).

Drip irrigation systems can either employ the recovery or non-recovery systems (Mugundhan, 2011; Lee and Lee, 2015). In the recovery drip system, nutrient solution is collected, drained back into the reservoir, and recirculated (Lee and Lee, 2015). Although this is an economical mechanism that circulates nutrient solutions efficiently and cut down costs, the system is at risk of failure due to erratic fluctuations in pH values and growth of algae and mold in the tubing system (Lee and Lee, 2015).

However, in the non-recovery drip system nutrient solution is wasted as run-off. Perpetually introducing new nutrient solution into the non-recovery drip system infers that pH balance is maintained at tolerable levels by the plants and that less maintenance is demanded to maintain sufficient nutrient concentrations (Mugundhan, 2011). Yet, the need for frequent monitoring of the supply of water enriched nutrient solution to the roots and the susceptibility to power outages demonstrate two key weaknesses of the non-recovery drip system (Lee and Lee, 2015).

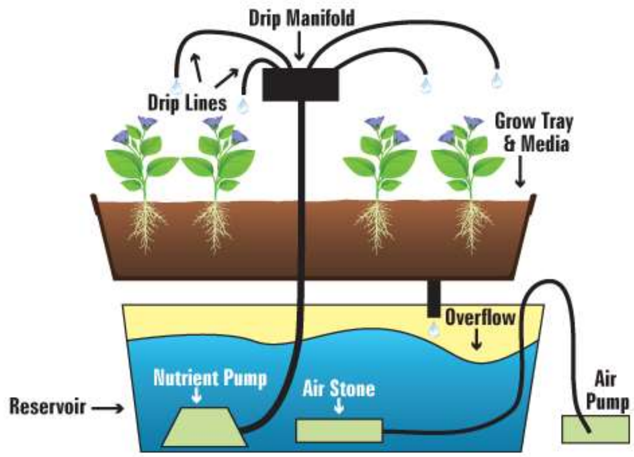

Figure 3. 6: The Drip Irrigation Hydroponic System. From "Why Hydroponics…," (Hummert International, Hummert International, Oct. 2013; Web; 1 Dec. 2016).

3.2.6. Aeroponic Hydroponic System

Invented in the 1980s, aeroponic systems is a novel and advanced form of hydroponic growth systems that offer growers and farmers more control over growth conditions. Two contemporary aeroponic technologies are the Root Mist Technique (RMT) and Fog Feed Technique (FFT). The system consists of plants supported in pots while their roots are suspended in the air. Aeroponics operates by spraying nutrient solution in the form of mist using micro-inject nozzle high pressure sprayers on the suspended roots of the plants. Moreover, the system is connected to an electronic timer that controls the frequent delivery of nutrient solution to the roots. The employment of an electronic timer presents an opportunity to customize the misting cycles to particular plants providing another level of control over plant growth (see figure 3.6.) (Mugundhan, 2011; Lee and Lee, 2015)

On one hand, the primary advantages of aeroponics are outlined in the absence of the growing medium, the ability to provide tighter control over the root zone environment, and the supplement of highly oxygenated nutrient solution to plants (Mugundhan, 2011; Lee and Lee, 2015)

On the other hand, the dependence of the system on electronically controlled equipment resemble a challenge for maintaining the continuum of ordinary operation of the system. System disruptions in the functions of the pumps or electronic timers will cause roots to dry out leading to plant death (Mugundhan, 2011). Additional disadvantages of the aeroponic systems is found in their susceptibility to outside temperatures, expensive installation and maintenance costs, and the need for continuous cleaning to prevent disease outbreaks and clogging of spray heads (Lee and Lee, 2015).

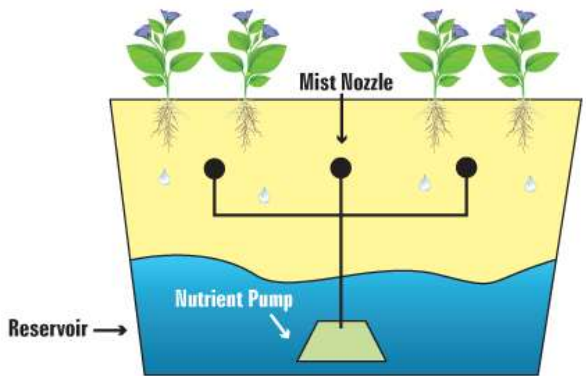

Figure 3. 7: The Aeroponic Hydroponic System. From "Why Hydroponics…," (Hummert International, Hummert International, Oct. 2013; Web; 1 Dec. 2016).

3.2.7. Aquaponics

It is an old technology that has been recently emerging as a sustainable agricultural technology due to increased interest in local sustainable agricultural initiatives. Aquaponic systems integrate two of the most established production technologies, aquaculture, which is the process of growing plants and fish in unison, and hydroponics, which is the soilless technique of growing plants. The integration of aquaculture and hydroponics enhances the grower's ability to control the environment of plant growth (see figure 3.7.) (Okemwa, 2015). In aquaponic systems, fish produce waste products such as ammonia. Next, nitrifying bacteria converts the waste products (mainly ammonia) into nitrates providing organic nutrients necessary for the normal growth of plants. Then, plants uptake these nutrients from the circulating nutrient solution and use them as their main nutrient supply. Subsequently, the uptake of nitric products from the nutrient solution filters the water resulting in a decrease the concentrations of ammonia. Thus, eliminating the risk of fish death due to the presence of toxic levels of nitrates in the water. Therefore, plants, bacteria, and fish work symbiotically to create a balanced environment that promotes their survival and growth (Okemwa, 2015).

Scientists and researchers are attracted to the possibilities of utilizing aquaponics technology in fields encompassing the remediation of nutrient waste produced by intensive aquaculture production and growing plants and fish in areas where water and soil deficiency are constant hindrances for farmers (Okemwa, 2015).

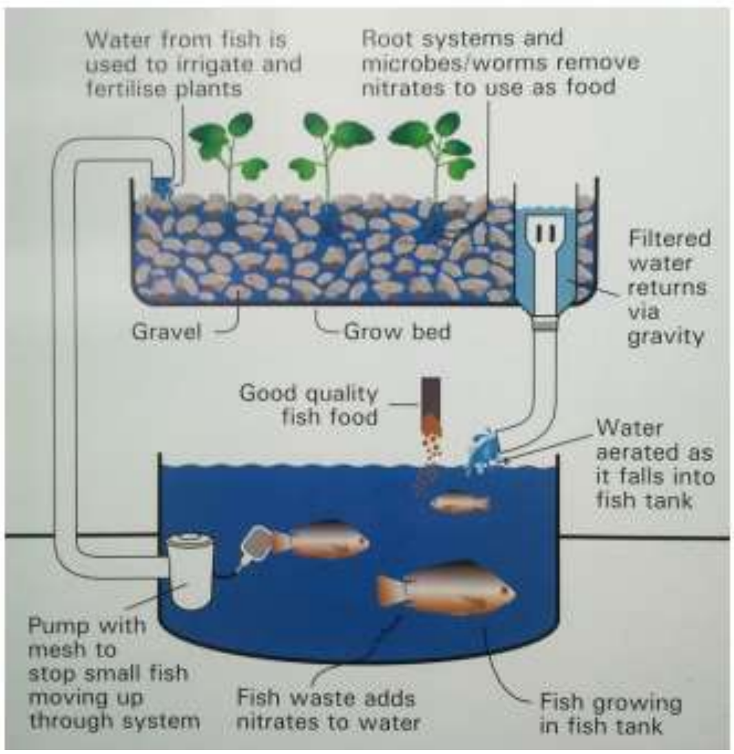

Figure 3. 8: The Aquaponic Hydroponic System. From "EFECTIVENESS OF AQUAPONIC AND HYDROPONIC GARDENING TO TRADITIONALGARDENING," by Okemwa Ezekiel (International Journal of Scientific Research *and Innovative Technology*, International Journal of Scientific Research and Innovative Technology, 12 Dec. 2015; Web; 1 Dec. 2016).

3.2.8. The Deep-Water Culture System

In this hydroponic system, plants are constantly suspended on floating platforms placed above a reservoir. The system was designed to offer the roots of plants maximum exposure to nutrient solution. Moreover, an airstone and an air pump perpetually aerate the nutrient solution sustaining a constant supply of oxygenated water (See Figure 3.8.). Finally, monitoring nutrient concentrations, oxygen levels, salinity, and pH are among the growers' foremost concerns for maintenance of normal operations of this system. One major weakness of using this system, is the possibility of rapid contamination of the reservoir with algae and mold growth which can affect the balance of nutrient concentrations and oxygen levels (Lee and Lee, 2015).

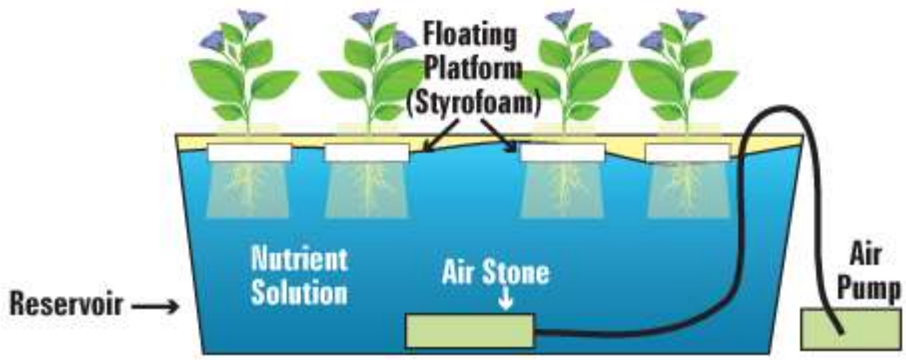

Figure 3. 9: The Dep-Water Culture Hydroponic System. From "Why Hydroponics…," (Hummert International, Hummert International, Oct. 2013; Web; 1 Dec. 2016).

3.3. Benefits of Hydroponic Agriculture

3.3.1. Reduction in Costs

Hydroponic systems can be installed in a variety of locations such as skyscrapers, full-fledged hydroponic growing buildings in residential areas, and on rooftops allowing for the reduction in production footprint and the cultivation of plants in urban areas. Hydroponics can be considered an urban form of local agriculture that contribute to the local economy and promotes a sustainable model for food security (Banerjee et al., 2013). Therefore, unlike he standard rural farming model, produce can be distributed and sold directly to the consumers within the city, decreasing transportation costs (Banerjee et al., 2013; Fahey, 2012).

For example, Lufa Farms which was founded in 2011, is a Canadian rooftop hydroponics startup and has installed a 31,000 ft^2 hydroponic setup in the Canadian city of Montreal. With this venture, Lufa Farms was the first company to install a commercial rooftop hydroponic greenhouse in the world. Lufa Farm's business model is based on customers signing a 12-week contract which allows them to receive fresh produce weekly. By following this business model which decreases the costs of the produce, Lufa Farm has not only broken even in its first year but they also secured funding to install two more greenhouses in the near future (Fahey, 2012).

3.3.2. Healthy and Fresh Produce

Hydroponic system such as commercial rooftop greenhouses play a vital role in attaining food security, providing an easy access to healthy food within the limits of urban cities, and providing high quality food (Fahey, 2012; Abdullah, 2016). Since harvest from rural areas might require several days to reach the consumers, it shrinks in size and loses essential vitamins and flavor. These factors contributing to the reduction in the quality of harvest can be avoided in hydroponic systems since transport distance of produce is shortened (Fahey, 2012).

Moreover, since hydroponics is based on soilless farming, plants absorbing nutrients directly from water are physically cleaner and ultimately healthier since their growth is going to be uniform with no stressing on plants to search for nutrients or competition between them to obtain nutrients (Abdullah, 2016). Additionally, several research efforts have documented that hydroponically cultivated plants possess high quality sensory attributes and high nutritional value compared conventionally cultivated plants (Treftz and Omaye, 2015).

3.3.3. Independence of Soil

Unlike conventional agriculture where plants' nourishment relies heavily either on presence of nitrogen fixing bacteria such as diazotrophs or nitrogen-supplemented fertilizers, soilless farming permits the plants to exert less effort in order to acquire the necessary nutrients. Thus, supplying plants directly with nutrients is a significant advancement in agriculture and can aid farmers in countries where nutrient enrichment of the soil is a long-standing difficulty (Abdullah, 2016).

3.3.4. Nutrient Availability and Recycling

Hydroponic agriculture offers a sustainable and efficient model for the regulation of nutrients (Sardare and Admane, 2013). Nutrients are dissolved in liquid water and fed directly into the roots. Thus, high levels of nutrient utilization can be achieved with the recycling of nutrient solution in closed hydroponic system (Abdullah, 2016). Nutrient solutions are rich in micro- and macro-nutrients, and since plants won't have to work hard to absorb them from the soil along with absence of competition between plants for obtaining nutritional elements and water, they can grow at faster rates with smaller roots and close to each other (Abdullah, 2016; 20; Sardare and Admane, 2013). Nutrient supply is closely monitored by experts who selectively choose among the distinct nutrient solutions, the optimum nutrient solution composition related to the biological need of the chosen plant species (Dinpanah and Zand, 2013; Abdullah, 2016). Correspondingly, the supply of nutrient solution correlates with the rate of growth of the plants and is supervised by experts from the day they were placed into the system to the time of harvest (Abdullah, 2016).

3.3.5. Water Conservation

Although hydroponic systems require large quantities of water to operate normally, they have the potential to decrease the overall water consumption (Almeer et al., 2015; Abdullah, 2016). These systems perpetually recycle nutrient solutions until plants are ready for harvest, allowing farmers to use 70-95% less water compared to conventional agricultural practices leading to noticeable reduction in water run-off (Fahey, 2012; Abdullah, 2016). One study found that 75,000 tons of fresh water can be saved annually if hydroponic system replaces conventional farming. Particularly, each hectare of hydroponic systems has the potential to replace 10 hectares of rural lands (Almeer et al., 2015). The action of planting seedlings close to each other have the potential to save saves 1/20th of the overall total water requirements in soilless agriculture in comparison to its soil-based counterpart (Sardare and Admane, 2013).

Hydroponic agriculture has been shown to conserve water in a plethora of research literature. For example, in an experiment performed by Barbosa et al. (2015), plant production through conventional agricutlural methods annually used 230 L/Kg/Year more water than their hydroponic counterpart (see figure 3.9).

Besides, advanced water conservation techniques such as the capturing evaporated water with cooling traps and returning it into circulation and the conversion of greywater into irrigation water have been developed, tightening the control over water circulation throughout the system and reducing water run-off (Almeer et al., 2015). In addition, rooftop hydroponic greenhouses reduce storm water run-off by capturing rainwater and introducing it into the existing circulating water (Fahey, 2012).

3.3.6. Controlled Environment

Since hydroponic systems are placed in greenhouses, warehouses, or office buildings, they rely heavily on several setups that strictly monitor, regulate, and control their environments (Mugundhan, 2011; Abdullah, 2016). The utilization of various cutting-edge sensors that monitor plant biology, temperature, light-exposure variations, light spectrum and wavelength, pH, humidity, oxygen availability, gas availability, CO2 supply, electrical conductivity and nutrient concentration dramatically increased the productivity of hydroponic systems and shortened the harvest cycle (Banerjee et al., 2013; (Abdullah, 2016; Marulanda et al., 1993; Fahey, 2012).

Hence, the use of high-tech monitoring systems that carry out screenings in order to maintain optimum growth conditions is vital for the successful growth of hydroponically grown plants (Abdullah, 2016; Marulanda et al., 1993; Fahey, 2012). Applications of controlled environment setups which extend to the computerization of the whole hydroponic system and desalination of water run-off can decrease the risk of potential dangers, reduce operational costs, and maximize the yields (Abdullah, 2016).

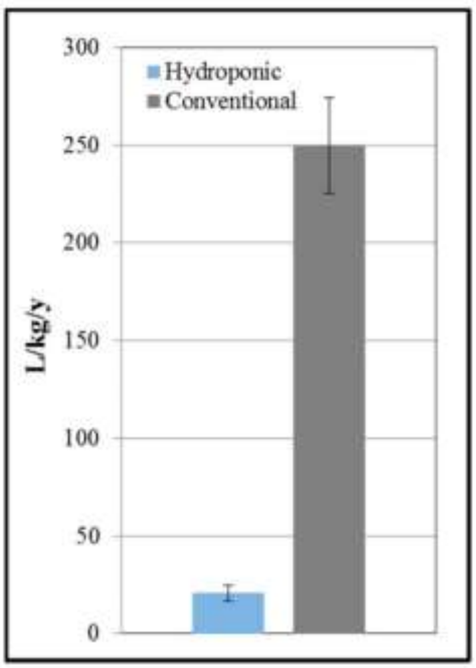

Figure 3. 10: Comparison between the annual water use of hydroponic and conventional plant production methods in Southwestern Arizona. The units are in liters per kilogram. From "Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic *vs.* Conventional Agricultural Methods," by Barbosa et al., (*Int J Environ Res Public Health*, Int J Environ Res Public Health, 16 Jun. 2015; Web; 2 Dec. 2016).

3.3.7. All-Year-Around Harvesting

Through the employment controlled environment principles, optimal conditions required for plant growth can be provided (Mugundhan, 2011). Thus, providing an opportunity to grow plants throughout the year regardless of climatic settings and weather disruptions (Fahey, 2012). This can prove to be beneficial for countries who lack self-sustainability in their agricultural sectors allowing them to produce climate-sensitive crops (Abdullah, 2016). Therefore, plants can be grown in and out of season throughout the year. Moreover, as opposed to soil-based monoculture which burdens the soil with decreased fertility, soilless agriculture allows for tighter control over biotic and abiotic stresses encouraging normal growth of the same plant throughout the year. For example, in North America, hydroponic cultivation allows for sustaining agricultural provisions of seasonal produce all-year-around in the supermarkets across the continent (Mugundhan, 2011; Abdullah, 2016).

Figure 3. 11: A Demonstration of an Indoor Hydroponic System with controlled environmental conditions in the Netherlands. From "Philips GrowWise City Farming research center in Eindhoven, the Netherlands," (*Royal Philips*, Royal Philips, N.p., n.d.; Web; 1 Dec. 2016).

3.3.8. Developing Non-Arable Lands

Worldwide, the availability in arable land is in decline, and new agricultural techniques are needed (Okemwa, 2015). Soilless agriculture is advantageous in that it doesn't require fertile or arable land

(Sardare and Admane, 2013). Soilless farms can be constructed in either vertical or horizontal configurations depending on the terrain and initial investment. However, since arable land is finite, vertical configurations maximize the use of space (Abdullah, 2016). Therefore, increasing the productivity of land and yielding more produce than conventional farming by utilizing less floor area (Touliatos et al., 2016; (Abdullah, 2016). Moreover, planting seedlings in close proximity to each other in hydroponic systems saves $1/5^{th}$ of the overall space compared to soil-based farming (Sardare and Admane, 2013).

Independence of soil aid in the development of hydroponic farms where land has been rendered non-cultivable by either natural or man-made actions. For instance, conventional agriculture techniques are neither applicable to grow plants in deserts where the climate is dry, nor in coastal and estuarine areas, and coral sand islands where soil has high salinity. Also, irresponsible activity of farmers can render arable lands sterile with the degradation and erosion of the soil by exercising excessive fertilization (Okemwa, 2015).

3.3.9. Eco-friendly Farming

Mass-cultivation of healthier agricultural plants can be achieved in hydroponic systems due to their ability to either reduce or eliminate the use of chemicals including herbicides and pesticides (Fahey, 2012; Dinpanah and Zand, 2013. This is primarily because unlike conventional agriculture where plants are exposed to open environments and are at risk of being infested with insects and contracting an ample of diseases, soilless farming is performed in sterilized confined spaces and supervised under aseptically-maintained conditions. Also, personnel can be trained in aseptic techniques to minimize plant's contraction of diseases (Abdullah, 2016). The aforementioned practices eliminate the risk of hydroponic systems' contamination with soil-borne pests, disease attacks, and weed infestation (Banerjee et al., 2013; Abdullah, 2016; Sardare and Admane, 2013)

Controlling the environment in a hydroponic system not only protect against contamination, but increase the yields due to higher nutrient uptake reducing the need for using fertilizers as opposed to soil-based agriculture. Furthermore, removing expensive fertilizers from the business model cuts-down costs, mitigate the negative environmental impacts, and provide healthier and cleaner products (Okemwa, 2015).

Moreover, in case of contamination, the infected section of the hydroponic system can be isolated and discarded preventing the propagation of the infection to other sections. The equipment in the infected section can be easily removed and treated with disinfectants (Abdullah, 2016).

3.3.10. Amplified Yields per Acre

High yields in hydroponic systems have been attained in commercial setups, personal gardening setups, and by researchers in under development laboratory systems (Mugundhan, 2011). Vegetables grown in hydroponic systems yield benefit from higher density planting resulting in increased harvest per acre as opposed to conventional agriculture (Mugundhan, 2011; Fahey, 2012; Sardare and Admane, 2013). Hydroponic systems that cover areas around 2 acres and more than 10 acres avail themselves to economies of scale and can produce 20 to 25% more harvest than conventional soil agriculture (see figure 3.12) (Mugundhan, 2011). Rounded down data obtained from research performed by hydroponic experts claim that hydroponic systems can potentially yield 2 to 5 times higher yield (Okemwa, 2015).

According to Dr. Resh, a hydroponic specialist, research pertinent to greenhouse cultivation have documented that hydroponic systems yield 3 times more tomato, 4 times more cucumber, and 4 times more lettuce and pepper (see tables 3.1. and 3.2.) (Mugundhan, 2011; Fahey, 2012). An example corroborating that the utilization of hydroponic systems result in a stark increase in the productivity of plants is in the US and Canada where soil-grown tomatoes yield on average between 40,000 to 60,000 pounds per acre whereas companies operating hydroponic systems reported yields of more than 650,000 pounds per acre. These figures are phenomenal expressly considering that ten years before reporting them, hydroponic system operators reported a produce of 400,000 pounds per acre. The increase in yields is attributed to improvements in cultivation techniques and the introduction of new sustainable technologies. Likewise, yields of conventionally grown cucumbers were limited to 10,000 pounds per acre while hydroponically-grown cucumbers have registered yields of 200,000 pounds per acre (Mugundhan, 2011).

Moreover, vertical farming hydroponic systems can produce 129 to 200% more plants compared to conventional techniques. This can potentially increase profits by factor of 3.5 to 5.5 US dollar/(m^2) (Touliatos et al., 2016).

Crops	Yield in VF due to Tech (tons/ha)	Field Yield (tons/ha)	Factor increase due to Tech	Factor increase due to Tech and Stacking
Carrots	58	30	1,9	347
Radish	23	15	1,5	829
Potatoes	150	28	5,4	552
Tomatoes	155	45	3,4	548
Pepper	133	30	4,4	704
Strawberry	69	30	2,3	368
Peas	9	6	1,5	283
Cabbage	67	50	1,3	215
Lettuce	37	25	1,5	709
Spinach	22	12	1,8	820
Total (average)	71	28	2,5	516

Table 3. 1: A comparison between the estimated yields of hydroponic plant production in a vertical farm and conventional soil-based plant production. Source: Up, Up and Away! The Economics of Vertical Farming, by Banerjee Chirantan (Journal of Agricultural Studies, Journal of Agricultural Studies, 23 Nov. 2013.; Web; 2 Dec. 2016).

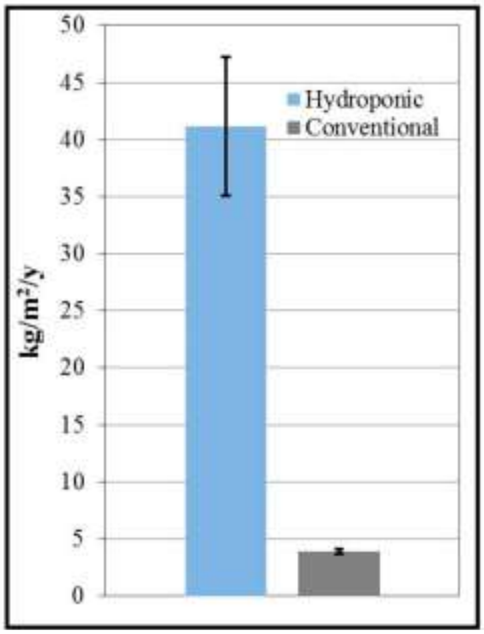

Figure 3. 12: Comparison between average yields of hydroponically and conventionally grown plants. The units are in pounds and tons per acre. Source: A Review on Plants Without Soil - Hydroponics, by Sardare et al., (International Journal of Research in Engineering and Technology, International Journal of Research in Engineering and Technology, Mar. 2013; Web; 2 Dec. 2016).

Name of crop	Hydroponic equivalent per acre	Agricultural average per acre
Wheat	5,000 lb.	600 lb.
Oats	3,000 lb.	850 lb.
Rice	12,000 lb.	750-900 lb.
Maize	8,000 lb.	1,500 lb.
Soybean	1,500 lb.	600 lb.
Potato	70 tons	8 tons lb.
Beet root	20,000 lb.	9,000 lb.
Cabbage	18,000 lb.	13,000 lb.
Peas	14,000 lb.	2,000 lb.
Tomato	180 tonnes	5-10 tonnes
Cauliflower	30,000 lb.	10-15,000 lb.
French bean	42,000 lb. of pods for eating	-
Lettuce	21,000 lb.	9,000 lb.
Lady's finger	19,000 lb.	5-8,000 lb.
Cucumber	28,000 lb.	7,000 lb.

Table 3. 2: Comparison between annual yields of hydroponically and conventionally grown lettuce in Southwestern Arizona. The units are in Kg/(m^2)/Year. From "Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic *vs.* **Conventional Agricultural Methods," by Barbosa et al., (*Int J environ Res Public Health*, University of Illinois at Chicago, 16 Jun. 2015; Web; 2 Dec. 2016).**

3.3.11. Availability of Infrastructure

Hydroponic systems can be installed in any closed environment compartments where all the conditions can be tailored and controlled for optimum plant growth. A great example of hydroponic systems in cities is rooftop hydroponics. The abundance of unused and empty roof space in cities can be exploited to increase food supply for local agglomerations and decrease energy expenditures by utilizing waste-heat technology that reduces heating costs by capturing heat from the building below (Fahey, 2012).

3.4. Social and Economic Influences

3.4.1. Boosts the Welfare of Farmers

In Chile, there has been diligent attempts to spread hydroponic techniques throughout the country. These attempts have helped many farmers across the country to increase their income and enhance their lifestyles and purchase power. Popular hydroponics employs the utilization of cheap tools and equipment. This gave the farmers a window to improve the quantity and quality of their annual produce without increasing their expenditure costs. Hence, strengthening the farmer's economic wellbeing. Moreover, since hydroponic systems can be installed in urban cities, the agricultural sector can evolve into being a job provider for city dwellers where there is no plenty of job opportunities chiefly for farmers who have left their farms in rural areas and who lack proper education (Marulanda et al., 1993).

3.4.2. Reduced Labor

Practices peculiar to conventional agriculture are mechanized and depend extensively on mass labor and fossil fuel-powered machinery (Okemwa, 2015). As opposed to conventional agriculture which requires digging, watering, fertilizing, manual plant care, and weeding, hydroponic agriculture demand less manual operational control (Okemwa, 2015; Abdullah, 2016). Thus, a team of 2 or 3 employees with good technical and scientific knowledge is sufficient to operate a hydroponic farm that produce 5 tons of crops per month (Okemwa, 2015; Abdullah, 2016).

Although less work is needed in hydroponic systems, high quality produce can be harvested. This is because the absence of soil allows for harvesting plants that are not coated with soil (Okemwa, 2015). The reduction in labor and machine intensive activities represent a cost-effective model to increase yields and decrease expenditure (Abdullah, 2016).

3.4.3. Improved Working Conditions

Employees working at hydroponic facilities must have a profound knowledge of safety protocols and standard operating procedures. Practices such as wearing gloves, using hair nets, hand washing, and sanitizing shoe entrances, doesn’t only promote a safe environment for the plants to grow but also secure the health and safety of the employees. As opposed to conventional farming where farmers are readily exposed to harmful carcinogenic and poisonous chemicals, fertilizers, herbicides, weedicides, and pesticides (Almeer et al., 2015).

3.4.4. A Stable Emerging Market

Hydroponic agriculture industry is currently valued at 2.4 Billion US dollars. It is experiencing an annual growth rate of 10 % and represent 95% of hydroponically grown vegetables in the US and Canada (Mugundhan, 2011). Furthermore, the increase demand on fresh produce that is grown locally has persuaded investors to invest in local hydroponic ventures, particularly rooftop hydroponic systems (see figure 3.12.) (Fahey, 2012).

Encouraged by economic gain and the fact that hydroponics can open a new frontier in employment opportunities, governments as well as local authorities are offering economic incentives and financial support for hydroponic farmers and researchers. For instance, the construction of green buildings and green roofs was promoted and financed by the Green Permit Program in the city of Chicago. The Small Business Improvement Fund, is a similar program that offers 45,000 US dollars for the construction of rooftop greenhouses. Moreover, hydroponic farmers who meet the standards and requirements of efficient energy consumption can take advantage of more governmental incentives (Fahey, 2012).

3.4.5. Possible Source of Energy Conservation

Hydroponic rooftop greenhouses are energy efficient plant producer in that they absorb the energy of the sun required for photosynthesis rather than reflecting it back to the atmosphere, subsiding the urban heat island effect. Thus, this technique provides passive insulation for the building and could possibly decrease energy expenditure to control temperature of the building below. This effect is reflected with warmer temperatures in cities during the summer and winter compared to their rural surroundings mainly due to human activities. Subsequently, the urban heat island effect is beneficial in winter months because it decreases the overall energy demands for maintaining heating setups in the system (Almeer et al., 2015).

Integration of hydroponic system into buildings may reduce energy costs and could remarkably save up to 41% of heating costs as opposed to typical standalone hydroponic systems. Likewise, the costs of cooling methods which consumes a significant amount of energy can be decreased with the usage of passive technologies such as evaporative cooling or natural ventilation (Almeer et al., 2015).

Moreover, the utilization of efficient artificial lightning systems such as LEDs can further decrease operational costs. These lights not only have long operating life but emit low levels of thermal radiation, decreasing cooling costs. In advanced hydroponic greenhouses, the intensity of illumination can be tailored at different power levels since various plant species exhibit distinct illumination requirements (Almeer et al., 2015).

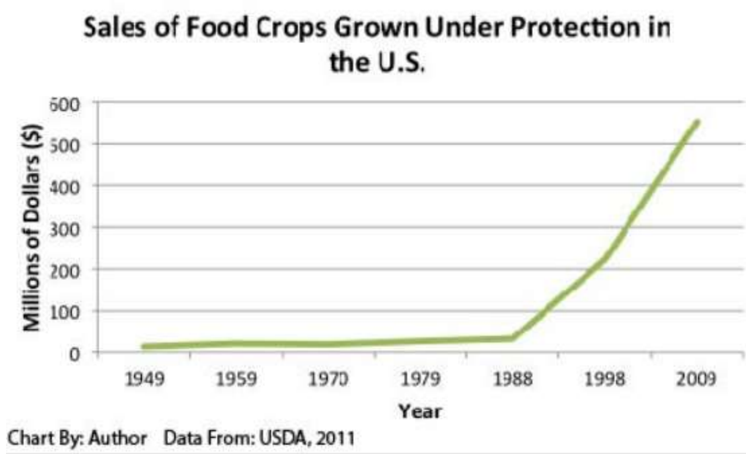

Figure 3. 13: An evident increase in sales of crops grown under protection, i.e. hydroponic plants, is an indicator of the rising demand. From "Rooftop Hydroponic Agriculture," by Fahey Christopher (*University of Illinois at Chicago*, University of Illinois at Chicago, 7 Dec. 2012; Web; 2 Dec. 2016).

3.5. Limitations of Hydroponic Agriculture

3.5.1. High Initial Start-up Investment

Although production costs in hydroponics are 90% cheaper than conventional agriculture and returns on investment are high, a major drawback associated with hydroponic systems at the commercial scale is the high initial start-up costs (Abdullah, 2016; Fahey, 2012; Sardare and Admane, 2013). Initial investment costs include the price of land on which the system will be installed, the costs of technical climate control equipment and advanced monitoring systems, and installment costs. The enormous figures of the initial investment make it difficult for individuals seeking funding to secure financing to start their business ventures (Fahey, 2012).

A company called Brightfarms manufactures rooftop hydroponic greenhouses and constructs them at the cost of $ 2 million per 43,560 ft^2 (Fahey, 2012). Hence, high installation costs are a factor that will discourage soil-based farmers from adopting any of the soilless cultivation techniques (Okemwa, 2015). Subsequently, commercial hydroponics has been for years limited to only high value crops (Sardare and Admane, 2013).

3.5.2. High Costs of Energy Inputs

To operate the hydroponic system, high energy requirements are needed (Sardare and Admane, 2013). Despite the prosperity hydroponic growers experience in obtaining high yields by using energy efficient technologies, energy costs related to the operation of hydroponic systems can persistently remain high. Expediting the growth of plants and extending the growth season requisites the use of energy demanding equipment such as heating equipment, lighting equipment, electrical pumps, and monitoring equipment (Fahey, 2012). Therefore, electricity constitutes the largest portion of operational costs (Fahey, 2012). Compared to conventional agricultural practices, hydroponic plant production systems used by Barbosa et al. (2015) required an additional 90,000 KJ/Kg/Year (see figure 3.13.). High electricity costs are an

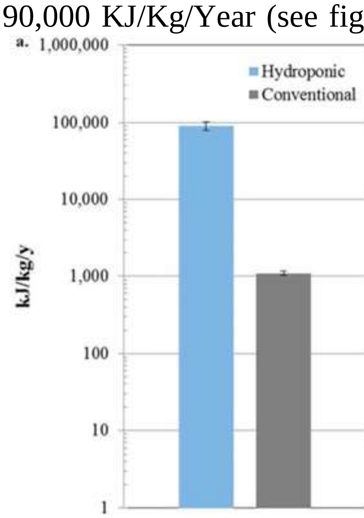

Figure 3. 14: A comparison between annual energy use between hydroponically and conventionally grown lettuce in Southwestern Arizona. The units are in kilojoules per kilogram. From "Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic *vs.* Conventional Agricultural Methods," by Barbosa et al., (*Int J Environ Res Public Health*, Int J Environ Res Public Health, 16 Jun. 2015; Web; 2 Dec. 2016).

important factor that could be preventing farmers and businesses from entering the hydroponics industry (Fahey, 2012).

3.5.3. Dependence on Science-Oriented Employees

Unlike conventional agriculture, great care and attention should be reserved when dealing with hydroponically grown plants (Mugundhan, 2011; Sardare and Admane, 2013). Otherwise, grown plants can potentially die due to the negligence of the staff members (Mugundhan, 2011). In order to obtain high yields, the plethora of sensitive operations have to be supervised by experienced and trained personnel with profound technical knowledge of the operations being monitored (Abdullah, 2016; Sardare and Admane, 2013). These operations include knowing the composition of nutrient solutions, types of media, types of irrigation, plant health control, and materials used in the desired hydroponic system (Mugundhan, 2011; Sardare and Admane, 2013). Therefore, the high cost of employing skilled workers is another factor that will discourage farmers from converting to hydroponic agriculture (Okemwa, 2015).

3.5.4. Failure of Electrical Systems

Hydroponic systems are automated and depend on electrical systems to maintain smooth routine operations Electrical systems are constituted from electronic timers, pumps, and computers that work in harmony to control critical routine operations. If the electrical systems experience failure or sudden electric outbreaks the plants could die and crops yields could decline. In addition, failure in the system regulating the circulation of nutrient solution threatens plants with the risk of disease outbreaks. Finally, system failure in water pumps results in the dry out of the roots and the subsequent death of plant due to water shortages (Mugundhan, 2011; Fahey, 2012).

3.5.5. Skepticism by Investors

One of the limitations constraining investors from investing in hydroponic systems are manifest in their skepticism and hesitation to embark on a new project that uses expensive advanced equipment needs high initial investment. The lack of a successful large-scale commercial business model in hydroponic can avert them from investing fearing they would not generate stable profits (Fahey, 2012).

3.5.6. Convoluted Regulatory Legislations

Complicated and vague language used in regulatory legislations are hindering the promotion of worldwide hydroponic farming. Particularly, rooftop hydroponic greenhouses operators face zoning regulations that are restricting their expansion further diminishing the reach of their companies. Hence, the absence of direct and clear language will delay the process by which the approval of installing the facility hinges upon. For example, it took Gotham Greens, a rooftop greenhouse company in New York, two years of extensive negotiations with New York City Department of Buildings to get their approval (Fahey, 2012).

3.5.7. Lack of Data Collection and Standardization

The majority of hydroponic farms operators do not collect the data related to energy, water, pesticide, fertilizers usages as well as accurate yield assortments and air quality. This lack of sufficient data collected from commercial-scaled hydroponics is limiting researchers from understanding the true mitigatory effects on the environment and the probable market potential of hydroponic farming. Moreover, if data was collected, a factor that complicate the understanding of the data is the absence of metric standardization (Almeer et al., 2015).

3.5.8. Opposition by Consumers

Negative perception of hydroponically grown plants by the general public is affecting its market. The manner in which hydroponic plants are grown is negatively conceived by consumers as if they were being grown in labs or factories. Also, consumers are inclined to think that the sensory attributes of hydroponically gown plants such as visual quality, taste, and odor are of less quality than those grown in soil-based agriculture (Fahey, 2012).

CHAPTER 4

ESSENTIAL PARAMETERS OF THE HYDROPONIC SYSTEM

4.1. Overview of the System's Operations

The plethora of operations in a hydroponic system has to be tightly supervised by experienced and trained personnel (Abdullah, 2016). The constant monitoring of the system is imperative for the maintenance of normal operations (Sardare and Admane, 2013). In order to continuously make rapid changes to the system's operations, computer technology and various sensors can be integrated to monitor the parameters of the abiotic production environment. The most important parameters consist of the temperature of production area and nutrient solution, relative humidity and carbon dioxide concentration of air, lighting supplement and intensity, pH, Dissolved Oxygen Levels (DO), and electrical conductivity of the nutrient solution (Brechner et al., n.d.).

Sensors will simultaneously collect data governing the parameters and send it to the main computer. Then, a series of environmental control measures such as ventilation, lighting, humidification, heating, and nutrient formulation will be activated (Abdullah, 2016; Brechner et al., n.d.).

Ventilation is manifested in the exchange of air between the interior and exterior of the facility. Thus, it provides an indispensable opportunity to filter the atmosphere rendering it free of pathogens and to optimize the growth temperature in the production area (Abdullah, 2016).

Humidification is employed to limit the periodic outbreaks of mildew and other diseases, to prevent the wilting and drying out of plants, and to provide another level of control over temperature. industrial-grade humidifiers can be potentially used by growers to control the overall atmospheric humidity of the production area (Abdullah, 2016).

Since plants will be grown indoors, artificial lighting is required for plants to photosynthesize and produce bio mass. Artificial lighting will enable growers to control the light spectra and optimize the amount of lighting provided to the plants (Abdullah, 2016).

The nutrient formulations can be monitored in real time and modified. Hence, growers can regulate the concentrations of essential nutrients to stabilize electrical conductivity and pH values. Abdullah (2016) reported that for five types of cultivars (Lactuca, Ocimum, Petroselinum, Fragraria and Mentha) the optimum pH values range between 5.5 and 6.0, EC values of more than 10, and optimum growth temperatures between 20 and 23 °C (Abdullah, 2016).

4.2. Necessities of the Growth Environment

4.2.1. The Nutrient Solution

Hydroponic systems allow growers to easily manipulate and control the environmental conditions of the cultivation area. Subsequently, yields can be increased and product's quality of the grown crops can be improved by controlling the parameters of the nutrient solution which encompass its temperature, pH, electrical conductivity, and dissolved oxygen content (Trejo-Téllez and Gómez-Merino et al., 2013).

4.2.1.1. Composition of the Nutrient Solution

The preparation and maintenance of nutrient solutions is a challenging task requiring great vigilance on behalf of the grower to ensure the attainment of optimum plant nutrition (Hershey, 1994; Christie, 2010). The response of plants to nutrients and the supply of nutrients are ought to be the two most important characteristics of plant nutrition (Sardare and Admane, 2013). Also, the concentration of the nutritional elements influences the electrical conductivity and the osmotic potential of the nutrient solution (Trejo-Téllez and Gómez-Merino et al., 2013).

A typical nutrient solution is defined as an aqueous solution composed of 17 nutritional elements important for plants' growth dissolved in water (Trejo-Téllez and Gómez-Merino et al., 2013). The elements are categorized and introduced into the circulating water based on their essentiality. A nutritional element is essential for a plant if its absence will beget unfavorable growth conditions (Christie, 2010). The nutrient solution mixture contains a variety of inorganic ions and organic compounds that are important for the healthy growth of plants (Mugundhan, 2011; Christie, 2010; Trejo-Téllez and Gómez-Merino et al., 2013).

Each element partakes an essential role in the physiological development of plants and a deficiency or an absence in of one of these elements results in the deterioration of plant's health (Trejo-Téllez and Gómez-Merino et al., 2013).

Although many recipes of nutrient solutions of the early days of hydroponics are still being used nowadays, one of the most widely studied and used nutrient solution in research and commercial hydroponics is Hoagland's Solution (Hershey, 1994; Christie, 2010). A large assortment of modified varieties of the same solution has been proposed (Christie, 2010).

During the process of designing the composition of any nutrient solution and during the maintenance of these solutions two vital parameters should be taken into consideration. Firstly, careful attention should be given to the uptake ratios of individual nutritional elements by the grown plant in either circulating or open hydroponic systems. Secondly, the composition of nutrient solutions must reflect the specific requirements of the grown species of plants (Trejo-Téllez and Gómez-Merino et al., 2013). As a result, researchers have determined over the years the critical levels of essential nutritional elements for commonly grown plants in hydroponics (Sardare and Admane, 2013).

The 17 essential elements used in nutrient solutions are carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, copper, zinc, manganese, molybdenum, boron, chlorine and nickel (see table 4.1.). All of the aforementioned elements, with the exception of oxygen and carbon which can be obtained from the atmosphere, are going to be obtained by the plants from the nutrient solution (Trejo-Téllez and Gómez-Merino et al., 2013). All the necessary nutritional elements have been identified and greatly documented in the scientific literature. These elements can be divided into two categories, the macronutrients with each element covering larger than 1000 mg/kg dry mass and the micronutrients with each element making up <100 mg/kg dry mass (Mugundhan, 2011; Christie, 2010).

The macronutrients are Carbon, Oxygen, Hydrogen, Nitrogen, Phosphorous, Potassium, Calcium, Magnesium, and Sulfur (see table 4.1.). Carbon is essential for the formation of organic compounds, oxygen for the release of energy from sugar, Hydrogen is acquired for the formation of water, nitrogen and sulfur for the synthesis of amino acids and proteins, Phosphorous is used in photosynthesis and plant growth, Potassium is vital for maintaining normal activity of the enzymes, Calcium is a primary component of the cell wall and Is important in the regulation of cell division and cell growth, and Magnesium is a component of chlorophyll and an element that activates the enzymes (Mugundhan, 2011).

Whereas the micronutrients are Iron, Manganese, Boron, Molybdenum, Copper, Zinc, Chlorine, Nickel, Cobalt, Sodium, and Silicon. The iron is an important component of the plant's photosynthesis, boron is vital for reproduction, Chlorine helps to grow the roots, copper for the activation of enzymes, Manganese is a component of chlorophyll and plays a role in the activation of enzymes, Zinc is a component of both enzymes and auxins, Molybdenum and cobalt are imperative the fixation of Nitrogen, Sodium for the movement of water, Nickel for the liberation of nitrogen, and Silicon for increasing the toughness of cell walls (Mugundhan, 2011).

Essential Elements for Plant Growth	
Macronutrients	**Micronutrients**
Carbon (C)	Iron (Fe)
Hydrogen (H)	Manganese (Mn)
Oxygen (O)	Boron (B)
Nitrogen (N)	Molybdenum (Mo)
Phosphorus (P)	Copper (Cu)
Potassium (K)	Zinc (Zn)
Calcium (Ca)	Chlorine (Cl)
Magnesium (Mg)	Nickel (Ni)
Sulfur (S)	Cobalt (Co)
	Sodium (S)
	Silicon (Si)

Table 4. 1: summary of the essential micronutrients and macronutrient required for the growth of plants. Source: Essential Nutrients for Plants, by Boundless (*Boundless*, Boundless, n.d.; Web; 2 Dec. 2016).

4.2.1.2. Maintenance of the Nutrient Solution

The failure or success of the hydroponic system is incumbent on the maintenance of a variety of important parameters such as pH, Electrical Conductivity (EC), temperature, and dissolved oxygen in the nutrient solution (Christie, 2010).

Because plants have to be fed daily, maintaining the water's chemical composition at tolerable levels should be carried out continuously to avert plant nutrient uptake plights (Christie, 2010; Sardare and Admane, 2013; Trejo-Téllez and Gómez-Merino et al., 2013). This process allows growers to identify and take decisions based on the concentrations of both deficient nutrients and available nutrients in the circulating nutrient solution (Trejo-Téllez and Gómez-Merino et al., 2013).

The maintenance of the nutrient solution is a task that requires keen vigilance since plants are continuously uptaking nutrients. Plants have the ability to uptake nutrients at very low concentrations when the nutrient solution is perpetually circulated throughout the system. Hence, large amounts of nutrient solution are lost since high proportion of nutrients are not used by plants (Trejo-Téllez and Gómez-Merino et al., 2013).

The frequency of replenishment and the volume of added nutrient solution is determined by several parameters such as the type of substrate used, the species of the crop, the rate of plant growth, the developmental stage of the crop, the size of the container, and the type of hydroponic and irrigation systems (Sardare and Admane, 2013; Hershey, 1994)

Each type of plants has different requirements for their growth environment. Henceforth, particular plants retain the ability to grow ordinarily under in the presence of abiotic stresses whereas other types cannot tolerate them. Abiotic stresses are recognized in the presence of high concentrated nutrient solutions leading to toxic effect on the plants or in low concentrated nutrient solutions leading problems in the growth of plants (Trejo-Téllez and Gómez-Merino et al., 2013).

However, certain plants can flourish in nutrient solutions with low concentrations of nutrients. For example, it has been reported by Zheng et al., (2005) that a 50% reduction in the concentration of the nutrient solution didn't affect the growth of Gerbera. Also, in an experiment done by Siddiqi et al., (1998) showed that with the reduction of the concentration of macronutrients by up to 50% compared to control levels and the termination of nutrient solution replenishment for 16 days after seven months of growth didn’t adversely affect the growth and quality of fruits. Nonetheless, low concentrations might not cover the minimal nutritional requirements of another species of plants (Trejo-Téllez and Gómez-Merino et al., 2013).

Moreover, certain species of plants can flourish in high concentrated nutrient solutions. A research done by Kang et al., (2004) showed that a 200% increase in the concertation of Hoagland Solution Induced Salvia to flower 8 days earlier than the same species grown in low concentrated nutrient solution. Another research performed by Fanasca et al., (2006) found that a substantial increase in fruit dry matter was noticed in the presence of high levels of Potassium in the nutrient solution (Trejo-Téllez and Gómez-Merino et al., 2013).

4.2.1.3. Electrical Conductivity of the Nutrient Solution

Since the continuous monitoring of the concentrations of every ion is expensive and the technology for monitoring some ions is not available yet, an indirect approach revolving around measuring the electrical conductivity (EC) of the nutrient solution can be employed (Hershey, 1994; Christie, 2010). Researchers and growers use electrical conductivity as a parameter to measure the concentration of the nutrient solution in the hydroponic system. Expressly, the monitoring of electrical conductivity of a recirculating nutrient solution in a closed system is important for plants’ health (Christie, 2010).

Several important parameters that are involved in the growth and development of plants rely on the total ionic concentration of the nutrient solution (Trejo-Téllez and Gómez-Merino et al., 2013). Nevertheless, electrical conductivity is measured by estimating the total amounts of dissolved salts in the nutrient solution (Brechner et al., n.d.; Trejo-Téllez and Gómez-Merino et al., 2013). Thus, electrical conductivity is a measure that reflects the overall concertation of available ions in the root zone. The ions that largely govern the electrical conductivity of the nutrient solution are Calcium, Magnesium, Potassium, Hydrogen, Sodium, Nitrate, Sulfate, Chloride, Bicarbonate, and Hydroxide (Trejo-Téllez and Gómez-Merino et al., 2013).

A useful piece of equipment that monitors the electrical conductivity is the EC meter (see figure 4.1.). On one hand, it helps growers know when their nutrient solutions have been depleted (Hershey, 1994). The displayed value on an EC meter decreases when plants uptake nutrients resulting in a substantial decrease in the concentration of salts (Brechner et al., n.d.). A visible decrease in ionic concentration of the system will adversely affect crops' yields and plants' health (Trejo-Téllez and Gómez-Merino et al., 2013). To compensate for this decrease in salts concentration, a small stock of nutrient solution can be added to the system (Brechner et al., n.d.).

On the other hand, the addition of pure water to the system is recommended once the displayed value on an EC meter starts to increase as result of water loss through evaporation and transpiration (Brechner et al., n.d.). A perceptible increase in the EC value will severely impede the uptake of nutrient by plants (Trejo-Téllez and Gómez-Merino et al., 2013).

Notwithstanding that defining the ideal EC values of nutrient solutions peculiar to the type of cultivated plant and is regulated by the environmental conditions, hydroponic systems generally operate at EC values ranging between 1.5 and 2.5 dS/m (Trejo-Téllez and Gómez-Merino et al., 2013).

The routine maintenance of the nutrient solution will avert the accumulation of toxic ions in the circulating nutrient solution. To achieve stable EC values in the root area, between 20 and 50% of the nutrient solution is ought to be drained-off, stored, and used in the next watering cycle. However, once a build-up in the concentration of toxic ions starts to become noticeable, the liquid should be discarded (Sardare and Admane, 2013). It has been reported that the nutrient solution must be replaced once the electrical conductivity of the nutrient solution reaches half the original value (Hershey, 1994).

Moreover, while measuring the EC value of the nutrient solution, it is of utmost importance to subtract the displayed value on the EC meter from the base EC value of the source water (Brechner et al., n.d.). Finally, since the concentration of every ion cannot be measured due to limitations in technology, Spectrophotometry a valuable alternative method that readily provides rapid and cheap way to monitor specific nutrient concentrations. The concentrations of nutrients are measured based on their light absorbance properties. Growers can later decide when to add stock nutrient solution to the system (Christie, 2010).

4.2.1.4. pH of the Nutrient Solution

The measurement of pH values of the nutrient solution is another important parameter in hydroponic systems because it affects the solubility of nutrients. Therefore, the pH controls the availability of nutrients and fertilizer salts to the plant (Gracia-Mier et al., 2013; Brechner et al., n.d.). Several factors such as the type of nutrients, the quantity of nutrients dissolved in water, and he pH of the water source influence the final pH of the nutrient solution (Saparamadu et al., 2010).

The determination of pH values which range between 0 and 14 are fundamentally related to the concentration of free ions Hydrogen (H+) and Hydroxide (OH-). Subsequently, affecting the acidity or alkalinity of the nutrient solution (Gracia-Mier et al., 2013). A neutral solution has an equal number of hydrogen and hydroxide ions leading to a pH of 7. Solutions with pH ranging between 0 and 6.9 are considered acidic since they have higher concentration of hydrogen ions whereas solutions with pH ranging between 7.1 and 14 are alkaline due to the presence of higher hydroxide concentrations (Brechner et al., n.d.). The pH of the nutrient solution can be adjusted and measured by using a pH meter (see figure 4.2.) (Saparamadu et al., 2010).

The optimum pH values depend on the grow species in the hydroponic system (Sardare and Admane, 2013). It is commonly accepted that pH levels fluctuating above and below the optimum suitable range might force plants to suffer from nutrient deficiency (Brechner et al., n.d.). However, several species of plants can flourish outside the optimum pH range (Sardare and Admane, 2013). Plenty of research have been done to identify the optimum pH range for growing plants in hydroponic systems. Generally, Clark (1982) and Graves (1983) reported that maximum ion uptake in plants occurs at pH values ranging between 5 and 7 (Christie, 2010). Moreover, Harris (1988) reported that plant growth is maximized at pH values ranging between 5.8 and 6.5 (Saparamadu et al., 2010). The latter pH range has been shown to possess the optimum availability of nutrients for most species of plants (Sardare and Admane, 2013). Nevertheless, Brechner et al., reported that pH ranging between 56 and 6.0 is considered the best for growing lettuce (Brechner et al., n.d.).

Plant productivity and nutrient uptake are affected by the pH of the nutrient solution in the root zone. The regulation of pH is important since plants uptake of certain nutrients shows differential responses to changes in the pH of the nutrient solution (Gracia-Mier et al., 2013; Christie, 2010).

For example, NH3 which forms a complex with H+, is available as NH4+ in the nutrient solution at pH ranges between 2 and 7. Any fluctuations in the pH above 7 will increase the concentration of NH3 while reducing the concentration of NH4+. Besides, Timmons et al., (2002) and Tyson (2007) concluded that at pH values higher than 6.5, nutrients such as Iron, Copper, zinc, Boron, and Manganese become unavailable. Also, Dyśko et al., (2008) found that the concentrations of Phosphorous drastically decrease in both basic and highly acidic solutions. Likewise, De Rijck and Schrevens (1998) showed that nutrient Potassium only exist as free ion in nutrient solutions between pH values ranging between 2 and 9. Tariq and Mott (2007) found that the nutrient Boron which is uptaken as Boric Acid is not dissociated until pH value is close to 7 (Trejo-Téllez and Gómez-Merino et al., 2013).

Moreover, the pH is always changing with time after its application in hydroponic systems due to several factors. The primary factor is the change in nutrient uptake rates in response to changes in the metabolism of plants as they grow (Saparamadu et al., 2010).

Research presented that deviations away from the optimum pH values by less than 0.1 units didn't show negative effects on plants. Low pH values promote the absorption of anions while hindering the absorption of cations. Whereas high pH values encourage the uptake of cations while reducing the uptake of anions (Saparamadu et al., 2010).

Unlike soil-based plants which rely on the composition of the soil to act as a pH buffer, hydroponically-grown plants cannot control the pH around them. Therefore, it is imperative to incorporate a constant artificial supply of buffer into the nutrient solution (Christie, 2010; Saparamadu et al., 2010). Various formulations of mild acidic or basic buffers can be added to the nutrient solution when the pH values depart from the tolerable range. Saparamadu et al., (2010) reported the design of the novel and cheap HPO4 2- / H2PO4 - buffer system which was prepared using KOH and H3PO4 (Saparamadu et al., 2010). This buffer system already contains two of the most essential nutrients for the growth of plants, Potassium and Phosphorous (Saparamadu et al., 2010). Thus, it is advantageous to use such a simple buffer system since there would be no need to add other nutrients to carry out the buffering process (Saparamadu et al., 2010).

4.2.1.5. Temperature of the Facility and Nutrient Solution

The temperature of the nutrient solution doesn't only impact the amount of oxygen consumed by plants but also affects the solubility of fertilizers and influences the uptake of nutrients and water by the plants (Trejo-Téllez and Gómez-Merino et al., 2013). Therefore, temperature is a parameter that directs the growth rate of plants (Brechner et al., n.d.).

Each species of plant requisites the maintenance of an optimum temperature during their development to promote their rapid and successful maturation (Brechner et al., n.d.; Trejo-Téllez and Gómez-Merino et al., 2013). However, plants can survive and grow in a wide range of temperatures as long as the values do not fluctuate above the maximum or the minimum growth temperatures (Trejo-Téllez and Gómez-Merino et al., 2013). Thompson et al. (1998) reported that dry mass of lettuce was affected by the temperature of the nutrient solution while the growth of lettuce was affected by the air temperature inside the facility (Sace and Estigoy, 2015). Additionally, Thompson et al. (1998) reported that high quality lettuce crop can be grown at elevated aerial temperatures, particularly at temperatures above 24 degrees Celsius, as long as the temperature of the nutrient solution was kept below 20 degrees Celsius (Both, 2013). On the other hand, it has been recorded that in the two flowering plants Rosa x Hybrida and Grand Gala, cold nutrient solutions increased the uptake of NO3- and decreased the uptake of water (Trejo-Téllez and Gómez-Merino et al., 2013).

Moreover, Calatayud et al. (2008) showed that rose plants grown in cold nutrient solutions reported higher effective quantum yields. Whereas Nxawe et al. (2009) found that spinach seedlings grown in nutrient solutions at elevated temperatures, expressly 28 degrees Celsius, conveyed longer leaf length, higher leaf number, and higher dry biomass per plant (Trejo-Téllez and Gómez-Merino et al., 2013).

Two evident effects manifest during increasing the temperature of the production area (Mugundhan, 2011). Firstly, an increase in temperature speed up plants' growth and accelerate the chemical processes in the cells (Mugundhan, 2011; Brechner et al., n.d.). Chemical processes in plants are controlled by enzymes. Thus, enzymatic activity reaches its peak when working under tightly monitored temperature range. Any deviations above or below this range will result in the deterioration of enzymatic activity leading to a deceleration in the rate of chemical reactions and growth rates of crops (Brechner et al., n.d.). Secondly, high temperatures forces plants to cool themselves through evaporation. This can be achieved by plants by means of increasing their water consumption (Mugundhan, 2011).

Hence, the temperatures of air and water should be perpetually monitored and controlled (Brechner et al., n.d.). The latter task requires the presence of a cooling and heating system that can aid in balancing the temperatures of the production and germination areas as well as that of the nutrient solutions. Villela et al. (2004) reported an increase in the productivity of Sweet Charlie variety of strawberries when nutrient solutions were cooled down to 12 degrees Celsius by using a heating exchange device. Moreover, the use of deep-sea water in pipes that runs through cultivation bed can potentially decrease the temperature of nutrient solution by the means of heat exchange between the deep-sea water and nutrient solution (Trejo-Téllez and Gómez-Merino et al., 2013).

4.2.1.6. Oxygenation of the Nutrient Solution

Temperature of the nutrient solution plays an important role in oxygen consumption by plants. Generally, as temperature increases, the consumption of Oxygen increases. It should be noted that the concentrations of Carbon Dioxide will increase in the absence of suitable aeration of the root-zone area. The optimum oxygen concentration in nutrient solutions rely on the demand by the grown crops (Trejo-Téllez and Gómez-Merino et al., 2013).

For instance, nutrient solutions with high temperatures (35 degrees Celsius) didn't only convey higher nutrient and water uptake by roots through a decrease in water viscosity but also resulted in a substantial reduction in the solubility of oxygen. Falah et al. (2010) reported that other effects of elevated nutrient solution temperatures include the stimulation of enzymatic oxidization of phenolic compounds in root epidermal and cortex tissues and the diminishing of nutrient concentration in root xylem sap (Trejo-Téllez and Gómez-Merino et al., 2013).

Graves (1983) reported that although temperatures of nutrient solution below 22 degrees Celsius resulted in the lessening of the DO requirements due to significant decrease in the number of physiological processes in tomato plants. On the other hand, temperatures above 22 degrees Celsius lead to an increase in the diffusion of Oxygen. Thus, Graves (1983) observed an unexpected and excessive vegetative growth, subsequently reducing fructification (Trejo-Téllez and Gómez-Merino et al., 2013).

Papadopoulous et al. (1996) reported that plants require more oxygen when their photosynthetic activity increases (Trejo-Téllez and Gómez-Merino et al., 2013). Goto et al. (1996) recommended the maintenance of dissolved oxygen concentrations above 4 mg/L to reach optimum plant growth and development. However, severe plant stress was reported by Goto et al. (1996) at concentrations of DO below 2 mg/L (Both, 2013). Moreover, in a different study done by Gislerød & Kempton (1983), concentrations of DO below 3 or 4 mg/L lead to inhibition of root growth. The symptoms of oxygen deficiency are visible on plants when their leaf color becomes brownish in color (Trejo-Téllez and Gómez-Merino et al., 2013).

Bonachela et al. (2010) reported that diffusion and supply of oxygen was impeded as a result of competition for oxygen in the root-zone area. This arise due to an increase in organic matter content and an increase in the activity of microorganisms. The deficiency in DO can be overcame by oxygen enrichment which is the artificial injection of pressurized oxygen gas to the nutrient solution (Trejo-Téllez and Gómez-Merino et al., 2013).

Besides, different methods can be used to generate oxygen in the nutrient solution of commercial hydroponic systems. Urrestarazu & Mazuela (2005) reported a method that applies Potassium Peroxide as an oxygen generator on vegetable crops. Their experiments on plants such as sweet pepper, melon, and cucumber indicated that the application of 1 g/L of Potassium hydroxide resulted in an increase in the crops yields by 20 and 15% for sweet peppers and melons respectively in comparison to control. However, the application of Potassium hydroxide didn't show any substantial difference in the yields of cucumber (Trejo-Téllez and Gómez-Merino et al., 2013).

4.2.2. Water Quality and Maintenance

The main component of a hydroponic system is water (Christie, 2010). Several factors including the concentration of ions, phytotoxic substances, presence of organisms, and the clogging of irrigation systems impact the quality of water (Trejo-Téllez and Gómez-Merino et al., 2013). While any type of water can be used in the hydroponic irrigation, contemporary practices which includes the chemical treatment of municipal water causes an upsurge in the quantities of chlorine residues (Mugundhan, 2011; Christie, 2010). These practices entail the buildup of toxic ions overtime taking into consideration continuous recycling and reuse of the nutrient solution inside the system. Thus, the use of municipal water is perilous to the plant nutrient uptake due to the high pH values varying around or above 7 (Christie, 2010).

Hydroponic systems ideally require water with an electrical conductivity of less than 500 uS/cm or total salt concentration less than 350 ppm (Mugundhan, 2011). Although a 30% increase in tomato yields has been reported by Chadirin et al. (2007) at an electrical conductivity of dS/m. Another study done by Pardossi et al. (2008) reported insignificant effects on crop yield and fruit quality at electrical conductivity of 9 dS/m (Trejo-Téllez and Gómez-Merino et al., 2013).

Moreover, in some areas around the globe, the presence of superfluous quantities of sodium and boron adversely affects the growth of plants (Mugundhan, 2011). It is imperative to provide the plants with high quality water to promote optimum growth and avoid their suffering from water stress (Sardare and Admane, 2013). To mitigate the distress on farmers, a variety of filtration systems can be employed along with sensors to monitor the concentrations of ions and maintain them at the ideal values (Christie, 2010).

To replenish the water lost by transpiration and evaporation, water should be frequently added to the nutrient solution (Hershey, 1994). To discard excess salts, it is recommended to irrigate the plants once a week with double the usual amount of nutrient-free water (Sardare and Admane, 2013).

Finally, watering requirements vary throughout the day, from one day to another, and are delimited by the dominant climatic conditions (Sardare and Admane, 2013).

4.2.3. Control of Contaminants, Diseases, Pests, and Fungi

In hydroponic systems, one of the main determinants of plant health and vigor is the maintenance of a sterile root-zone environment (Sardare and Admane, 2013; Brechner et al., n.d.). Therefore, before planting the seedlings, it is vital to devise a plan to evade the contamination of the growth area and for the treatment of disease and pests if contaminations were detected (Brechner et al., n.d.).

Amongst the most commonly encountered diseases in hydroponics are the Powdery Mildew during winter and wilt which is caused Fusarium and Verticillum (Sardare and Admane, 2013; Brechner et al., n.d.). Moreover, root areas can be sporadically destroyed by diseases in the presence of several species of Pythium and Phytophthora (Sardare and Admane, 2013).

It is a difficult duty to prevent the contamination of the root-zone area and to control the spreading of plant pathogens (Brechner et al., n.d.). To maintain a healthy production area, adequate lighting, supply of nutrients and other environmental conditions should be sustained. To avert the contamination of the root-zone area, it is recommended not to bring plant material or soil into the growing area and to limit visits to the production area to technicians and staff members (Brechner et al., n.d.).

First, regarding algae growth. Because algae flourish in wet and lit areas, to inhibit their growth in hydroponic systems, it is suggested to keep the nutrient solution tanks as well as the input and output pipes and other wet equipment shaded (Brechner et al., n.d.). Preventing algae growth is important because there are no fungicides that can be used safely in hydroponics (Sardare and Admane, 2013). For instance, Metalaxyl is an effective fungicide employed to control Pythium on vegetable crops, though it is not registered for commercial hydroponics use (Sardare and Admane, 2013). Algae growth will not harm plants directly but might result in the deterioration of plants help by making them susceptible to contracting diseases (Brechner et al., n.d.).

Second, there are several ways to achieve effective control over root disease. For if disease was detected in the root-zone area, the crops must be discarded while the ponds as well as the nutrient solution tanks are ought to be drained-off. Before reusing either the ponds or tanks, they should be sanitized and cleaned (Brechner et al., n.d.). A wide variety of cheap sanitization products are easily available in the market such as sodium hypochlorite, chlorine dioxide (Brechner et al., n.d.; Trejo-Téllez and Gómez-Merino et al., 2013). Nevertheless, sanitizing by using 2% bleach is the most widely used method and its practice is considered to be a safe (Brechner et al., n.d.). In case of contamination of the germination area, the benches, nutrient solution tanks, trays, and other equipment should be sanitized as well.

Effective control over the occurrence of algae growth and disease outbreaks especially in recirculating hydroponic systems can be achieved by using heat treatment, UV radiation, and membrane filtration (Sardare and Admane, 2013; Trejo-Téllez and Gómez-Merino et al., 2013). One research has reported that treating nutrient solutions with heat ranging between 20 and 22 degrees Celsius was found to be effective in overcoming infections resulting from the parasite Pythium. Heat treatment of nutrient solutions has also been found to accelerate the maturation of ginger plants in aeroponic systems (Sardare and Admane, 2013). Furthermore, it is recommended to wash, clean, and sanitize the equipment before every reuse of the materials to prevent the spread of disease (Brechner et al., n.d.).

Third, although pests are not considered to be a major problem in hydroponics, several measures can be employed to secure the production areas from infestation risks. In a study done by Cornell University's in the field of Controlled Environment Agriculture, pests such as shore flies, fungus gnats, thrips, and aphids have been noticed in lettuce greenhouses. One advantage of hydroponic systems is that the prompt growth of plants make it difficult for pests to widely infest them. Yet, pests might have a chance to infest the crops in continuous crop production in closed hydroponic systems (Brechner et al., n.d.).

To attain control over pests, several precautionary measures including the screening of ventilation inlets, mowing the grass and weeds outside the facilities, or using commercial pesticides registered for hydroponics use can be implemented (Brechner et al., n.d.).

Finally, growers should take notice to avoid applying nutrient solutions to the leaves and apply it directly to the roots. This practice will thwart the appearance of diseases and the damaging of plants (Sardare and Admane, 2013).

4.2.4. Carbon Dioxide Enrichment

In hydroponic systems, if the rate of Carbon Dioxide consumption in photosynthesis is more than the supply rate of ventilation system, concentrations of Carbon Dioxide inside the facility drop below atmospheric levels (FAO, 2013). Thus, the availability of adequate concentrations of Carbon Dioxide in the production area greatly influence the growth of plants, the quality of the produce, and their yields (Brechner et al., n.d.). Carbon Dioxide enrichment offers an additional layer of control over the aerial environment of the greenhouse. Baille (1999) reported that growing seasons were extended when the greenhouse’s climate was controlled (FAO, 2013).

There are several methods to maintain an adequate supply of Carbon Dioxide inside the facility. Improving the ventilation of the facility can be achieved by either pumping more air into the facility, refining the design of the ventilation system, or providing Carbon Dioxide enrichment (FAO, 2013). Another possible method to supply Carbon Dioxide to the hydroponic system is by adding liquid Carbon Dioxide (Brechner et al., n.d.). Another alternative is the use of heaters that generate Carbon Dioxide as a by-product of the combustion of gases (FAO, 2013; Brechner et al., n.d.). The latter method is not recommended by experts for two major reasons (Brechner et al., n.d.). First, it provides an easy access for contaminants slowing down the growth of the crops (Brechner et al., n.d.). Second, levels of SO2, SO3 and NOx should be cautiously monitored because at either low or high concentrations, they have the potential to damage and destroy the crops (FAO, 2013).

To increase the efficiency of hydroponic systems and to avoid the emergence of negative effects on yield, periodical Carbon Dioxide enrichment has been found to increase the quality of the produce. Carbon Dioxide enrichment have been widely used in Europe for years to grow plants during winter under low radiation conditions (FAO, 2013).

However, the dependency of decision making strategy regarding Carbon Dioxide usage in the facility on several factors that include the rate of photosynthetic assimilation, the rate of ventilation, the consumption quantity of Carbon Dioxide, and the price of Carbon Dioxide make it cumbersome task for researchers and scientists to outline the optimum concentrations of Carbon Dioxide (FAO, 2013).

Nederhoff (1994) reported that concentrations of Carbon Dioxide ranging between 700 and 900 μmol/mol, drastically increased the yield and quality of crops. Shanchez-Guerrero et al. (2005) observed a 20 percent rise in dry and fresh matter in the presence of CO2 enrichment in greenhouses (FAO, 2013). Both et al. (1998) reported an increase in lettuce growth in the presence of Carbon Dioxide enrichment method coupled with adequate lighting (Both, 2013). The concentration of Carbon dioxide outdoor is approximately 390 parts per million (ppm). In closed hydroponic systems, the concentration of Carbon Dioxide can be decreased to 100 ppm by plants. Therefore, increasing the concentrations of Carbon Dioxide in hydroponic systems to values ranging between 1000 and 1500 ppm can prevent the reduction of photosynthesis rates in plants and speed up their growth (Brechner et al., n.d.). Moreover, Both et al. (1998) showed that by increasing the carbon dioxide in the greenhouse, the number of lighting hours necessary to reach target light integral could be reduced. DeVilliers et al. (1999) also reported a novel control strategy that monitors the lighting and Carbon Dioxide enrichment systems to provide an optimum growth environment for the production of lettuce (Both, 2013).

The figure below shows that Carbon Dioxide enrichment can increase shoot dry mass by decreasing lighting hours and increasing Carbon Dioxide concentrations. For example, in lieu of exposing lettuce to ambient concentrations of Carbon dioxide and 17 mol*(m^ -2) *(d^ -1) of daily integrated light level in order to produce 7 g of shoot dry mass, grown lettuce can be exposed to 12 mol*(m^ -2) *(d^ -1) of daily integrated light level while keeping the concentration of Carbon Dioxide around 1300 μmol*(mol^ -1) to produce the same amount of shoot dry mass (Both, 2013).

4.2.5. Humidification and Dehumidification

The transpiration rate, growth, and yield of plants is greatly influenced by the humidification and dehumidification of the hydroponic system (Brechner et al., n.d.; Sace and Estigoy, 2015).

An important concept in this section is Relative Humidity which is described in percentages as the ratio of the actual water vapor pressure to the saturation vapor pressure. Moreover, the biochemical processes involved in the enlargement of plants cells are indirectly affected by Relative Humidity (Sace and Estigoy, 2015). Under optimum Relative Humidity conditions, cells are enlarged when transpiration is reduced and turgor pressure is increased. However, elevated Relative Humidity levels inside the facility induce a noticeable reduction in the rates of water transpired from plants. Subsequently, driving less cooling of the leaf surface and diminishing the transport of nutrients from roots to leaves, damaging the tissue of plants (Brechner et al., n.d.). In addition, high levels of Relative Humidity boost the growth of botrytis and mildew rendering plants vulnerable to many diseases. Relative Humidity values ranging between 50 and 88% were found to be the best for growing lettuce since they will not spend a great deal of energy to pump water into the air (Sace and Estigoy, 2015).

Furthermore, condensation is described as the formation of water drops from water vapor and their subsequent condensation onto surfaces. This phenomenon transpires from sunset to several hours after sunrise when cold surfaces are contacted by the surrounding warm and moist air of the facility. Unusual high levels of humidity in inside the facility is a factor that promotes condensation. In the light of the previous information, several problems which include the germination of fungal pathogen spores. It is important for the growers to decrease humidity at night to ranges between 70 and 80% to prevent condensation (FAO, 2013).

There are numerous available methods to dehumidify the air of the facility (FAO, 2013).

In case there is an abundance of heat inside the facility, growers can use an energy efficient method of ventilation in which the windows of the facility are opened. Thus, replacing the moist air of the interior of the facility with the dry outdoor air while simultaneously decreasing the temperature.

On the other hand, the exchange of moist inside air with dry outside air can be achieved by mechanical ventilation systems (see figure 3.4.). Campen et al. (2003) concluded that a mechanical ventilator capable of supplying 0.01 (m^3)/s is sufficient for all crops (FAO, 2013).

Furthermore, though a not favorable dehumidification method due to the presence of chemicals, a more technically advanced way is the utilization of hygroscopic materials. In this method, once the moist air contacts the hygroscopic material, absorption of water vapor is recorded as a result of the release of latent heat of vaporization. Although high temperatures are required for the regeneration of the hygroscopic material, by using a set of complex heat exchange systems 90% of the provided energy for the regeneration processes can be returned to air of the facility (FAO, 2013).

A different method condenses water by forcefully pumping humid air to a cold surface stationed inside the facility. The collected water can be reused later. For example, by using finned pipes maintained at a constant temperature of 5 degrees Celsius, 54 g of water vapor is removed per hour from air at a temperature of 20 degrees Celsius (FAO, 2013).

Finally, anti-drop materials which contain special additives dehumidify the interior of the facility by forming a continuous thin layer of water that runs down the sides of the hydroponic system on anti-dripping films (FAO, 2013).

4.2.6. Light Requirements

Growing plants in hydroponic systems is advantageous because the unpredictability of available sunlight limits the growth and development of soil-based plants. However, hydroponic systems require the supplementation of artificial lighting due to the absence of sunlight (Mugundhan, 2011).

Primarily, LED (Light Emitting Diodes) Technology is employed to provide artificial lighting for hydroponically grown plants (see figure 4.5.) (Mugundhan, 2011). Several factors play an important part in decreasing the cost of maintenance including the emission of low levels of thermal radiation, the absence of hot electrodes, the long operating life averaging between 10 and 12 years, and the absence of high voltage ballasts. Therefore, the use of LED technology is a practical cheaper choice for the long-term production of plants and maintenance of the hydroponic systems (Banerjee et al., 2013).

A unique feature of LED technology is the possibility to adjust the output of irradiated light (Banerjee et al., 2013). Thus, growers can control and change the color spectrum of light by approximating the peak absorption zone of their chlorophyll to reach their optimum growth rate (Mugundhan, 2011).

Particularly, the wavelengths of growing lights are adjusted to the wide-spectrum red light and the narrow-spectrum blue light. The wide-spectrum red light is used to mimic the illumination of natural sun rays whereas the narrow-spectrum blue light is an ideal lights source utilized to optimize the growth of plants. The Blue-Spectrum ranges between 450 and 475 nm whereas the Red-Spectrum ranges between 625 and 660 nm (see figure 4.6.).

It should be noted that not only different plants species need different periods of light exposure but also illumination should be adjusted to meet the plants' needs (Banerjee et al., 2013). Therefore, the illumination requirements of plants are defined in terms of PPF (Photosynthetic Photon Flux). Another type of measurement can be obtained by measuring the Photosynthetically Active Radiation (PAR), having the units µmol/m^2/s. PAR represents the useful light used for the photosynthetic processes in plants, reflecting the amount of growth achieved by the plants (Brechner et al., n.d.). The optimum illumination period varies between 12 and 16 hours (Banerjee et al., 2013). The measurements of light can be recorded by using a quantum sensor (Brechner et al., n.d.).

In comparison to other traditional lighting methods, LED technology uses less amount of electricity (Mugundhan, 2011). Moreover, LED technology can save power by means of programming the lights to operate in shutter sequence (see figure 4.6.) (Banerjee et al., 2013). Besides, since LED lights are already available with plugs, they will require no ballasts to initiate and regulate themselves and consequently eliminating the risk of burning ballasts. Hence, LED technology can potentially decrease power consumption of hydroponic systems requiring less than 5 watts of power to operate (see figure 4.6.) (Mugundhan, 2011). Furthermore, unlike fluorescent lights and metallic vapor, LED technology doesn't use the toxic mercury. Also, LED technology releases less heat than the other lighting technologies leading to a considerable reduction in plat water requirement. The latter advantage allows growers to not use fans and cooling ducts as well as eliminates the problems of plant dehydration and root damage due to high temperatures, consequently increasing the rate of plant survival (Mugundhan, 2011).

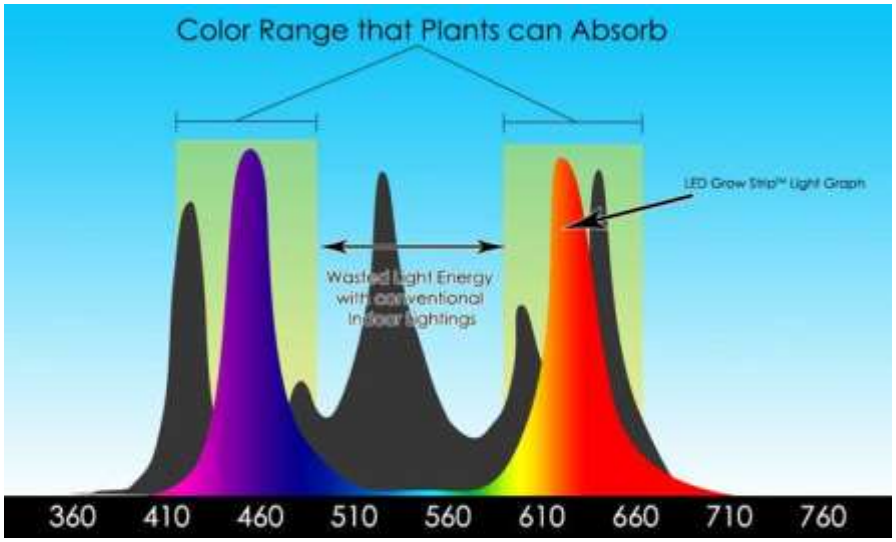

Figure 4. 2: The wavelength spectrum that plants can absorb. The Blue-Spectrum ranges between 450 and 475 nm whereas the Red-Spectrum ranges between 625 and 660 nm. From "LED Grow Strip Plant Light," by LED WORLD Inc., (*LED WORLD Inc.*, LED WORLD Inc., n.d.; Web; 11 Dec. 2016).

Figure 4. 1: Plants grown hydroponically and illuminated with LED lighting system. From "LED Grow Lights: Hobbyist Growers & Commercial Greenhouses," by Organica, (*Organica*, Organica, n.d.; Web; 3 Dec. 2016).

CHAPTER 5

MATERIALS FOR PRIMING THE GERMINATION AND PRODUCTION PROCESSES

5.1. Necessary Equipment

There are several requirements for the initiation of the operations in both of the Germination and Production Chambers. (The two terms Germination and Production Chambers will be extensively defined in the ensuing Chapter).

5.1.1. Plant Material

Moreover, the plant material that will be used in this project is the loose-leaf lettuce species, Oscarde (Asteraceae Lactuca Sativa L.). The determination of plant material has been done in Chapter 6, Section 6.2.

Figure 5. 1: A figure showing the loose-leaf lettuce Oscarde. From "Lettuce Oscarde," by KINGS Seeds, (KINGS Seeds, KINGS Seeds, n.d.; Web; 11 Dec. 2016).

5.1.2. Equipment of The Germination and Production Chambers

One floor below the Germination Chamber, there will be a huge number of nutrient solution tanks. Plumbing will allow for a continuous supply of nutrient solution to the seedlings. It is recommended that nutrient solution tanks for small-scale hydroponics to be made of fiber glass. However, for large-scale commercial hydroponics, nutrient solution tanks made of any rigid material can be used as long as they won't be worn out with time and harm the plants. Likewise, many nutrient solution tanks will be installed one floor below the Production Chamber. In both the Germination and Production Chambers, Valves and pumps can be utilized to control the flow of water out of the nutrient solution tanks. Plumbing connecting the various components of the System can be made of rigid, non-degradable, and food-safe PVC (Poly Vinyl Chloride) pipes. A small pump with (1/50) horse power. A time clock can be used to regulate the pumping activity from the nutrient solution tanks. On top of every Module, if the seedlings are not pelleted, a humidity cover should be placed to provide high humidity conditions for the them. The seeds will be sowed in Rockwool slabs. Furthermore, an independent cooling and heating systems can be used to regulate the temperature. For the sake of simplicity, ordinary fans were used in the prototype.

5.1.2.1. LED Grow Light Strips

Moreover, in both the Germination and Production Chambers ventilation tubes should be placed above each Module to continuously aerate them. Regarding the lighting systems, in the Germination Chamber Red-Spectrum LED lights will be only used whereas in the Production Chamber, a combination of Red-Spectrum and Blue-Spectrum LED lights will be used. The chosen grow lights are waterproof and have a lifespan of 50,000 hours. They can operate under temperatures ranging between -20 and 60 degrees Celsius. The length of the LED grow lights is 50 cm. while their width is 1.4 cm. The LED grow light is customizable and every 3 patches of diodes can be removed and added. They require an input voltage of 12 V and each light strip consume 1 W. A color controller is going to be bought to control the wavelength spectrum of the LED lights.

5.2. Sensors of the Production and Germination Chambers

The environmental parameters in the Germination and Production Chambers will be monitored by several sensors (Brechner et al., n.d.).

5.2.1. The Sensors

For monitoring Carbon Dioxide, a Carbon Dioxide Infrared Sensor will be used. For monitoring light intensity, a Quantum PAR Sensor will be used. For monitoring concentrations of dissolved Oxygen, a Dissolved Oxygen Sensor will be used. A flow meter will be utilized to control the flow of Oxygen into the system. A temperature sensor will monitor the temperature of the Germination Chamber. Finally, for monitoring the pH and EC a pH Meter and an EC Meter are going to be used correspondingly (Brechner et al., n.d.).

5.2.2. The Aspirated Box

An Aspirated Box is a box that houses all the sensors that will monitor the internal environment of a facility. A series of Aspirated Boxes will be installed all over the facility at the level of plant production to ensure accurate measurements. The collected data will then be sent to a central computer which will make control decisions after assessing the status of every variable of the internal environment. Aspirated Boxes can be either home-made or bought from markets. The role of Aspirated Boxes is to aerate the sensors by drawing air past them, consequently preventing the damage of the sensors due to unwarranted heat exposure (Brechner et al., n.d.).

5.2.3. The Calibration of Sensors

Routine calibration of the sensors is imperative for sustaining stable and accurate measurements throughout the life cycle of these sensors (Brechner et al., n.d.).

CHAPTER 6

DESIGN OF THE HYDROPONIC SYSTEM

6.1. The Determination of the Site

The first step in designing a hydroponic system is to determine the site on which it is going to be installed. Unlike conventional agriculture, the installment of hydroponic systems is dynamic and they can be installed in any environment and in most locations, due to the tight control of system's indoor environment. For the hydroponic systems to reach optimum maintenance of plant's growth conditions, they are ought to be installed in well-insulated buildings constructed with concrete infrastructure (Abdullah, 2016).

The selection of site greatly affects the profitability, productivity, and sustainability of the hydroponic systems. The success of production in hydroponic systems requires the foundation of a strategy that deals with two sensitive topics. Hence, growers should decide whether their products will be sold in domestic or export markets and whether the type of their product will be edible or ornamental (FAO, 2013).

Several factors influence the selection process of the hydroponic system's installment site. These factors include the sophistication level of technology and their associated costs, the costs of acquiring skilled labor, the costs of production of plants, the quality of the produced cultivar, proximity to transportation routes, transportation costs to both foreign and domestic markets, the topography and microclimate of the site, the availability of water, access to rainfall drainage infrastructure, pollution around the site, and the availability of basic infrastructure (FAO, 2013).

Constructing hydroponic facilities in either close proximity to urban areas or major naval ports will reduce the transportation costs to local and global markets consecutively. Moreover, installing the facility in well-illuminated regions far away hills and foggy areas will result in the effective drainage of cold air during calm nights. Subsequently eliminating the continuous need for the use of cooling systems and slightly decreasing operational costs (FAO, 2013).

Furthermore, to ensure the production of high quality crops, it is essential to assess the availability of water and to determine if water with low salinity can be provided at all times to the facility. It is important to note that excessive salinity has resulted in the abandonment of many sites in the Mediterranean Basin region. Also, in the incidence of heavy rainfall, ready access to water drainage infrastructure will ensure the maintenance of the integrity of the facility's interior and the survival of plants grown inside (FAO, 2013).

Finally, growers should also take into consideration the proximity to roads, the access to communication systems and internet connection, and the availability of electricity (FAO, 2013).

6.2. Determination of Plant Material

The Lettuce variety that will be produced in this hydroponic system is going to be the loose-leaf lettuce variety Oscarde (Asteraceae Lactuca Sativa L.) (Dave's Garden, 2016). It is one of most commercially produced variety in hydroponic systems and along with the other species of lettuce it is considered as an important component of salads in the Philippines and all over the world. Besides, Barry (1996) indicated that lettuce is rich in a wide variety of nutrients and vitamins such as Vitamin A and Potassium (Sace and Estigoy, 2015).

6.3. Design of Plant Germination Area

There are several important terms that must be understood before continuing reading this section.

First, a Module is defined as the sum of a container and the light emitting LED situated above it.

Second, a Level is defined as a single horizontal level where many Modules are going to be installed.

Third, a Unit is defined as a single stack of many horizontal Levels installed in a vertical configuration.

Fourth, a System is defined as the sum of all Units installed in one Floor of the whole facility.

The design of the germination area will require the incorporation of Nutrient Film Technique (NFT) system. The growth trays are going to be stacked in vertical and horizontal configuration in a separate growth chamber that will be called the Germination Chamber. Along with the fact that seedlings need small space to grow, the latter configuration maximizes the number of germinating seedlings in the germination chamber.

It is recommended that the Germination Chamber be located underneath the Production Chamber to save space and reduce construction costs.

6.3.1. The Module in the Germination Chamber

One Module in the NFT will be composed of a rectangular container that has the following dimensions: a length of 66 cm, a width of 36 cm, and a height of 8 cm (see figures 6.1.) (see table 6.1.).

The Red-Spectrum LED lights are going to be placed 10 cm above the edge of the container. Therefore, the total height of the module will be considered as 21 cm (the sum of the height of the container and the height where light is emitted) (see figure 6.2.) (see table 6.1.).

Moreover, an aeration system will be installed alongside the illumination system to circulate the air over the Module and pump either CO2 or O2 depending on the quantity of deficient gas.

Holes will be made in the Rockwool slabs big enough to hold the seeds. The centers of the holes will be 3 cm apart from each other. The holes located on the borders of the container will be made 3 cm away from the borders. Then, the Rockwool slabs will be placed inside the containers. One Module will have holes in 20 vertical columns and 10 horizontal columns. The major benefit of this configuration is that it will allow growers to germinate 200 seedlings in only one Module (see figure 6.1) (see table 6.1.).

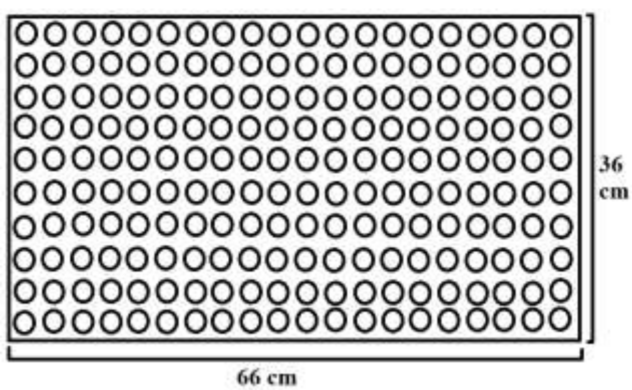

Figure 6. 1: An inferior view of the configuration of a Module in the Germination Chamber. The length of the Module is 0.66 m and its width is 0.36 m. The figure is not adjusted-to-scale and is only representing a preliminary conformation.

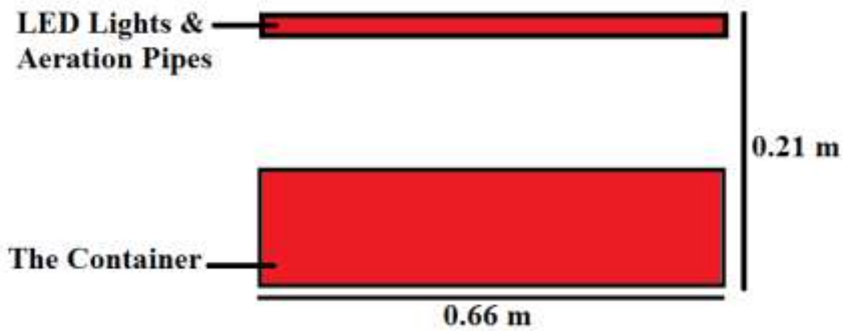

Figure 6. 2: A Lateral view of the configuration of a Module in the Germination Chamber. The height of the Module is 0.21 m and its length is 0.66 m. The figure is not adjusted-to-scale and is only representing a preliminary conformation.

Table 6. 1: The dimensions of one Module in the Germination Chamber per Month.

Length of Module	Width of Module	Height of Module	Germinating Capacity per Month
0.66 m	0.36 m	0.21 m	200 Seedlings

As a summary, one Module, 0.66 m long, 0.36 m wide, and 0.21 m high incorporates one Container with the capacity to germinate 200 plants per Month.

6.3.2. The Level in the Germination Chamber

One Level in the Germination Chamber will be constituted of one single horizontal Level. On this one horizontal Level, six Modules are going to be installed. The correct configuration will be achieved by installing the modules in two rows and three columns (see figure 6.2.).

In total, the length of one horizontal Level will be 1.98 m, its width will be 0.72 m, and its height will be 0.21 m (see figure 6.2.) (see table 6.2.).

Since one horizontal Level contain 6 Modules, it will have the capacity to germinate 1200 seeds per Month. The number 1200 was obtained by multiplying 200 by 6, such that 200 represents the total number of seedlings per container and 6 represents the total number of Modules in a single Level (see table 6.2.).

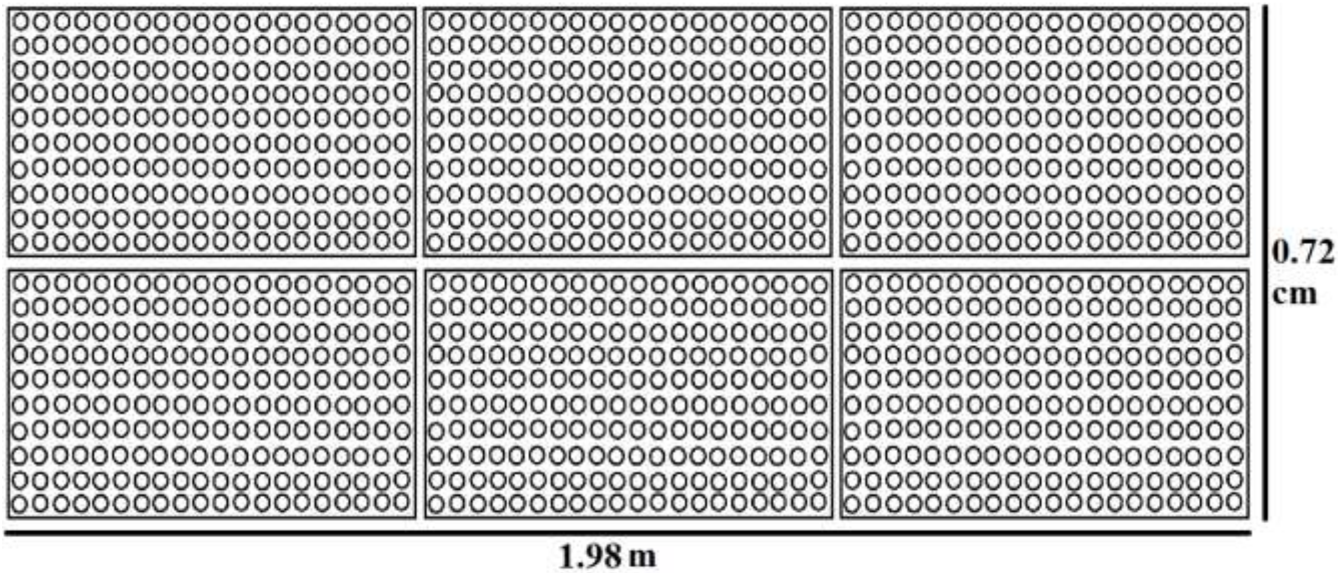

Figure 6. 4: An inferior view of the configuration of a Level in the Germination Chamber. The length of the Level is 1.98 m, its width is 0.72 m, and its height is 0.21 m. The figure is not adjusted-to-scale and is only representing a preliminary conformation.

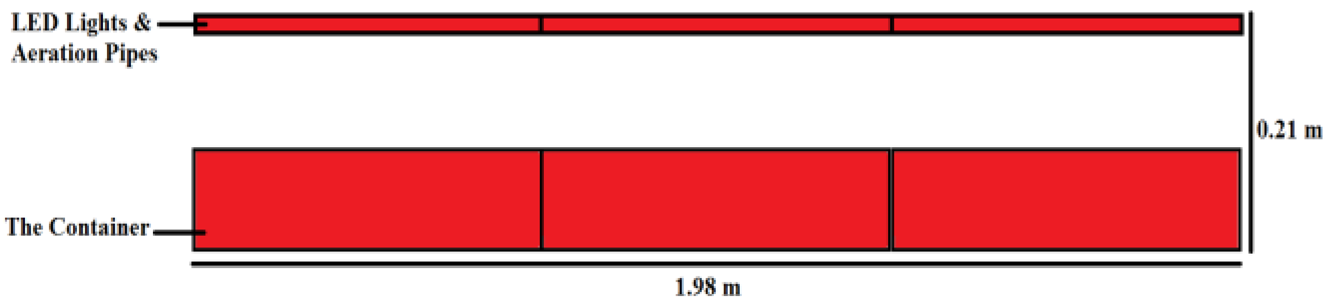

Figure 6. 3: A Lateral view of the configuration of a Level in the Germination Chamber. The length of One Level is 1.98 m and its height is 0.21 m. The figure is not adjusted-to-scale and is only representing a preliminary conformation.

Length of One Level	Width of One Level	Height of One Level	Number of Modules per One Level	Germinating Capacity per Month
0.66 m	0.72 m	0.21 m	6 Modules	1200 Seedlings

Table 6. 2: The dimensions of one Level in the Germination Chamber.

As a summary, one horizontal Level is 0.66 m long, 0.72 wide, and 0.21 m high and incorporates 6 Modules which can germinate 1200 seeds per Month.

6.3.3. The Unit in the Germination Chamber

One Unit of the Germination Chamber is composed of several horizontal Levels stacked on top of each other. As mentioned in sub-section 6.3.1. the height of one Module is 0.21 m. A single unit is composed of 20 horizontal Levels stacked on top of each other. This configuration will give one Unit the height of 4.2 m, the length of 1.98 m, and the width of 0.72 m. However, since the Units are going to be arranged next to each other, 1 m gap will be made between each Unit and the other. Therefore, the width of one unit is going to be considered as 1 m.

Moreover, one Unit has the capacity to hold 120 Modules. The number 120 was obtained by multiplying 20 by 6, such that 20 represents the number of horizontal Levels and 6 represents the total number Modules in a single horizontal Level. Since one Unit can hold up to 120 Modules, 24 000 seeds can be germinated per Month. The number 24 000 was calculated by multiplying 120 by 200, such that 120 is the total number of Modules in one Unit and 200 is the number of seedlings that can be planted in each Module.

6.3.3. Area of One Unit in the Germination Chamber

One Unit is going to occupy an area of 3.4 m^2. This was obtained by multiplying the length of one Unit (1.98 m) by its width (1.72 m).

6.3.3. Volume of One Unit in the Germination Chamber

One Unit is going to have a volume of 14.3 m^3. The latter number was obtained by multiplying the length (1.98 m), width (1.72 m), and height (4.2 m) of one single Unit. As a summary, one Unit contains 120 Modules installed in 20 Levels. One Unit has the capacity to germinate 24 000 seeds per Month (see table 6.3.).

Table 6. 3: The dimensions of one Unit in the Germination Chamber.

Length of One Unit	1.98 m	Volume of One Unit	14.3 m^3
Width of One Unit	0.72 m	Number of Modules per One Unit	120 Modules
Height of One Unit	4.2 m	Number of Levels per One Unit	20 Levels
Area of One Unit	3.4 m^2	Germinating Capacity per Month	24 000 Seedlings

6.3.4. The System in the Germination Chamber

To determine how many units can be installed in the Germination Chamber, the number of plants to be produced in the Production Area has to be determined. The calculations have been done in sub-section number **6.4.3.3.** The number was found to be 1,010,544 Plants per Month.

6.3.4.1. Calculating the Total Number of Needed Modules in the Germination Chamber

By dividing the total number of plants to be planted in the Production Chamber (1,010,544 Plants) by the total number of seedlings in one module (200 seedlings), the total number of modules needed can be calculated (5052 Modules).

6.3.4.2. The Total Number of Needed Units in the Germination Chamber

As previously mentioned in sub-section 3.4.3.3, one Unit contains 120 Modules. Thus, to install the calculated number of Modules in sub-section 6.3.4.1. (5052 Modules), the number of Units has to be determined. The latter can be done by dividing the total number of Modules in the Germination Chamber (5052 Modules) by the number of Modules in one single Unit (120 Modules). Hence, 42.1 ~ 42 Units are needed to be installed in the germination Chamber to achieve successful and uninterrupted production of the 1,010,544 Seeds per Month in One Floor of the Production Chamber.

6.3.5. The Arrangement of Units in the Germination Chamber

As it is going to be explained in the following sections, the overall footprint of the Production Chamber will be 1500 m^2 with a length of 137 m and a width of 10.95 m. Therefore, since the Germination Chamber will be constructed below the Production Chamber it is better to organize the Units of the Germination Chamber in a way that can fit in the same area (1500 m^2). Each Unit in the Germination Chamber will have the height of 1.95 m, the width of 1.72 m, and the height of 1.95 m.

To evaluate how many units can fit along the length of the facility (Vertical Configuration), the length of the Production Chamber (137 m) was divided by the length of the one Unit in the Germination Chamber (1.98 m). The result is 69 Units.

To evaluate how many units can fit along the width of the facility (Horizontal Configuration), the width of the Production Chamber (10.95 m) was divided by the width of one Unit in the germination Chamber (1.72 m). The result is 6.3 ~ 6 Units.

Therefore, since only 42 Units in the Germination Chamber are needed to supply seedlings for one System in the Production chamber, more Units can be installed in the Germination chamber allowing for an increased seedling germination capacity.

Thus, in an area of 1500 m^2, a Germination Chamber full of Units can hold up to 1,035 Units (69 Vertically installed Units * 6 Horizontally installed Units) and can germinate as much as 24,840,000 seeds per Month (1,035 Units per System * 120 Modules per Unit * 200 Seedlings per one Module).

The total number of Modules in One Floor of the Facility is 124,200 Modules. The latter can be determined by multiplying the number of Units in One Floor (1035 Units), by the number of Modules per One Unit (120 Modules).

The total number of Levels in One Floor of the Facility is 20,700 Levels. The latter can be determined by multiplying the number of Levels in One Unit (20 Levels), by the number of Units per One System (120 Modules).

Table 6. 4: The dimensions of one System in one Floor of any Germination Chamber.

Length of One System	137 m	Seed Capacity of One System per Month	24,840,000 Seedlings
Width of One System	10.95 m	Number of Modules per One System	124,200 Modules
Height of One System	1.95 m	Number of Levels per One System	20,700 Levels
Area of One System	1500 m^2	Number of Units per One System	1,035 Units

6.4. Design of Plant Production Chamber

Similar to section 6.3, there are several important terms that must be understood before continuing with reading section 6.4.

First, one Module is going to have the shape of a hexagonal prism. It will be defined as the sum of the container used in the Production Chamber, the light emitting LED situated above it, and the aeration pipes.

Second, a Unit is defined as a single stack of many horizontally and vertically installed Modules. The structure of one Unit in the Production Chamber will resemble a honeycomb-like configuration.

Third, a System is defined as the sum of all Units that will be installed in one Floor of the whole facility.

In this section, the author's proposed hydroponic system in this paper has been dimensionally compared to a hypothetical NFT system that has been proposed to be constructed in Qatar by Nik-Othman Abdullah (2016). The production capacity of the system as well as the overall area and volume footprint of every Module, Unit, and the overall Production System are inclusive in the comparison process of the two proposed hydroponic systems.

The design of the Production Area will incorporate a novel system that resembles a honeycomb-like configuration. This configuration has been found to increase the production capacity of one Floor of the Whole Facility when compared to other systems, although the author's proposed System occupies the same area as that of the other hydroponic systems. The proposed System will be installed in what will be called the Production Chamber.

It is recommended that the Production Chamber be located above the ground and above the floor where nutrient filled tanks will be installed.

6.4.1. The Module in the Production Chamber

One Module in the Production Chamber will have the shape of a hexagonal prism.

6.4.1.1. The Design of the Module in the Production Chamber

The length of the hexagonal prism Module will be 0.84 m.

To calculate the height of the Module, the length of the side has to be determined. So, the side was given a value of 0.33 m. Therefore, the height can be determined by using the following formula:

$h = (\sqrt{3}) * s$

After substituting the length of one side, the height of the Module would be 0.571 m.

Therefore, the hexagonal prism will have the following dimensions: a length of 0.84 m, a height of 0.571 m, and a side of 0.33 m (see figures 6.6. and 6.7.) (see table 6.5.).

6.4.1.2. The Container in the Production Chamber

The Module will incorporate four 0.84 m long, 0.07 m wide, and 0.1 m high containers for the production of plants. The containers will be installed 0.175 m apart from each other (see figures 6.8. and 6.9.) (see table 6.6.).

Moreover, three straps of light emitting Red-Blue-Spectrum LED light will be placed in an isosceles triangle configuration above the container. Also, an aeration system will be placed alongside the lighting system to aerate and circulate the air in every Module in the Production Chamber.

It should be noted that the total height of the Module, 0.571 m, include the height at which both the lighting and aeration systems are installed at.

The containers are going to be placed on top of a small rail. This rail would allow growers to extend the containers during the transplantation of the seedlings and the cultivation of the plants. The rails should have the same length as the Module, 0.84 m.

Since the containers are going to be moved on a rail, their extension might leak some water to the Module, which could promote uncontrolled algae and bacterial growth. Therefore, a food-grade flexible and retractable pipe, similar to the washbowl plastic and flexible sink basin water drain pipe, is going to be used. This pipe would connect the pluming from which the nutrient solutions are fed through and the containers themselves. The flexible retractable pipe should have a length of 1 m and it should be installed at an inclined angle to prevent inefficient supply of nutrient solution to the containers.

On top of the container, the hydroponic growth bed which have a length of 0.84 m, a width of 0.07 m, and a height of 0.01 m, will be mounted. The hydroponic growth bed will contain 6 holes for the production of plants. The holes located at the boundaries of the plastic block should be made 1 cm away from the boundaries. However, the 6 holes should be made vertically 0.1 m apart from each other.

As a summary, one Module in the proposed hydroponic system contains four 0.84 m long, 0.07 m wide, and 0.1 m high Containers with the capacity to produce 24 plants.

6.4.1.3. The Area of the Hexagonal Prism (The Module)

This configuration will allow growers to produce 6 plants in a Module that has an area of 0.2829 m^2. The latter number was obtained with the following equation:

Area (Hexagonal Prism) = $\left[(S^2)\left(3\sqrt{3}\right)\right]/2$. Such that, 1 side of hexagonal prism has a value of 0.33 m.

Table 6. 5: The dimensions of the Module's components in the Production Chamber.

Length of Container	0.84 m	Length of the Rails	0.84 m
Width of Container	0.07 m	Length of Growth Bed	0.84 m
Height of Container	0.1 m	Width of Growth Bed	0.07 m
Number of Containers in One Module	4 Containers	Height of Growth Bed	001 m
Length of Retractable Pipes	1 m	Production Capacity	24 Plants

6.4.1.4. The Volume of the Hexagonal Prism (The Module)

The Module is going to have a volume of 0.1615 m^3. This number was obtained by using the following equation:

Volume (Hexagonal Prism) = $\left[(h)(S^2)\left(3\sqrt{3}\right)\right]/2$

Such that the hexagonal prism has a side of 0.33 m and a height of 0.571 m.

6.4.1.5. A Comparison Between the Hexagonal Hydroponic System and a NFT Hydroponic system

Furthermore, Nik-Othman Abdullah had proposed another NFT hydroponic system composed of individual Modules that have the following dimensions: a length of 1.542 m, a width of 0.228 m, and a height of 1.625 m.

Therefore, by multiplying the width, 0.228 m, by the length, 1.542 m, the area can be determined, 0.347 m^2. Nevertheless, by multiplying the length, 1.542 m, by the width, 0.228 m, and height, 1.625, the volume of one Module can be determined, 0.564 m^3.

The proposed Module in this paper has an area of 0.2829 m^2 and a volume of 0.1615 m^3 which are smaller than those of Nik-Othman Abdullah's (2016) proposed hydroponic system, 0.347 m^2 and 0.564 m^3 respectively.

Thus, more Modules can be fitted in the same area and more modules can be stacked on top of each other. This results in better exploitation of the land by decreasing the footprint of individual Modules, a noticeable decrease in costs, and a substantial increase in the overall productivity of the proposed hydroponic system.

6.4.2. The Unit in the Production Chamber

In the Production Chamber, one Unit will be composed of several stacks of modules installed in honeycomb-like configuration.

One Unit will have the width of 0.84 m. Since the width of the facility is 10.95 m, the length of One Unit will also be 10.95 m. The height of one

Since several Units are going to be installed in one Floor of the facility, there should be some vacant gap between each Unit and the other. Thus, a 1 m gap was assigned. This gap will make total width of One Unit 1.84 m instead of 0.84 m.

Using the value 1.84 m will ease the determination of the number of Units that can fit into One Floor of the Facility.

6.4.2.1. The Area of One Unit

One Unit will have a length of 10.95 m and a width of 1.84 m. The area of One Unit can be calculated by using the following formula:

Area of One Unit = Length of One Unit * Width of One Unit

Area of One Unit = 10.95 m * 1.84 m

Area of One Unit = 20.148 m^2

6.4.2.1. Fitting Modules into the Area

It has already been mentioned that one Module occupies an area of 0.2829 m^2. Then, to determine the number of units that can fit into an area of 20.148 m^2, the following method will be used:

Number of Units that fit in 20.148 m^2 = 20.148 m^2 / 0.2829 m^2 = 71.2 ~ 71 Modules

6.4.2.2. Number of Levels in One Unit

One Module has the height of 0.571 m. Since the desired number of levels is 8, by multiplying the first, 0.571 m by the latter, 8 m, the height can be determined, 4.568 m.

6.4.2.3. The Volume of One Unit

One Unit will have a length of 10.95 m, a width of 1.84 m, and a height of 4.568 m. The volume of One Unit can be calculated by using the following formula:

Volume of One Unit = Length of One Unit * Width of One Unit

Volume of One Unit = 10.95 m * 1.84 m * 4.568 m

Volume of One Unit = 92 m^3

6.4.2.4. Fitting Modules into the Volume

It has already been mentioned that one Module occupies a volume of 0.1615 m^3. Then, to determine the number of units that can fit into an area of 92 m^3, the following method will be used:

Number of Units that fit in 92 m^3 = 92 m^3 / 0.1615 m^3 = 569.6 ~ 569 Modules

6.4.2.5. Production Capacity of One Unit per Month

With taking into consideration that each Module can produce 24 plants, the total number of produced plants per Unit can be estimated to be 13,656 plants per Month. The latter number was obtained by multiplying the number of Modules in one Unit (569 Modules) by the number of holes in each module (24 Holes) (see table 6.7.).

Length of One Unit	10.95 m	Volume of One Unit	92 m^3
Width of One Unit	1.84 m	Number of Modules per One Unit	569 Modules
Height of One Unit	4.568 m	Number of Levels per One Unit	8 Levels
Area of One Unit	20.148 m^2	Production Capacity per Month	13,656 Plants

Table 6. 6: The dimensions of a Unit in the Production Chamber.

6.4.3. The System in the Production Chamber

The system is going to be composed of many units that will be installed in one Floor of the entire facility.

The dimensions and parameters of one Unit that have been earlier recorded are a height of 1.8 m, a width of 1.84 m, a length of 10.95 m, an area of 20.148 m^2, and a volume of 92 m^3.

6.4.3.1. Area of One System

One System will have a length of 137 m and a width of 10.95 m. Therefore, it will occupy an area of 1500 m^2

6.4.3.2. The Total Number of Needed Units in the Production Chamber

Since the total area of the whole facility is 1500 m^2, the number of units that can fit into the System can be calculated by dividing the total area of the System (1500 m^2) by the New Area (20.148 m^2). The result is going to be 74 Units. This evaluation is important because it takes into consideration the 1 m Gap between every Unit and the other.

6.4.3.3. The Total Number of Needed Modules in the Production Chamber

In One Floor of the Facility, 74 Units are going to be installed. Since each Unit can hold up to 569 Modules, the total number of Modules that fit in one Floor can be determined, 42,106 Modules.

6.4.3.3. Production Capacity of One System per Month

In One Floor of the Facility, 42,106 Modules are going to be installed. Since each Module can produce 24 plants, the total number of plants that are produced by one Floor can be determined, 1,010,544 plants.

6.4.3.4. Volume of One System

One System will have a length of 137 m, a width of 10.95 m, and a height of 4.568 m. Therefore, it will occupy a volume of 6852.68 m^3.

Length of One System	137 m	Area of One System	1,500 m^2
Width of One System	10.95 m	Volume of One System	26852.68 m^3
Height of One System	4.568 m	Number of Modules per One System	42,106 Modules
Production Capacity of One System per Month	1,010,544 Plants	Number of Units per One System	74 Units

Table 6. 7: The dimensions of One System in the Production Chamber.

Germination Capacity of One Germination System per Year	298,080,000 Seeds
Production Capacity of One Production System per Year	12,126,528 Plants

Table 6. 8: Production and Germination Capacities of System per Year.

CHAPTER 7

STAGES OF PLANT PRODCUTION

7.1. Set-Points of the Environmental Parameters for the Production Chamber

In a research done at Cornell University's Closed Environment Agriculture Program, the optimum set points for the environmental parameters in the system were identified for the production of lettuce.

7.1.1. Air Temperature

It was determined that the set points for air temperature during daytime should be 24 degrees Celsius while air temperature during the night should be 19 degrees (Brechner et al., n.d.).

7.1.2. Water Temperature

The temperature of water should be maintained at 25 degrees Celsius. If the temperature of water increases above 25 degrees Celsius the water should be cooled down whereas if the temperature decreases below 25 degrees Celsius the water should be heated up (Brechner et al., n.d.).

7.1.3. Relative Humidity of the Facility

The Relative Humidity of the system should not drop below 50% and should rise above 70% (Brechner et al., n.d.).

7.1.4. Concentration of Carbon Dioxide

The concentration of Carbon Dioxide should be preserved at 1500 ppm (Brechner et al., n.d.).

7.1.5. Light Intensity

The researchers at the University of Cornell also mentioned that the configuration of the lights and light intensity should be adjusted as to provide a uniform lighting over the entire length of the growing area

(Brechner et al., n.d.). The set point for light intensity and the hourly PAR can be evaluated by using the following equation:

$$\text{Hourly PAR} = \frac{(Required\ light\ Intensity)\ \mu mol}{m^2 * s} * \frac{60\ s}{1\ min} * \frac{60\ min}{1\ hour} * \frac{1\ mol}{1 * 10^{-6}\ mol}$$

For example, if the required light intensity is 100 µmol/ (m^2 * s), the value of the Hourly PAR will be:

$$\text{Hourly PAR} = \frac{(100)\ \mu mol}{m^2 * s} * \frac{60\ s}{1\ min} * \frac{60\ min}{1\ hour} * \frac{1\ mol}{1 * 10^{-6}\ mol} = 0.36\ \frac{mol}{m^2 * s}$$

However, the optimum set-point for the system was found to be 17 µmol/ (m^2 * day) (Brechner et al., n.d.).

For 35 days, as the daily light integral of plants increased from 8 to 22 mol/ (m^2 * day), the shoot dry mass increased rapidly. Therefore, plants exposed to more illumination periods will grow faster and bigger than those grown under lesser illumination periods.

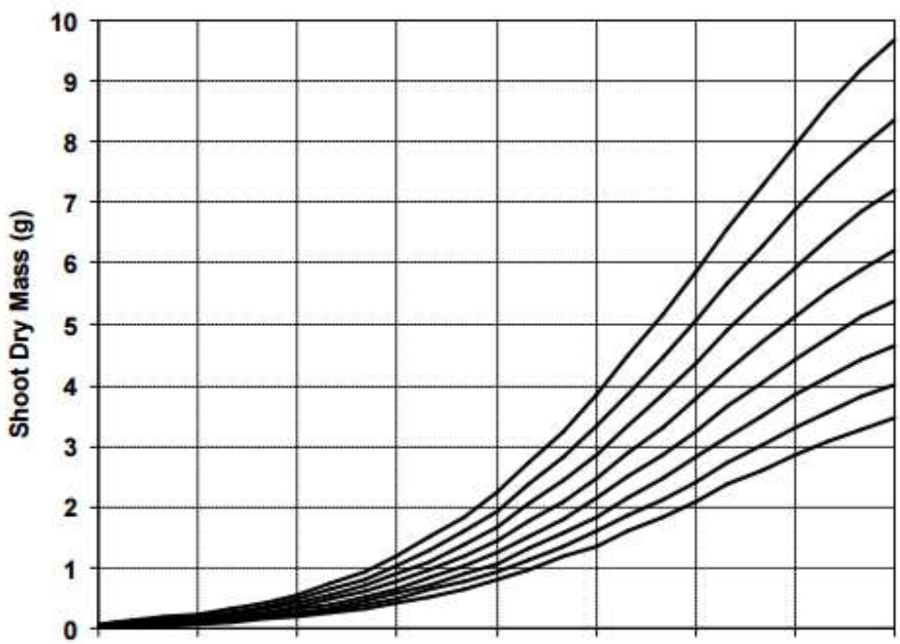

Figure 7. 1: The figure shows 8 fitted growth curves for the production of butterhead lettuce variety based on the daily integrated light level. Lettuce was grown under daily light integrals of 8, 10, 12, 14, 16, 18, 20, and 22 mol/ (m^2 * day) (from bottom to top). The duration of the production was maintained for 35 days. From "Ten Years of Hydroponic Lettuce Research," by A.J. Both, (*The State University of New Jersey,* The State University of New Jersey, n.d.; Web; 4 Dec. 2016).

7.1.6. Quantity of Dissolved Oxygen

It was determined that 7 mg/L or ppm of oxygen is optimum for the growth of plants. It was noticed that crop failure resulted from the decline of the quantity of Dissolved Oxygen below 3 ppm (Brechner et al., n.d.).

7.1.7. Optimum pH

The monitoring of pH values should be performed daily to prevent any negative effects on plant's health. The optimum value for pH was evaluated to be between 5.6 and 6 (Brechner et al., n.d.). Also, Touliatos et l. (2016) found that the optimum pH value varies between 5.6 and 6 (Touliatos et al., 2016). On one hand, if the pH drops below 5.6, it can be increased with the addition of a base such as Potassium Hydroxide (KOH) (Brechner et al., n.d.). On the other hand, if the pH grows above 5.8, it can be decreased with the addition of an acid such as Nitric Acid (Brechner et al., n.d.).

7.1.8. Optimum Electrical Conductivity

The typical optimum value for EC was evaluated to be between 1,150 and 1,250 µS/cm above the source water (Brechner et al., n.d.). However, since half-strengthened Hoagland Solution is going to be used, the EC should be maintained between 0.8 and 1.2 dS/m (Touliatos et al., 2016).

7.1.9. Nutrient Solution Composition

Developed by Hoagland and Arnon (1950), the type of the nutrient solution will be a half-strengthened Hoagland's solution. It is recommended that the nutrient solution should be replaced weekly by the growers. Regarding the composition of the nutrient solution, the values suggested by Touliatos et l. (2016) will be used. The concentration of NH4O3 was 0.5 mmol/L, the concentration of Ca(NO3)2*4H2O was 1.75 mmol/L, the concentration of KNO3 was 2.01 mmol/L, the concentration of KH2PO4 was 1.01 mmol/L, the concentration of MgSO4*7H2O was 0.5 mmol/L, the concentration of MnSO4*5H2O was 1.57 µmol/L, the concentration of H3BO3 was 11.3 µmol/L, the concertation of CuSO4*5H2O was 0.3 µmol/L, the concentration of (NH4)6 Mo7 O24*4H2O was 0.032 µmol/L, the concentration of

$ZnSO_4*7H_2O$ was 1.04 µmol/L, and the concentration NaFe EDTA was 0.25 mmol/L (see table 7.1.) (Touliatos et al., 2016).

7.1.10. Calculating the Energy Requirements

The energy demand of the LED grow light strips, water, heating systems, and cooling systems was evaluated for the proposed hydroponic system (Barbosa et al., 2015).

The assumptions made by Barbosa et al., (2015) were followed in this paper.

7.1.10.1. Calculating Energy Requirements of LED Grow Light Strips

A photoperiod o f24 hours was used for the determination of energy se of LED grow light strips. Moreover, it has been identified in Section 7.1.5. that the optimum PAR for the growth of lettuce is 17 mol/(m^2*Day). The wavelength associated with the artificial lighting system was assumed to have the value of 660 nm. For the determination of the energy demand of mole of photons for the LED grow light strips, the following equation was used (Barbosa et al., 2015):

$$E = \frac{h*c}{\gamma} * \frac{6.022*(10^{23})}{mol}$$

Such that, (E) is the energy per mole of photons in (J/mol), (h) is Plank's Constant (6.626 * 10^-34) in (J*s), (c) is the speed of light (2.998 * 10^8) in (m/s), and γ is the wavelength of light in (m). It is important to note that the energy demand of the LED grow light strips in KJ/Kg/y was calculated by using the estimated yields of the proposed hydroponic system in combination with the resulting value from the above equation (Barbosa et al., 2015).

7.1.10.2. Calculating Energy Requirements of the Pumping System

The pumping time in the Germination Chamber is different than that in the Production Chamber. Also, pumping time changes in the Germination and Production Chambers since plants require more frequent irrigation as they grow. Regarding the pumping period in the Germination Chamber, from the first day until the sixth day, the rate of irrigation was maintained at 15 minutes every 12 hours. After the sixth day and until the eleventh day, the watering was maintained for 15 minutes every 6 hours (Brechner et al., n.d.).

Regarding the watering of plants after transplantation which takes place on the eleventh day, the pumps in the Production Chamber will operate for a total period of Four hours and Thirty minutes every day. Therefore, every Four hours and Forty minutes, the pumps will operate for 54 minutes. The pump used in the Germination and Production Chambers is a German made circulation pump.

It is important to note that the estimated yields of the proposed hydroponic system were used in combination with the horse power per plant along with the average pumping time per day to create a metric in units of kJ/kg/y (Barbosa et al., 2015).

7.1.10.3. Calculating Energy Requirements of the Pumping System

The design heat load of the Germination and Production Chambers was calculated to estimate the energy required by the cooling and heating systems. A standard heat transfer equation was used for the determination of the energy demand of the cooling and heating systems (Barbosa et al., 2015):

$$Q = U * SA * (Tin – Tout)$$

Such that, (Q) is the heat lost or gained due to outside temperature in (KJ/h), (U) is the overall heat transfer coefficient in (KJ*(h^-1) *(m^-2) *(C^-1)), (SA) is the surface area of the greenhouse in (m^2), (Tin) is the inside air set point temperature in (degrees Celsius), and (Tout) I the outside air temperature in (degrees Celsius). Moreover, the heat transfer coefficient of the material used in the construction of the Module in the Germination and Production should be taken into consideration in the calculation (Barbosa et al., 2015).

It has been determined in Section 7.1.1. that the optimum set point for air temperature during the day is 24 degrees Celsius whereas the optimum set point for air temperature during the night is 19 degrees Celsius (Brechner et al., n.d.). It is important to note that the estimated yields of the proposed hydroponic system were used in combination with the final energy estimates to create a metric in units of kJ/kg/y (Barbosa et al., 2015).

7.2. Stages of the Production of Lettuce

The production of plants requires careful oversight of the plant’s germination in the Germination Chamber and their subsequent transplantation into the modules of the Production Chamber. After the Maturity of plants, they will be harvested. Moreover, post-harvest practices require the storage of the plants if they were not going to be directly sold after their harvest.

7.2.1. Germinating the Plants

The lettuce seeds will spend the first 11 days in the Germination Chamber (Brechner et al., n.d.).

7.2.1.1. Treatment of Rockwool Slabs with Nutrient Solution

For the removal of pockets of high pH contaminants, it is imperative to moisten the Rockwool slabs with a low pH (approximately 4.5) nutrient solution (Brechner et al., n.d.).

7.2.1.2. Control of Humidity

For the prevention of seeds' desiccation, the seedlings are ought to be covered on the first day with humidity to covers to maintain a high Relative Humidity environment. On the second day, all the humidity covers can be removed (Brechner et al., n.d.).

7.2.1.3. Removal of Double Seedlings

There might be a growth of more than one seedling per hole. Therefore, to prevent the suppression of growth of neighboring plants, it is recommended that double seedlings be removed on the third and fourth days (Brechner et al., n.d.).

7.2.1.4. Intensity of Light

During the first 24 hours after their sowing on the Rockwool slabs, a light intensity of 50 µmol/ (m^2 * s) should be maintained in the Germination Chamber. It has been evident that under the aforementioned value of light intensity, the stretching of seedlings was prevented as well as the drying out of the surface of the medium was minimized. Later on, and for the rest of the 10 days, a 250 µmol/ (m^2 * s) light intensity should be maintained. During the nursery of seedlings in the Germination Chamber (the first 11 days), the photoperiod, known also as the length of the day, will be taken as 24 hours. This means that per day, plants will be exposed to 21.6 mol/ (m^2 * day) of light (Brechner et al., n.d.). It should be noted that photoperiods of less than 24 hours can be maintained as long as the intensity of light is increased to provide the required quantity of daily light exposure, 22 mol/ (m^2 * day) (Brechner et al., n.d.).

7.2.1.5. Irrigation of the Seedlings

For the first 12 hours after sowing the seeds on the Rockwool slabs, the containers will be irrigated for 15 minutes every 12 hours. Likewise, the irrigation will continue at a fixed rate of 15 minutes every 12 hours until the sixth day. After the sixth day, seedlings will require more frequent watering. Thus, the pumps will be adjusted to pump water for 15 minutes every six hours. The latter rate will be maintained until the eleventh day (Brechner et al., n.d.).

7.2.1.6. Maintenance of Temperature

For the first day, the temperature will be fixed at 20 degrees Celsius However, for the remainder of the Germination Period, the temperature will be raised and fixed at 25 degrees Celsius (Brechner et al., n.d.).

7.2.1.7. The Values of pH and EC

The EC of the water is maintained at 1200 µS/cm 1 above source water EC. The pH of the solution is adjusted to 5.8 with possible addition of a base, potassium hydroxide (KOH) and nitric acid when it is too high.

7.2.2. Transplanting and Maturity of the Plants

The environmental parameters mentioned in section 7.1 will be maintained throughout the production period of lettuce. The seedlings are going to be transplanted into the Modules of the Production Chamber on the eleventh day. They will be given a period of 24 days to fully grow before being harvested. It is important to transplant the plants when the irrigation system has stopped working to prevent their desiccation during the transfer process (Brechner et al., n.d.).

7.2.2.1. Irrigation of the Plants

After the eleventh day, transplantation takes place. Then, the watering of plants has to be adjusted to accelerate the growth of plants by providing them more nutrients to develop shoot and roots. It has been estimated before in Section 7.1.10.2. that the pumps in the Production Chamber will operate for a total period of Four hours and Thirty minutes every day making the total period in which the pumps will operate equal to 54 minutes every Four hours and Forty minutes.

7.2.3. Harvesting the Plants

Harvesting the lettuce plants can be done on the thirty fifth day after sowing the seeds on the Rockwool slabs in the Germination Chamber (Brechner et al., n.d.).

7.2.4. Post-Harvest Practices

The equipment that were in direct contact with the plants are going to sterilized and cleaned after every growing cycle with a weak 2% bleach solution. Unlike soil-based agriculture, there is no need to clean the lettuce plants because their root has been in direct contact with water during the production process. Therefore, it is possible to package hydroponically-grown directly after their harvest before transporting or shipping them to consumers. Any food-grade and food-safe packaging material can be used. In case the lettuce was not going to be transported to consumers directly after harvest, it is recommended to store the lettuce plants under a temperature of 4.4 degrees Celsius (Brechner et al., n.d.).

CHAPTER 8
CYPRUS AS A CASE STUDY

8.1. Exposure to Long Sunlight Hours

The island of Cyprus experience sunny days throughout the year with few cloudy days. Throughout January to June, the average monthly sunhours increase from approximately 180 hours to 380 hours. Then, the average monthly sunhours reaches its peak in July with 400 hours. Finally, the average monthly sunhours declines throughout August to December from approximately 380 hours to 179 hours. Therefore, by installing solar panels on the exterior walls of the Facility, high power outputs can be generated throughout the year. Finally, by using the data supplemented in figure 10.1. the total amount of sunlight hours per year can be estimated to have a value of 3,380 hours.

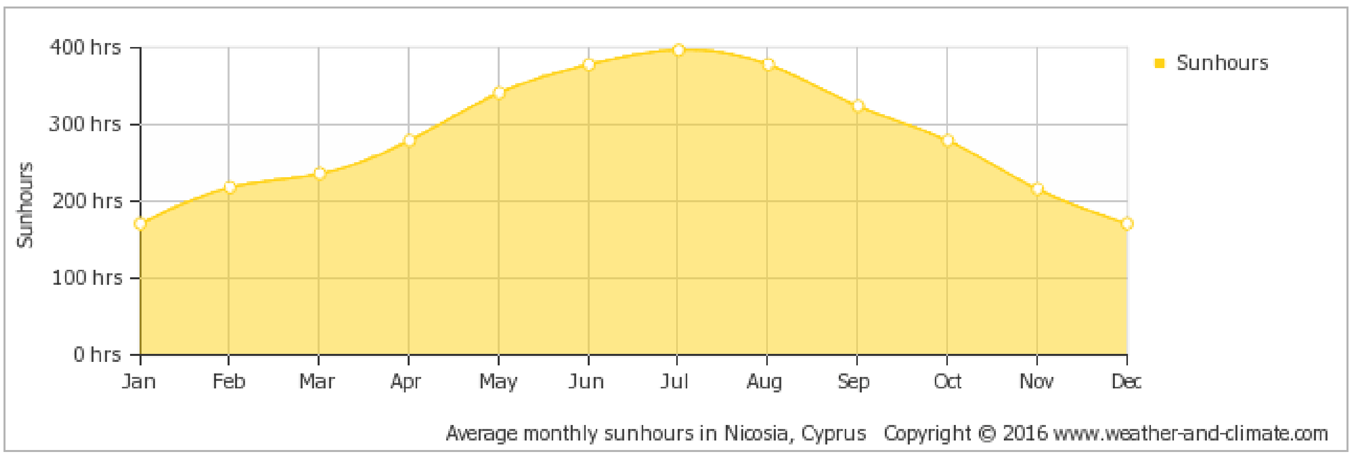

Figure 8. 1: The figure depicts the average monthly sunlight hours for Nicosia, the island of Cyprus. The units are in hours. The figure depicts the average monthly sunlight hours for Nicosia, the island of Cyprus. The units are in hours. (AVERAGE MONTHLY WEATHER IN NICOSIA, CYPRUS," by World Weather and Climate Information, (*World Weather and Climate Information* World Weather and Climate Information, n.d.; Web; 8 Dec. 2016).

8.2. Prospects for Conserving Water in Cyprus

8.2.1. Precipitation in Nicosia

Water is a scarce source on the island of Cyprus. For the past few decades, the island was falling short of both surface water and groundwater as result of inadequate snow and rainfall (Wikipedia, 2016). Therefore, hydroponic plant production systems which use water efficiently can decrease the irrigation requirements, subsequently conserving water and decreasing water consumption. In fact, hydroponic plant production systems can use 95% less water than conventional agricultural techniques (Return to Chapter 3, Section 3.3.5.). The average monthly precipitation of snow and rainfall decreases from 49 mm in January to few millimeters in July. Then the average monthly precipitation increases to 58 mm to reach its peak in the month of December (see figure 10.2.).

Moreover, due to the geographical location of the island of Cyprus, the island experiences few rainy days throughout the year with the sole exception of the month of December. The average monthly rainy days decrease from 10 to 1 day from January to June. Then, the average monthly rainy days continue to be the same throughout June to August. Finally, the average monthly rainy days increases from 5 days in September to 30 days peaking in the month of December.

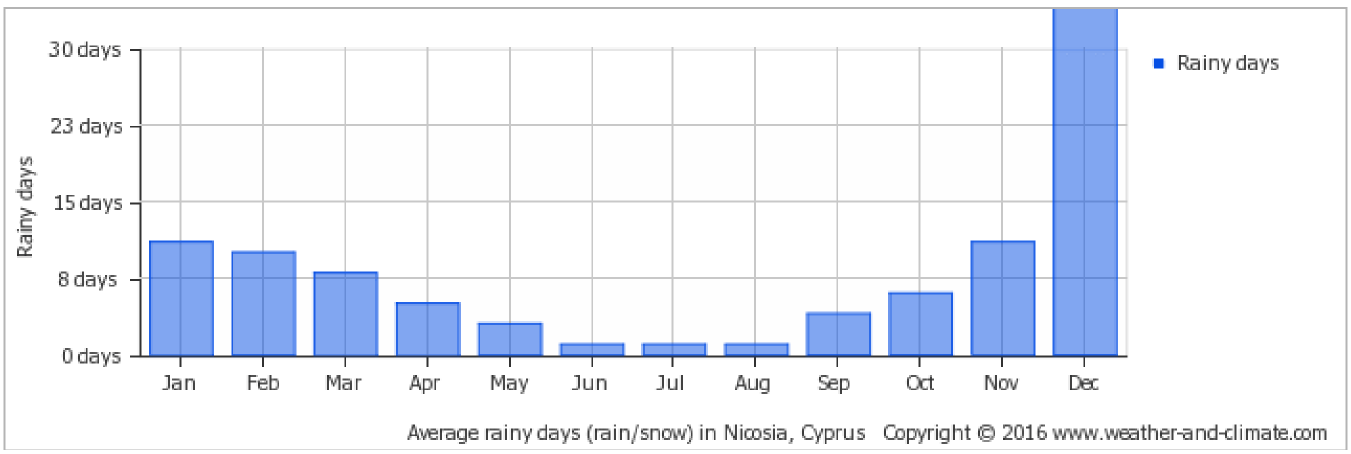

Figure 8. 2 The figure depicts the average monthly rainy days in Nicosia, the island of Cyprus. The units are in days. From (AVERAGE MONTHLY RAINY DAYS IN NICOSIA," by World Weather and Climate Information, (*World Weather and Climate Information*, World Weather and Climate Information, n.d.; Web; 12 Dec. 2016).

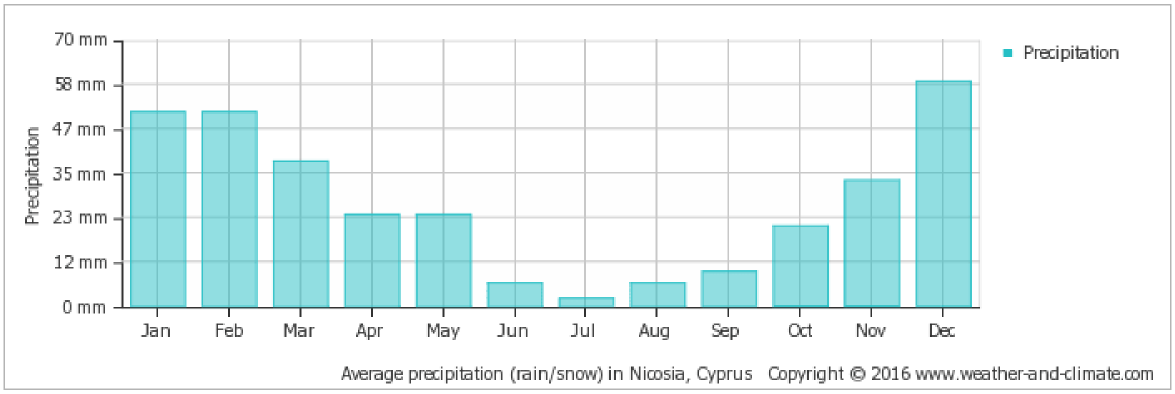

Figure 8. 3: The figure depicts the average monthly snow and rainfall for Nicosia, the island of Cyprus. The units are in millimeters. The figure depicts the average monthly snow and rainfall for Nicosia, the island of Cyprus. The units are in millimeters. (AVERAGE MONTHLY SNOW AND RAINFALL IN NICOSIA (MILLIMETER)," by World Weather and Climate Information, (*World Weather and Climate Information,* World Weather and Climate Information, n.d.; Web; 12 Dec. 2016).

8.3. Temperature in Cyprus (Relevant to the Heat Transfer Calculations)

The temperature in Cyprus is considered to be moderate in comparison to the surrounding countries. The average monthly maximum temperature increases from 16 degrees Celsius in January to 36 degrees Celsius in July. The average monthly maximum temperature then remains steady throughout July and august then decreases to 19 degrees Celsius in December. Similarly, the average monthly minimum temperature increases from 5 degrees Celsius in January to 21 degrees Celsius in July. The average monthly maximum temperature then remains steady throughout July and august then decreases to 8 degrees Celsius in December.

Since the optimum growth temperature for lettuce is 24 degrees Celsius during the day, it is going to be necessary to activate heating system from January to March in order to increase the inside temperature of the Facility. However, throughout April, the outside temperature during the day varies closely around 24 degrees Celsius. Henceforth, there is no need to activate either the heating or cooling systems during the day. Nonetheless, May to October the temperature rises above 24 degrees Celsius. Then, it is important to activate the cooling system to decrease the interior's temperature. Finally, throughout November and December, the temperature drops below 24 degrees Celsius, necessitating the need to activate the heating system to increase the temperature to 24 degrees Celsius.

Furthermore, since the optimum growth temperature for lettuce is 19 degrees Celsius during the night, it is going to be necessary to activate heating system from January to May in order to increase the inside temperature of the Facility. However, thorough June to September, the outside temperature during the night varies closely around 19 degrees Celsius. Henceforth, there is no need to activate either the heating or cooling systems during the night. Nonetheless, from October to December the temperature drops below 19 degrees Celsius. Then, it is important to activate the heating system to increase the interior's temperature.

8.2.2. North Cyprus Water Supply Project

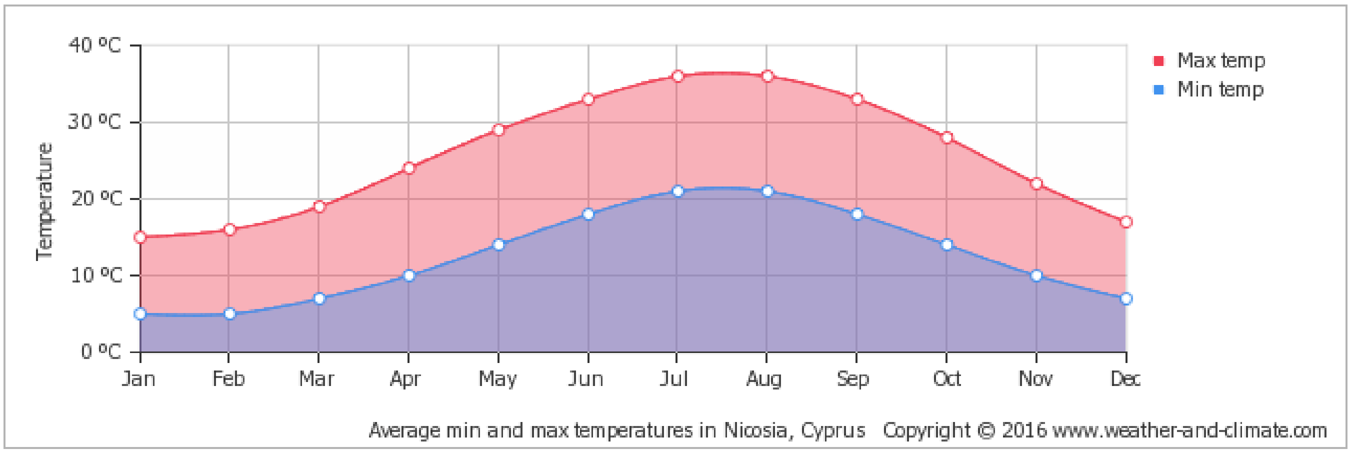

Figure 8. 5: The figure depicts the average minimum and maximum temperatures in Nicosia, the island of Cyprus. The units are in degrees Celsius. From (AVERAGE MONTHLY RAINY DAYS IN NICOSIA," by World Weather and Climate Information, (*World Weather and Climate Information*, World Weather and Climate Information, n.d.; Web; 16 Dec. 2016).

The North Cyprus Water Supply Project is a water diversion project that will that will supply water to Geçitköy Dam and Reservoir in TRNC from Alaköprü Dam in Mersin Province, Turkey. The 1.2 Billion Turkish Lira project whose construction started in 2011 was inaugurated on August 7, 2015. The project will annually supply 75 million cubic meters of fresh and pure drinking water that will be used in agriculture, industry, and daily use for the next 30 years (Wikipedia, 2016; North Cyprus International, 2015; Daily News, 2015).

Since fresh and drinking water is a valuable resource, the proposed hydroponic system in this project can potentially enhance the conservation of this indispensable resource. In hydroponics, the water is recycled and reused throughout the system. The nutrient solutions are only drained off once the values of electrical conductivity and pH are deemed to be exceedingly toxic for the plants.

CHAPTER 9

GENERAL CONCLUSION

This report has discussed conventional agriculture, hydroponic production systems. The author has proposed a new multi-floor hexagonal design for the production of lettuce Oscarde. The methodology for the production which include the germination and the transplantation of lettuce Oscarde has been discussed. In the latter discussion, several parameters were identified and the optimum values required for the production of lettuce Oscarde were determined. The hexagonal design of the hydroponic system was shown to improve the productivity and efficiency of plant production. For example, less water was used, the nutrient solution was recycled throughout the system, no pesticides or insecticides were used, and amplified yields were recorded as compared to conventional agriculture, as has been shown in the various recorded literature. The simple design has shown to be cost effective, reducing further the costs of construction and operational costs. The utilization of hydroponic-related accessories and supplementary materials such as plastic containers could even make the project more affordable and an even more attractive investment for small and medium-sized businesses. Finally, the benefits of using the proposed hydroponic system including accelerated growth and enhanced health of plants positively improves the productivity of the proposed hydroponic system.

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