

Floating Hydroponic and Drip-irrigated Soil Growing Methods: A Comparative Study of Sustainability

By: Nazli Shahzamani

Supervisor: Dr. Laurent Mesbah

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Faculty of Science
Baha'i Institute for Higher Education (BIHE)**

Abstract

We are headed for global food security crisis in the coming years. Increasing population and the level of consumption on one hand, and the overarching effects of climate change on the other are leading the system towards unsustainability in food production. Adoption of unsustainable agricultural practices to produce more and more food for a rising world population are degrading land, water, and biodiversity on a global scale. The situation is worst in Middle East. Food had been the Achilles' heel of many earlier civilizations and the same would apply to our time unless we adapt our practices accordingly. Shortage of suitable land and the insufficiency of renewable water resources, make it inevitable to shift towards climate-smart growing methods and technologies. To effectively address the region's unique challenges, technical changes should be accompanied by favorable economic and political reforms. In Iran, the combination of technocratic populism, hostile external policy and unstable national economic policies, have impeded potentials, both at the government and farmer levels, to invest in sustainable agricultural practices. Within this context, floating hydroponic and drip-irrigated soil growing methods were investigated and compared against a set of economic and environmental criteria to suggest the system that can provide a more suitable balanced mixture of economic and environmental benefits. The economic evaluation entailed plant growth, yield, plant survival, and production cost, while the environmental assessment focused on water consumption, electricity consumption, and fertilizer consumption. Drip-irrigated soil method proved to be the better alternative, supported by its lower production cost and its ability to achieve higher environmental efficiency in terms of total water consumption (3.8 times lower), as well as electricity and fertilizer consumption.

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List of Abbreviations

WP: Water Productivity

DWC: Deep-water Culture

NFT: Nutrient Film Technique

GH(s): Soil-based Greenhouse Horticulture

GH(h): Hydroponic Greenhouse Horticulture

FS: Floating System

SC: Soil Culture

PC: Substrate Culture

OF: Open-field Farming

WUE: Water Use Efficiency

SC: Soil Cultivation

LCA: Life Cycle Assessment

DLR: Direct Leachate Recycling

CP: Chemical Precipitation

MF: Membrane Filtration

CWP: Crop Water Productivity

PH: Plant Height

CD: Crown Diameter

ANOVA: Analysis of Variance

HWS: Hydroponic Waste Solution

CEA: Controlled Environment Agriculture

TSR: Targeted Subsidy Reform

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Chapter 1: Introduction

We are headed for global food security crisis and shortage of food as well as higher prices will be expected in the coming years (Brown, 2012; Gashgari et al., 2018). Accelerating positive feedback loops are exacerbating the upcoming crisis. Increasing population and the level of food consumption on one hand, and the overarching effects of climate change on the other are leading the system towards unsustainability in food production (Mesgaran et al., 2017).

Expansion of unsustainable agricultural practices to produce more and more food for a rising world population are degrading land, water, biodiversity and climate on a global scale (Foley et al., 2011). Similarly, climate change has been taking its toll on agricultural sector through warmer temperature, decrease in diurnal temperature range, heat waves, droughts, increased pest population, water shortages, shorter and more intense periods of rainfall and its accompanying soil erosion on low-quality land (Lawrence et al., 2017; Battisti et al., 2009).

The situation is worst in Middle East. Food had been the Achilles' heel of many earlier civilizations in this region (Diamond, 2004) and the same applies for our time unless we can adapt more sustainable practices. Lacking sufficient renewable water resources and shortage of suitable land in the region (Mesgaran et al., 2017; FAO, 2002) make it crucial to make climate-smart agricultural adaptations, such as agroecology, organic farming, reduced tillage, precision agriculture, agroforestry and protected agriculture (Dahl, 1990).

In this study, drip-irrigated soil-based growing method and floating hydroponic method will be investigated and compared against a set of economic and environmental criteria to provide the most suitable option for vegetable production considering the current socio-economic

landscape as well as natural resource availability in the context of Iran. Both of these methods have proven to be resource efficient and offer solutions to growers in locations facing water scarcity and fertile land shortages, such as arid and urban areas. The main goal is to apply a more holistic approach which takes into consideration an integrated account of economic and environmental criteria.

Drip-irrigation and hydroponic methods have gained popularity in Iran, showing significant increase in the cultivation areas of drip-irrigated and vegetable hydroponics. The claim is that it provides a more sustainable alternative conducive to produces that requires less water, less fertilizer and pesticide, and less growing time in comparison to conventional soil-based growing systems. Numerous literatures could be found to back this claim; however, the aim of this research is to evaluate if any of these methods would show a higher suitability in the Iranian context by comparing the efficiency and sustainability of floating hydroponic to drip-irrigated soil-based systems.

Devouring the country natural resources, pouring them into large-scale construction projects that has weaken our natural capital base, coupled with corruption and lack of consideration for national benefits in external policy, has led to a situation of economic bankruptcy, that the farmers and government potential to invest in agricultural efficiency has been lowered down while at the same time the wrong policies and incorrect subsidies has unincentivized farmers to factor in natural resource conservation while planning for the growing methods and plantation systems. It is in light of this complex economic and socio-political backdrop that the most suitable alternative will be advised.

Background and significance

Located in an arid and semi-arid region and suffering from years of water mismanagement, Iran is experiencing unprecedented water shortage problem and about 92% of water consumption in this country is used in agriculture to produce food (Mesgaran et al., 2017; McCartney & Lefsrud, 2018).

Marginal agricultural lands and other lower quality lands comprises about 50% of existing croplands in Iran. Widespread land degradation and desertification resulting from unsustainable agricultural practices in low-quality lands are also making it more difficult to expand production and will further lower down the agricultural capacity of the country in the long run (Mesgaran et al., 2017).

This already serious situation will almost certainly get worse by climate change. While not getting any close to the ambitious plan of achieving food self-sufficiency during the last four decades, in light of the environmental crisis we face and unsuitability of more than 90% of surface soil in Iran (Mesgaran et al., 2017), there isn't any chance for allocating more lands to combat upcoming food crisis. A portion of endeavors should be focused on alternative systems that allow sustainable intensification of agricultural practices (Tilman et al., 2011). Within the landscape of the economic and socio-spatial circumstances of Iran, two growing methods, namely drip-irrigated soil-based and floating hydroponics, will be compared from an economic and environmental perspective in order to suggest a more sustainable alternative to meet the current and near future food production needs.

Hydroponic systems could be an alternative solution in urban areas and regions lacking fertile soil, as being independent on soil for producing food (Barbosa et al., 2015; Zhang et al., 2019; Sanye- Mengual et al., 2015). It could be defined as “the science of growing plants without the use of soil, but by use of an inert medium to which is added a nutrient solution containing all the essential elements needed by the plant for its normal growth and development” (Jones, 2014).

Water use efficiency will be better satisfied in all forms drip-irrigated soil-based and hydroponic agriculture (Mesgaran et al., 2017). Higher water efficiencies, lower levels of pest damage and the accompanying elimination or significantly reduction of pesticide and herbicide use in comparison to field crops, are all the leading cause of the efficiency and suitability of these systems. High production per square meter in hydroponic and drip-irrigated systems in comparison to field farming allow those who are willing to get into this business to begin with minimal land and start-up cost (Freedgood & Dempsey, 2014).

Taking into account all these benefits, this study tried to approach a holistic evaluation. Most Studies have been focused on only one or a limited number of criteria which restrict proper contextual decision-making. “The great failings in the application of science to human well-being have come about not because of the failure to know the details of the structure or workings of something but rather because of the failure to examine the system in its complexity” (Levins, 1986).

“Besides, given the environmental, social and economic challenges for each site, opinions about the importance of various trade-offs will inevitably differ (Allen et al, 2019). In a business context, productivity and yield might outweigh the importance of preserving natural resources and the health of ecosystem; When it comes to sustaining food production activities in proximity to

environmentally vulnerable areas, the preservation of natural resources and the health of the ecosystems take on higher importance. A study that assigns varying weights to the scores based on the relative importance of each criterion for a specific site can provide insights into which system would be more suitable for different projects.

While considering as many aspects as possible in comparative studies can provide a more comprehensive understanding of the strengths and weaknesses of each system, there are some limitations to this approach. Cultivation systems are complex and multifaceted and there are many variables that can affect their performance. Hydroponic and soil-based systems both involve a range of interacting factors, such as the physical properties of the growing medium, nutrient availability, water quality and quantity, temperature, humidity, and light intensity. The performance of each system can be influenced by the interactions between these variables, as well as by management practices such as pruning, fertilization, and pest management. The complexity of each system can also vary depending on the crop being grown. Different crops have different requirements for nutrients, water, and light, and different susceptibilities to pests and diseases.

Because of this complexity, comparing hydroponic and soil systems from multiple aspects can be challenging and the findings might not be applicable to all projects or be valid for all regions. Researchers and growers must consider a wide range of context-specific variables and interactions to develop accurate and meaningful comparisons. They may need to conduct experiments in different growing conditions or with different crops to fully understand how each system performs under different circumstances.

Despite the challenges posed by the complexity of these systems, addressing it can help growers and researchers make more informed decisions about which growing method is best

suited for their specific needs and goals. Future researches can be more focused on understanding the complexities of each system in order to provide advice and suggestions for growers on how they can optimize their management practices and identify areas for improvement to maximize crop yield, quality, and sustainability.

Objectives

General objective

The main goal of this study is to conduct a holistic comparison of two growing methods, namely floating hydroponics and drip-irrigated soil, against a set of economic and environmental criteria for growing vegetables, lettuce in particular.

Specific objectives

To compare plant growth, yield, and survival rate between drip-irrigated soil-based and floating hydroponic systems in open-field growing condition.

To compare production cost between the two systems.

To compare water consumption, energy demand, and fertilizer consumption between the two systems.

Research question

To compare floating hydroponic and drip-irrigated soil growing methods in order to suggest the more economically and environmentally sustainable option for growing vegetables, lettuce in particular.

Chapter 2: Literature Review

Natural Resources and Agriculture

Located in an arid and semi-arid region, the scarcity of freshwater resource has been the reality of Iran for eons (Chardin, 2010). The average annual precipitation for the country is 228 mm which is less than one third of the global average (FAO Aquastat Database, 2022(a)). There's no uniformity in spatial-temporal distribution of this amount in a way that some areas receive less than 50 mm of annual precipitation, while the northern parts of the country receive a slightly more than the global average annual precipitation; about two-thirds of this amount evaporates before it reaches the surface freshwaters or ground water reservoirs (Azadbakht & Noruzi, 2008).

Suffering from years of water mismanagement, the country is experiencing unprecedented water shortage problem and about 92% of water consumption (more than 70% of the global average) is used in agriculture to produce food (Mesgaran et al., 2017; McCartney & Lefsrud, 2018; FAO Aquastat Database, 2022(b)). As quantity and distribution of precipitation varies considerably across the country, groundwater is one of the most reliable sources of water and it has massively intertwined with food security (Ashraf et al., 2021). In research published in April 2021, Ashraf and her colleagues relate the massive depletion in groundwater storage mainly to extensive human water withdrawals, particularly, to support the growing demand for agriculture. The number of registered wells has increased from ~45,000-50,000 in the 1970s to ~794,000 in 2015, while the unregistered wells thought to equal one-third of the registered figure (Ashraf et al., 2021; Michel, 2017). Iran aquifers cannot sustain such demand and without a serious shift, there will be major concerns for maintaining irrigated agriculture; no need to mention the

irreversible impacts on land and environment, including the nationwide growing salinity and more than 98% land subsidence to name a few (Negahdari, 2022).

Available renewable surface water supplies, including rivers and lakes, have all been already exhausted and the level of withdrawals exceeded available resources. Decades of unsustainable water use has dried up lakes throughout the country (AghaKouchak et al., 2015; Esandari et al., 2013). Iran's technocratic hydraulic mission, embodied by dams and interbasin transfers, has dried up the whole Iranian Plateau and diverted every ounce of the available freshwater to unsustainable and inefficient agricultural, industrial and domestic practices (Akhani, 2021). In other words, not only there will be no room for more irrigated conventional agricultural expansion in the future but also skewing perceptions of water availability, has led the country to the brink of a socio-economic water bankruptcy, "where water demand has exceeded the natural water supply" (Madani et al., 2016).

Marginal agricultural lands and other lower quality lands comprises about 50% of existing croplands in Iran. Widespread land degradation and desertification resulting from intensifying water stress and unsustainable agricultural practices in low-quality lands are also making it more difficult to expand production and will further lower down the agricultural capacity of the country in the long run (Mesgaran et al., 2017; Michel, 2017).

This already serious situation will almost certainly get worse by climate change. Higher temperatures predicted by IPCC (2021), will be translated to augmented water demand for irrigation, more severe droughts, soil erosion and dust storms which all reduce Iran's biocapacity for agricultural practices. In northern provinces, climate change, along with widespread land-use and land-cover change, influences soil carbon cycle in the Hyrcanian forests. Continued

production of rice and corn, two strategic and water-thirst crops which have been cultivated in the dry region of Zayande Rud basin, can be compromised under climate change due to their high irrigation water demand (Gohari et al., 2012).

The desire for self-sufficiency in essential crops, before any sustainability and productivity goals, has been manifested itself in the Five-Year National Economic, Social, and Cultural Development Plans as dual-subsidy programs to encourage both producers and consumers. In 2007, food subsidies represented 2.8 percent of the GDP which led to increased cereal production and made Iran the 12th leading producer of wheat in 2012, lifting it from the world's 16th largest producer in 1999 (FAO, 2014). Wheat and rice cultivation expanded to many regions without regard for their agroecological conditions and water availability conditions in those areas. To incentivize the process even further the government also heavily subsidizes agricultural water use and electricity and fuel prices. Cheap electricity was being used to extract groundwater from wells with average depth of 90 meters, making Iran's irrigation and production efficiencies far beneath the global average (Michel, 2017; FAO, 2014)). Massive migration from rural to urban areas has been one of the implications of such an unsustainable vision and policy making. Farmers income has decreased over time due to increasing water scarcity and decreasing productivity (Madani et al., 2016).

While not getting any close to the ambitious plan of achieving food self-sufficiency during the last four decades, in light of the water shortages crisis we face and unsuitability of more than 90% of surface soil in Iran (Mesgaran et al, 2017), there isn't any chance for allocating more lands to combat upcoming food crisis. All endeavors should be focused on alternative systems and development of technologies that allow sustainable intensification of agricultural practices and rational use of water and land resources (Tilman et al., 2011).

Drip Irrigation Systems

In arid regions where water scarcity is a significant issue, the focus should be on improving irrigation efficiency. Currently, only around 37 percent of the irrigation water used worldwide is actually utilized by crops, with the remainder being lost through runoff, evaporation, and leakage (Dahlman et al., 2011). There is a potential for reducing these losses through advancements in irrigation technology. Drip irrigation is a method that precisely delivers the required amount of water directly to the roots of plants, minimizing wastage.

Drip irrigation is a type of micro-irrigation involving tubing with emitters laid on the surface or buried below the surface to deliver water to plants drop by drop. The method has been shown to be associated with increased crop yield, improved water and nutrient efficiency, eliminates the risk of disease transmission and reduced weed pressure. Compared to conventional methods, water loss through deep percolation and evaporation is greatly reduced and soil erosion and nutrient leaching are minimized (PennState Extension, 2016). “Yield gains and water savings of drip over conventional surface irrigation methods have been reported to be in the order of 11 to 97% and 13 to 514%, respectively, for several horticultural crops” (Morgan & Kadyampakeni, 2015)

Plant Growth and Yield in Drip-irrigated Soil-based Systems

Irrigation systems can have positive effect on crop yield through controlling water supplies and managing certain crop diseases and pests (Ayers et al., 1999; Megersa & Abdullahi, 2015; Michael, 2008). Irrigation systems could bring about precision and uniformity over water

application rates and distribution. Drip irrigation is claimed to have positive effects on crop productivity through enabling farmers to deliver water directly to the plant's root zone with high uniformity and avoid overwatering or underwatering, which can both negatively impact crop yield.

Using drip irrigation as opposed to more water-intensive irrigation methods, Yildirim (2000) reported a higher crop yield and more balance soil moisture in the active root zone with minimum water losses. An experiment was conducted in the eastern plateau and hill region of India to assess the benefits of drip irrigation among tribal farmers. The study compared drip irrigation with furrow irrigation for tomato, potato, cauliflower, French bean, and pea cultivation in a village in Jharkhand, India. Higher yields were reported for all vegetable crops when water was applied through drip irrigation. Drip irrigation significantly improved yields in the range of 38.2 to 65.8 % over furrow irrigation with highest yield increase in case of pea (65.8%) and tomato (58.7%). Higher net return and a 33% higher cost-benefit ratio were assessed for all vegetable crops grown under drip irrigation (Jha et al., 2017). Singh et al., (2009) reported about 55% higher fruit yield for tomato when using drip irrigation.

In modern agriculture, drip irrigation is often combined with plastic mulch to further reducing evaporation (Locascio, 2005). A field experiment was conducted over two years in Bhubaneswar, India, to assess the yield, water-use efficiency, and economic feasibility of capsicum (bell pepper) cultivation using drip and surface irrigation methods with and without black Linear Low Density Poly Ethylene (LLDPE) plastic mulch. Drip irrigation with LLDPE mulch resulted in better plant growth and a 57% increase in yield and a 54% increase in net seasonal income compared to conventional surface irrigation without mulch, with a benefit-cost

ratio of 2.01. In the absence of mulch, drip irrigation increased yield by 28% compared to surface irrigation, while LLDPE mulch alone increased yield by 13% (Paul et al., 2013).

Irrigation practices can influence crop yield by affecting the occurrence and severity of crop diseases and pests. Yield along with incidence and severity of three lettuce diseases (lettuce drop, downy mildew, and corky root) were compared in subsurface drip irrigation with furrow irrigation in a study performed in the Salinas Valley, California (Subbarao et al., 1997). Subsurface drip irrigation resulted in lower incidence and severity of lettuce drop and corky root, as well as higher yields, although there were no significant differences in the incidence and severity of downy mildew between the two irrigation methods. The microclimates created by the irrigation treatments did not seem to impact downy mildew infection significantly. Overall, the study concluded that subsurface drip irrigation is a viable long-term strategy for managing soilborne diseases in lettuce cultivation in the Salinas Valley.

The existing literature presents contrasting ideas and viewpoints as well. In a research study conducted in 2005 at the Zholube irrigation scheme in Zimbabwe to compare low-cost drip irrigation technologies with conventional surface irrigation systems in terms of water and crop productivity, the type of irrigation system did not significantly affect English giant rape (*Brassica napus*) yield; instead, the method of fertilizer application played a more significant role. The study recommended using low-cost technologies alongside effective water and nutrient management to achieve higher water and crop productivity compared to surface irrigation systems (Maisiri et al., 2005). Also, Sammis (1980) while comparing the effectiveness of trickle, subsurface, sprinkler, and furrow irrigation methods in terms of yield and water-use efficiency for potato and lettuce crops, found that differences in lettuce yields were not significant among the different irrigation methods.

Factors such as soil type, crop characteristics, climate conditions, and management practices can interact to make the differences between irrigation methods less profound. For instance, if a particular crop has a high tolerance to water stress or if the soil has good water-holding capacity, the impact of different irrigation methods on yield may be minimal. Certain crops may have physiological adaptations or root systems that enable them to extract water efficiently, making them less sensitive to variations in irrigation techniques. Moreover, all these technologies, including drip irrigation, requires understanding of the system to assure good management and maintenance. System mismanagement can lead to under irrigation, less crop yield quality reductions, and over irrigation. The last may result in poor soil aeration and deep percolation problems. Timely and consistent maintenance and repairs are therefore a requirement (Megersa & Abdullahi, 2015).

Water Consumption in Drip-irrigated Cultivation Systems

Hydroponic and soil-based drip-irrigated cultivation methods both can be efficient in terms of water usage compared to traditional soil-based methods. However, the specific water consumption in each method can vary depending on factors like crop type, system design, management practices, and environmental conditions.

Increases in the use of low-flow and more-targeted irrigation techniques could lower the overall water use of conventional farming (Barbosa et al., 2015). Israel has been at the forefront of innovation in this area, with the development of drip irrigation serving as a successful example. Despite facing challenges such as water scarcity and arid climate conditions, Israel has managed to achieve remarkable advancements and success in agriculture, thanks in large part to the

prominent role played by technologies like drip irrigation. This technique with a water efficiency rate of 70 to 80% (compared to conventional flood irrigation which achieves only 40%) are the primary method of irrigation in the country (Megersa & Abdullahi, 2015).

Drip Irrigation systems have the potential to be highly efficient in terms of water usage because of its ability to apply low volumes of water to plant roots, reduce evaporation, run off and deep percolation losses, and improve irrigation uniformity compared to traditional surface irrigation (Flood and furrow) (Megersa & Abdullahi, 2015; Sharma, 2001). Water savings of 70 to 80% compared to conventional flood irrigation methods (Megersa & Abdullahi, 2015) and up to 50% compared to sprinkler irrigation are common (Lamont et al., 2002). In widely spaced crops, a smaller fraction of the soil volume can be wetted which reduces unnecessary irrigation water losses while at the same time reduce weed germination and weed growth (Megersa & Abdullahi, 2015). Environmental problems associated with the surface method of irrigation like waterlogging and salinity are also completely absent under drip method of irrigation (Narayanamoorthy, 1997), make it a very efficient water management system in arid and semi-arid regions.

In surface irrigation systems, water moves over and across the land through simple gravity flow in order to wet and to infiltrate into the soil. Surface irrigation can be subdivided into furrow, border strip or basin irrigation. It is often called flood irrigation when the irrigation results in flooding or near flooding of the cultivated land (Megersa & Abdullahi, 2015). A research study conducted in 2005 at the Zholube irrigation scheme in Zimbabwe's semi-arid agro-tropical climate compared low-cost drip irrigation technologies with conventional surface irrigation systems in terms of water and crop productivity. The researched showed that Drip irrigation used only about 35% of the water used by surface irrigation (Maisiri et al., 2005).

In an experiment done in the eastern plateau and hill region of India to assess the benefits of drip irrigation among tribal farmers, Drip irrigation consistently demonstrated higher water productivity (WP), with more than a fivefold increase in potato and cauliflower crops. Average WP of all crops under drip and furrow method was 6.89 and 1.31 kg/ m³, respectively. The highest WP was observed in tomato (13.7 kg m⁻³) under drip irrigation. The study's findings highlight the advantages of drip irrigation, including precise water use, increased productivity, and improved financial outcomes (Jha et al., 2017). Higher yield (18-24%) and water use efficiency (35 - 103 %) of drip over furrow method has also been reported in potatoes (Ibragimov et al., 2007).

Another study aimed to compare the effectiveness of trickle, subsurface, sprinkler, and furrow irrigation methods in terms of yield and water-use efficiency for potato and lettuce crops, showed that trickle, subsurface, and sprinkler irrigation systems generally led to higher yields and water-use efficiencies compared to the conventional furrow irrigation method. The subsurface irrigation method appeared to offer the best method of supplying uniform soil moisture in the root zone throughout the growing season, resulting in highest yields and high water-use efficiencies (Sammis, 1980).

Majority of studies compare water usage of either drip irrigation and hydroponic systems with surface irrigation or conventional methods and few papers specifically compare water consumption between drip-irrigated soil-based systems and hydroponics. Going by the fact that water usage in both of these systems can vary significantly depending on several factors (e.g., system design, crop type, management practices, and environmental conditions), by solely depending on the literature, it becomes challenging to provide a definitive conclusion on which system has the lowest water usage.

Two experiments were conducted over two consecutive seasons in Egypt to compare the performance of deep-water culture (DWC) hydroponic system with drip irrigation systems in open fields and greenhouses for lettuce cultivation. DWC allowed for over 50% savings in irrigation water and mineral fertilizers compared to the farming systems using drip irrigation in both greenhouses and open fields (Hamza et al., 2022). It's worth mentioning that deep water culture (DWC) and floating systems could be very similar in terms of water usage as in both of these methods roots are submerged in a nutrient-rich water solution. Though, the actual water usage in both systems can still vary depending on factors such as crop type, environmental conditions, system design, and management practices.

Hydroponic Systems

According to Khan et al, (2018), there are two main categories of hydroponic methods:

- 1- Solution culture methods in which plants are grown directly in a nutrient-rich solution without any growing medium. In this system, nutrient solution is not circulated but provided only once when EC changes.

There are several types of solution culture methods, including:

- Root dipping method
- Floating method
- Capillary action method

- 2- Media culture method in which plants are grown in a solid growing medium e.g., sand, perlite, rockwool, or peat moss, that provides support and helps to deliver nutrients and water to the roots.

Soilless methods can further be classified into closed and open system. In closed systems, the same nutrient solution is recirculated and reuse over a period of time, providing economy in water and nutrient use and reduce environmental pollution. While in open systems, nutrient solution is delivered directly to the plant roots and excess solution is discarded (Badgery-Parker 2002; Raviv & Lieth 2008; Engindeniz & Gul, 2019).

Plant Growth and Yield in Hydroponic Systems

Many studies proven that the potential yield with hydroponics and soilless culture can be greater compared to conventional soil-based production (Rouphael et al., 2004; Blom et al., 2022; Resh & Howard, 2012; Sardare & Admane, 2013; Manzocco et al., 2011; Nicola et al., 2005; Sonneveld, 2000). This increase in yield is partially related to the physiological effect that hydroponic and soilless culture can have on plant growth. This effect stem from several conditions, including a more accurate control over the pH and EC of nutrient solution which provide optimal conditions for plant growth. Transport rates of water and nutrients in substrate are higher than in soil and plants never come under stress because of availability of water and nutrients. Hydroponic systems allow for a better control of the root environment (e.g., water and nutrient availability, EC, pH, oxygen availability, root temperature) compared to cultivation in soil bound systems. Roots are isolated from soil-borne pests and diseases (Blok et al., 2017).

Physiological parameters of the crop are influenced by different growing systems and this in turn affects the growth and yield. Thomas et al. (2021) evaluated three loose leaf lettuce cultivars in three growing systems; soil-based growing system, hydroponics system with cocopeat as substrate, and nutrient film technique (NFT). maximum yield was also found to be in NFT system (260.66 g/plant) whereas minimum was in soil based growing system (123.92 g/plant). Gashgari (2018) found that planting system has a significant effect on plant growth with hydroponic system having a higher growth rate. Makendi (2014) experimented on different kind of plants grown in hydroponic and soil systems under the same germinating and growing conditions and concluded that hydroponic plants do germinate and grow faster than soil plants.

Comparing two systems of soil-based greenhouse horticulture [GH(s)] and hydroponic greenhouse horticulture [GH(h)] within similar growth condition, the hydroponic system showed a 1.8 times higher yield (Zhou et al., 2021). A greenhouse at Viterbo, Central Italy, reported a higher Zucchini yield (total, marketable and fruit number) for the soilless system compared to those grown in soil (Rouphael et al., 2004). Another study done by El-Shinawy and Gawish (2006), have also shown higher productivity in hydroponic cultivation compared to sandy soil cultivation, with increased yields in lettuce grown hydroponically compared to organic or conventional methods (Hamza et al., 2022).

Grewal and Grewal (2012) quantified the potential productivity of urban agriculture, taking into account various cultivation scenarios ranging from conventional to hydroponic production. The study highlighted the larger food supply capacity of hydroponic systems, thanks to their higher efficiency compared to conventional methods.

Moboko and Bertling (2009) compared yield and quality parameters of four tomato cultivars planted in-soil under a shade net structure with an open bag hydroponic (soilless) system in a plastic tunnel. A higher total yield was reported for the soilless system. The difference in average marketable yield was 92.1% to 77.0% in soilless vs. in-soil, respectively. Lower marketable yield in soil cultivation was partially due to higher incidence of physiological disorders and diseases such as early blight. The high rainfall experienced during the experiment created favorable conditions for the growth of fungal pathogens within the shade net structure. According to the researcher impression, if efficient control measures can be implemented, in-soil cultivation under a shade net structure might have the potential to outperform those in soilless system.

By implementing effective control measures, it is indeed possible to achieve higher yields in soil-based systems. In a study conducted by Frezza et al., (2005) to evaluate the quality of butterhead lettuce in a soilless culture system, the yield of soil-grown lettuce was shown to be higher. The study involved the cultivation of the butterhead lettuce cultivar "Lores" and consisted of two experiments. In the first experiment, carried out during the fall (autumn) of 2002-2003, a comparison was made between a floating system (FS) and soil culture (SC). In the second experiment, performed during the spring production of 2003, a substrate culture (PC) using plastic gutters filled with perlite was compared with three different levels of calcium (0, 3, and 6 me L⁻¹) in the nutrient solution. Both years yielded similar results in terms of growth parameters, with the soil system proving to be superior. The soil culture plants exhibited higher aerial fresh and dry weight, leaf area, aerial-to-root biomass ratio, as well as length and width ($p=0.0003$), in comparison to the plants in the floating system.

Within the literature, instances of similar results favoring soil-based systems in terms of yield and plant growth are in minority. These exceptions typically involve comparisons between two or more different hydroponic systems vs. soil systems, in which the soil system tends to show better performance in comparison to only one of the hydroponic systems. It is highly plausible that different hydroponic systems may exhibit varying performances depending on their design and how efficiently they are managed. Soil systems, if managed properly, have the potential to outperform the less efficient hydroponic systems.

In an experiment done in Bologna, Italy, lettuce was grown using three techniques: nutrient film, floating hydroponic and soil cultivation in open air under similar conditions. Hydroponic lettuces grown in NFT system had a lower crop yield (1.3 Kg/m²) than lettuce production in soil (1.5 Kg/m²). Whereas floating system had the highest yield, having 46% more yield in comparison to NFT (Sanye-Mengual et al., 2015).

Depending on the specific conditions, such as nutrient availability, environmental factors, and plant requirements, different hydroponic systems may have different levels of effectiveness and productivity. Majid et al., (2021), evaluated and compared two hydroponic techniques viz. deep-water culture, and nutrient film technique to the conventional soil-based cultivation method under protected conditions. In all the growing systems, the highest yields for both crop cycles were recorded in deep water culture plants having significantly higher yields of 1.636 and 1.645 kg/plant for cycles C1 and C2, respectively. Similar results for floating raft culture were earlier documented by Fallovo et al., (2009) and Sapkota et al., (2019). The highest growth in terms of plant height and number of leaves was observed in deep water culture plants. The number of leaves was highest for deep-water culture substantiating higher yields in deep-water culture. In addition to plant growth, higher yield was also found to be the result of lower crop period, with

deep-water culture causing a reduction in the plant growth period by 15 days (16%). The total growing days were highest for conventional soil-based cultivation system. The reduction in the growing period observed in deep water culture can be explained by the capacity of the growth tanks to hold ample volumes of the nutrient solution and the timely availability of the nutrients and water; and the well-aerated nutrient solution which is conducive to optimal conditions for the efficient uptake of nutrients and water by the crops

Efficient nutrient uptake, coupled with the controlled environment conditions (Qureshi, 2017), shortens the harvest time in hydroponic systems, meaning you will get a higher yield per year in hydroponic gardens compared to traditional soil-based vegetable gardens (Okemwa, 2015; Banerjee & Adenaeuer, 2014). Nicola et al., (2005) and Fontana and Nicola (2009) compared cultivation of rocket and lettuce plants in soil and soilless media (floating systems and soil substrates) and reported higher yield and early maturity for floating system culture comparing to conventional soil culture. According to Selma et al., (2012), to reach the same maturity stage in lettuce, a longer growing period was needed in the soil than in the soilless systems, which were 102 and 63 days after planting, respectively.

Several authors confirm that with supplemental artificial lighting and temperature controls, hydroponic lettuce production can be continuous year-round, with a full harvest cycle completed every 28-30 days (Donnell et al., 2011; Mendez Perez, 2014; Cometti et al., 2013). While, in tropical climates, a lettuce crop cycle is around 70 days in soil cultivation (Cometti et al., 2013).

On average, yield improvement in hydroponic systems is assumed to be 10% in the same growing conditions; whereas, by factoring in the shorter life-cycle of crops in hydroponic systems,

yield improvements of 15 to 40% is foreseeable (Heuvelink & Marcelis, 2018). According to Okemwa (2015), The most intensive hydroponic culture can achieve 20–25 percent higher yields than the most intensive soil-based culture. The unexpectedly large differences in yield reported in some studies, being as much as 10 to 20 times higher, is almost completely the result of comparing greenhouses (optimal growth environment and longer cultivation season) with open field (Heuvelink & Marcelis, 2018).

Hydroponic systems have predominantly been designed for implementation in controlled environments, such as greenhouses. Higher yield is more attainable in controlled environments where lighting and temperature can be carefully regulated creating the possibility to grow food all year round. Soilless systems in open air, without the benefits of controlled environments, tend to be less productive (Samangooei et al., 2016).

Singh and Singh (2012) reported that the higher yield per unit area in hydroponic greenhouses is primarily due to the controlled environment. Growing crops in a greenhouse environment giving growers the ability to better monitor the plants' water usage (Giacomelli, 1998; Jones & Tardieu, 1998) and to implement more efficient irrigation technologies (Beerling et al., 2014; Stanghellini, 2014). Greenhouses also offer better control over climatic conditions compared to field crop production systems (Durazzo et al., 2013). Furthermore, they are conducive to increased protection against pests and pathogens that have been known to damage field crops (Parry et al., 2004; Rosenzweig et al., 2001) and reduce yield and quality. This is due to growers' improved ability to limit the introduction of pests and pathogens to the greenhouse environment and to manipulate the environment to discourage their growth and spread (Chidiac, 2017). "Plants in carefully controlled hydroponic systems may be grown year-round, placed closer

together physically, or even stacked vertically, leading to higher production yields” (Christie, 2014).

Barbosa et al., (2015), reported 11 ± 1.7 times greater yield per area for the lettuce hydroponic production in Arizona compared to conventional lettuce production. Greenhouse hydroponic lettuce yield was calculated as 41 ± 6.1 kg/m²/y, while conventional lettuce production yielded only 3.9 ± 0.21 kg/m²/y. This significant difference in yield was specifically obtained out of comparing open field production (two crops per year) with greenhouse production (12 crops per year), with each square meter accommodating 24 plants and each lettuce plant gaining approximately 144.6 grams. Maestre-Valero et al., (2018) reported 5.5 times higher yield for NFT in comparison to the soil cultivation again, due to NFT system support for year-round production.

Qureshi carrying out a study in Abbotabad, Pakistan in 2017, observed a tomato yield of 12.5 ± 0.5 kg/sqm/crop for greenhouse hydroponic system compared to a yield of 1.04 ± 0.06 kg/sqm/crop in soil-based open field production (Qureshi, 2017). Higher yields in hydroponic production were mainly due to the year-round production in the closed and controlled environment and a shorter crop life-cycle in the hydroponic greenhouse system. The crop period was mentioned as 3 months compared to 4 months in soil-based system.

In a one-year study conducted by Treftz and T.Omaye (2015) to observe the feasibility of growing strawberries in hydroponic conditions compared to conventionally soil-grown conditions, a 17% higher yield was observed in hydroponic strawberries. In addition to the effect of controlled environment, the higher survival rate of hydroponic plants could have been the reason behind the spotted higher yields. The higher survival rate of 80% in hydroponically grown

strawberries, compared to less than 50% in soil-grown strawberries, are believed to be attributed to an increased pest issues in the soil-based cultivation method as opposed to the hydroponics. Although both growing systems received identical integrated pest management treatments, the soil plants suffered more. Needless to say, greenhouses offer increased protection against pathogens and pests that have been known to damage field crops.

One of the other contributing factors to higher yields in hydroponic systems is the ability to support higher plant densities. Plants can be spaced closer together because the roots do not need to expand outwards to support the weight of the plant (Okemwa, 2015). This, along with direct delivery of nutrients to the roots allows for denser cultivation, with only 1/5 of the total area and 1/20 of the total water to grow plants under hydroponic culture compared to soil-based culture (Silberbush & Ben-Asher, 2001). US branch of WWF in 2020 (WWF-US, 2020), while examining the feasibility of growing leafy greens in St. Louis, USA, estimated an occupational arable land requirement of 0.25 m²a (square meter-years) for conventional open-field soil-based cultivation and 0.024 m²a for greenhouse hydroponic production with the underlying logic that less land is needed due to growing density. These figures serve as rough estimates and can vary depending on factors such as crop type, system efficiency, and operational considerations.

Overall, hydroponic systems, particularly in a greenhouse setting, have the potential to achieve higher plant growth and survival, higher growing density and resource efficiency, lower crop period, hence higher yield and productivity compared to traditional agriculture.

Water Consumption in Hydroponic Systems

Inefficient water usage in conventional agricultural practices negatively impacts water resources. When water is sprayed or flooded across fields, a substantial amount is lost through evaporation, particularly on hot days. Another portion of the water seeps beyond the reach of plant roots, carrying along chemical fertilizers, herbicides and pesticides, that contaminate water tables (Okemwa, 2015).

Soilless culture, through its direct delivery of nutrients to plant roots, lower volume of substrate and the efficient recirculation of nutrient solutions, significantly reduces water usage compared to conventional systems (Doty, 2020; Treftz & T.Omaye, 2015; Engindeniz & Gul, 2009; Blom et al., 2022; Gonnella & Renna, 2021; Resh & Howard, 2012; Banerjee & Adenaeuer, 2014; Khan et al., 2018; Al-Shrouf, 2017; Grewal et al., 2011). The water used is carefully controlled and minimized to the absolute essentials for optimal plant growth; water loss through evaporation is also reduced to a negligible level (Okemwa, 2015). The volume of water consumed per plant in a hydroponic system is not different from that grown using conventional methods; however, the hydroponic system delivers the water more efficiently, with a larger percentage of the water going to plant evapotranspiration. For example, lettuce has shallow roots, but is primarily irrigated through flood furrow irrigation in southwestern Arizona and the water not quickly absorbed by the roots is lost to percolation (Barbosa et al., 2015).

According to Putra and Yuliando (2015), conventional soil-based techniques when set up in protected environment, may be highly productive but their water usage relative to output may be elevated due to runoff and infiltration, resulting in relatively low water-use efficiency.

Given the water losses from overwatering and evaporation, a higher water consumption ranging from 10-100% is quite likely in soil-based systems. When considering water productivity in terms of yield per unit of applied water, the difference can escalate to a staggering 90% more water consumption in traditional soil-based systems compared to hydroponic systems (Heuvelink & Marcelis, 2016; Al-Shrouf, 2017). Another paper reported that hydroponic growing methods can utilize as little as one-twentieth of the total water required in traditional systems (Silberbush & Ben-Asher, 2001). Future Foods Farm uses only one gallon of water to produce one head of lettuce in 28- 30 days in their recirculating hydroponic greenhouses located in Brea, California; while, conventional soil-based farming uses 10 to 15 gallons of water to grow one head of lettuce in 38-45 days (Mendez Perez, 2014).

Soilless systems increase water use efficiency in two ways (Heuvelink & Marcelis, 2018):

1. Irrigation efficiency itself through recirculating drain water and closely monitoring nutrient solution and keep the constituents in line with optimal growth conditions.
2. Water productivity through higher yields per cubic meter of water used (Putra & Yuliando, 2015; Barrett et al., 2016).

In the one-year study conducted by Treftz and T.Omaye (2015) to observe the feasibility of growing strawberries in hydroponic conditions compared to conventionally soil-grown conditions, the hydroponic system used 30% less water compared to the hydroponic system.

In a greenhouse study at Viterbo, central Italy, zucchini plants grown in a closed soilless system exhibited higher yield, harvest index, and water use efficiency compared to those grown in soil (Rouphael et al., 2004). The water use efficiency, measured as the ratio of fruit dry weight

per unit of applied water, was found to be 76% higher in the soilless treatments compared to the soil-grown plants (Heuvelink & Marcelis, 2016).

WWF conducted a study in 2020 (WWF-US, 2020) to suggest the most feasible option for growing leafy greens in St. Louis, USA. Greenhouse hydroponic agriculture received the best scores for water use modeled at 5.96 kg of water/kg lettuce, with vertical hydroponics coming in second, followed by conventional agriculture with water use modeled at 146.6 kg of water/kg lettuce.

Similar to soil-based systems, water use efficiency in hydroponic systems is also influenced by the chosen irrigation strategy. Saha et al., (2008) compared six different irrigation strategies and highlighted substantial variations in water use efficiency among them. Although, among different hydroponic techniques, most use approximately 70 – 95% less water than open field agriculture (Despommier, 2010).

A Life Cycle Assessment (LCA) study investigated the environmental implications of hydroponic tomato production by examining three distinct systems; two nutrient film technique (NFT) setups and one drip system with granulated rockwool. While each system exhibited varying levels of water consumption, the overall environmental impact of water consumption was low in all systems, with drip irrigation having the lowest water consumption (Tewolde et al., 2016).

Blom et al., (2022) did a comparison of vertical farming (VF), greenhouse hydroponic [GH(h)], and open-field farming (OF) for lettuce production in the Netherlands. Greenhouse hydroponic GH(h) with a drip irrigation system showed a remarkable six-fold reduction in water consumption compared to VF, although the contribution of water in both GH(h) and VF remained below 1%.

In another study, Majid et al, (2021) found that the transpiration rate of deepwater culture was significantly higher compared to the nutrient film technique (NFT) system, but comparable to the growth pots utilized in VF. This finding supports the notion that water consumption in deepwater culture and floating systems may potentially go beyond that of drip-irrigated and even NFT hydroponic methods. This result can be explained considering the shallow root system of lettuce, which was unable to utilize most of the water in the deep-water culture system (Majid et al., 2021). Chidiac (2017) also confirms that large quantities of water and nutrients are required to operate DFT systems, relative to NFT. It's worth mentioning that findings for the floating system may not necessarily align with the data obtained for deep-water culture, as Sanyé-Mengual et al., (2015) proposed the floating system as a more water-efficient technique when compared to nutrient film technique (NFT). The difference between the two systems was meager though.

As discussed in 'Yield and Crop Growth' section, Hydroponic systems are commonly set up in controlled environments like greenhouses or indoor facilities. It is well-known that greenhouse cultivation improves water use efficiency compared to open field production (Heuvelink & Marcelis, 2016). Enclosed structures offer better control over moisture levels, minimizing water loss and creating favorable conditions for plant growth (Stanghellini, 2014). Utilizing advanced irrigation methods such as hydroponics or drip irrigation provides further control over growing conditions in controlled environments (Doty, 2020). The implementation of recirculating systems in controlled-environment hydroponic systems adds another layer of efficiency (Grewal et al., 2011; Stanghellini, 2014). When evaluating water efficiency in hydroponics, it is important to consider the impact of controlled greenhouse environments on crop productivity. Despite higher water efficiency, controlled settings increase water productivity

through shorter crop cycles and year-round production. Therefore, it is important to recognize these added benefits while assessing water efficiency in hydroponic systems.

A case in point is water use efficiency in conventional and hydroponic growing systems as reported by Barbosa et al., (2015). In their study on lettuce production in Arizona, they observed that the water consumption for both hydroponic and conventional systems was similar when considering the area of cultivation but when normalized by yield, hydroponic production required 13+- 2.7 times less water on average compared to conventional production. Factoring in the difference between open field production (conventional – two crops per year) and greenhouse production (hydroponics – 8 crops per year), an estimated water demand of 20 ± 3.8 L/kg/y and 250 ± 25 L/kg/y was calculated for hydroponic and conventional lettuce production, respectively.

Qureshi (2017) collated the water data obtained from a hydroponic system in a greenhouse unit with size of (2950 ± 100 sqm) with data gathered from the soil-based cultivation of tomato in a field adjacent to hydroponic farm. When compared in terms of yield, hydroponic system was 83.08 ± 8.25 times lesser water demanding compared to soil-based system. The tomato yield of 12.5 ± 0.5 kg/sqm/crop had water demands of 5.41 ± 0.55 L/kg/crop ($\pm$ S.D), whereas a water demand of 449.48 ± 89.89 L/kg/y were observed for 1.04 ± 0.06 kg/sqm/crop yield in soil-based system. In order to obtain a comprehensive assessment of the actual efficiency level, one must take into account two factors. Firstly, the field cultivation employed flood irrigation, which is widely recognized as one of the most water-intensive irrigation systems. Secondly, the increased yield observed in hydroponic production was to a full extent the result of year-round cultivation within a closed and controlled environment, which reduces the days required to complete the harvesting cycle and allows continuous production of the crop throughout the year. To rephrase the statement, the enhanced efficiency of hydroponic system was the result of comparing the least

efficient irrigation method employed in open-field to one of the most acclaimed water-efficient production systems within a controlled environment.

Maestre-Valero et al., (2018) reported 3.5 times higher water productivity for NFT in comparison to the soil cultivation; again, attributed to the NFT system continuous production throughout the year, allowing for higher yields, and thus higher water efficiency, when compared to conventional soil cultivation (SC).

In a comparative study of lettuce production in deep-water culture, nutrient film technique and conventional soil-based cultivation in northern India (Majid et al., 2021), after normalizing water consumption by yield, the conventional soil-based method showed the maximum water consumption per day (3.106 and 3.128 Lkg⁻¹ day⁻¹ for cycles 1 and 2, respectively). These figures differed significantly from those obtained from the deep-water culture system ($P < 0.05$) and nutrient film technique system ($P < 0.01$), with the estimated water demand of the deep-water culture system being higher than that of the nutrient film technique. These results are also in close concordance with the findings of a previous studies (Barbosa et al., 2015; Qureshi, 2017; Maestre-Valero., 2018) that showed hydroponic lettuce production had less water demand than conventional production (when normalized by yield).

Similarly, Sany'e-Mengual et al., (2015) after a comparative analysis of the nutrient film, floating, and soil production concluded that the soil-based lettuce production was the least water-efficient (0.39 m³/kg) compared to the floating method (0.04 m³/kg) which was the most efficient technique in terms of water production. The increased water consumption, amounting to 10 times larger, was because of a longer crop cycle, a lower crop yield (1 kg m⁻², the lowest of the three techniques) and larger irrigation requirements per kilogram of product.

As mentioned earlier, the inclusion of recirculating and nutrient recycling systems in hydroponic setups brings an additional layer of efficiency, allowing these systems to achieve the possibility of zero emissions, in principle; it is possible to collect and reuse the drain water in these systems, while this is usually not feasible in soil systems. Nederhoff and Stanghellini (2010) reported 20-40% less water and nutrients consumption in closed hydroponic systems compared to their open counterparts. These figures are in line with 33% reduction in water consumption reported by Christie (2014), the 31% reduction that Van Kooten et al., (2008) reported for hydroponic systems with 100% recirculation, and 21% reduction that Stanghellini (2014) observed when drain water were re-used in soilless tomato cultivation. Bradley and Marulana (2001) reported 90% reduction in water use for hydroponic systems with circulation compared to conventional agriculture. Another study reported that by circulating the nutrient solution within a closed system, hydroponic can use only a quarter of the water required to achieve the same yield in industrial field agriculture (Astee & Kishnani, 2010).

Despite the added benefits of closed system, farmers often prefer to use open hydroponic methods because closed systems are more difficult to monitor and maintain (Nederhoff & Stanghellini 2010). As the nutrient solution recirculates, root exudates and sloughed-off materials as well as ions accumulate in the solution (Lykas et al., 2006). Furthermore, the implementation of recirculation necessitates the establishment of reservoirs and pumping systems that require regular monitoring and maintenance for optimal performance (Christie, 2014).

Around 90% (8500 hectares) of the greenhouse horticulture in the Netherlands relies on soilless cultivation methods. In these greenhouses, it is mandatory to collect and reuse drained water. However, this doesn't imply that the systems are completely closed, as there are instances where discharge of the nutrient solution becomes necessary (Beerling et al., 2014). In the

Netherlands, the top 20% of tomato growers have achieved nearly zero emissions through effective management practices, while the bottom 20% of tomato growers have an emission rate of 746 m³ per hectare per year, which accounts for approximately 10% of the total nutrient solution used annually (Beerling et al., 2014; Heuvelink & Marcelis, 2018). Conventional soil-based cultivation of tomatoes has become almost non-existent in the Netherlands (Heuvelink & Marcelis, 2018). It is worth mentioning that in high-tech closed greenhouse systems, such as the one in Naaldwijk (Wageningen-UR), in addition to recycling and reusing nutrient solution, a good amount of water supplied to the crop is recovered by condensation of water vapour from the greenhouse air (Kooten et al., 2008). According to Toyoki Kozai, the Chief Director of the NPO Japan Plant Factory Association, utilizing hydroponics or aeroponics with dehumidification of the air and water recirculation can result in a remarkable water use efficiency of up to 97% (Mendez Perez, 2014).

The Water Use Efficiency (WUE), calculated by multiplying the transpiration efficiency by the harvest index, provides an indication of a crop's water utilization efficiency (Kooten et al., 2008). The WUE in open field horticulture is alarmingly low, causing large volume of fresh water to be wasted in agriculture. On average, the production of one kilogram of field-grown tomatoes requires approximately 200 ± 100 liters of water. In Israel, this amount has been reduced to about 60 liters per kilogram through drip irrigation. In Dutch greenhouses that employ open irrigation systems, the average water usage currently stands at around 22 liters per kilogram, while with closed irrigation systems, this average is further reduced to 15 liters per kilogram of harvested product (Kooten et al., 2008). The above suggests that the water use efficiency of hydroponic systems could potentially be lower than drip irrigation on soil, even if hydroponic system uses open irrigation.

In the San Joaquin Valley of California, the WUE for tomato production in open field conditions was found to range from 10 to 12 kg/m³ of water applied for flood irrigation, 11 to 19 kg/m³ for sprinkler irrigation, and 19 to 25 kg/m³ for drip irrigation. In the Netherlands and France, open hydroponic irrigation systems in greenhouses (without recirculation of unused water by plants) have been reported WUE values of 45 and 39 kg/m³, respectively. Closed irrigation systems, which involve the recirculation of irrigation water, have shown higher WUE values, reaching 66 kg/m³ in the Netherlands and 25 and 30 kg/m³ in the warmer climates of Spain and Italy, respectively (Al-Shrouf, 2017). In regions with warmer climates, the water usage in closed hydroponic systems may be comparable to or slightly higher than that of drip-irrigated soil-based systems operating in similar climatic conditions.

The above data shows that although closed systems have the best performance in terms of water and nutrient consumption, open loop systems still remain as suitable, more efficient options (in terms of water efficiency) when compared to soil cultivation. Fandi et al., (2008) conducted a study in the Jordan Valley during the 2001 and 2002 growing seasons to compare the water use efficiency of tomatoes grown on substrate versus soil. The study aimed to assess the use of locally available tuff (a type of zeolite substrate made of soft volcanic rock) and sand substrates in open soilless tomato cultivation compared to traditional soil cultivation. Substantial water savings of approximately 65-70% were achieved in open soilless system compared to conventional tomato farming under plastic houses.

In arid and semiarid areas, like where Iran is located, a major challenge in recirculating nutrient solutions is the high concentration of saline ions, specifically sodium (Na⁺) and chloride (Cl⁻), in the irrigation water. The excess amount of ions cause larger-than-usual increases in the electrical conductivity (EC) of the recirculating nutrient solution, complicating the management

and maintenance of optimal EC levels (Gonnella & Renna, 2021; Heuvelink & Marcelis, 2016). When there is the slightest doubt about the water quality, the nutrient solution is discarded. Improving the water quality and making it more suitable for reuse and recycling could be costly and growers (and their advisors) tend to avoid risk especially when costs and legal consequences of discarding are relatively low (Gonnella & Renna, 2021; Heuvelink & Marcelis, 2016; Engindeniz & Gul, 2009).

Production Costs in Soil-based and Hydroponic Systems

When comparing different growing methods, it is important to prioritize economic considerations and the overall economic feasibility of a system. While environmental benefits are undoubtedly significant, it is essential to recognize that a system must be financially viable in order to be practically adopted. Therefore, when evaluating and selecting growing methods, careful attention must be given to the economic aspects to ensure long-term sustainability and practical implementation. This approach aligns with the understanding that economic viability serves as a foundational requirement, providing a solid basis upon which environmental benefits can be effectively incorporated.

The majority of studies claim that hydroponic systems tend to have higher overall costs compared to soil-based systems. This is primarily due to the significant initial investment required for setting up a hydroponic system (Fussy & Papenbrock, 2022; Doty, 2022; Treftz & T.Omaye, 2015; Al-Shrouf, 2017; Samangooei et al., 2016; Kaiser & Ernst, 2016; Christie, 2014). Purchasing all new equipment for hydroponic systems would be cost prohibitive, and not make financial sense for most growers (Doty, 2022). However, Al-Shrouf (2017) and Engindeniz and

Gul (2009), added that once the system is set up, it can be cheaper than running a conventional farm.

In a one-year study conducted by Treftz and T.Omaye (2015) to observe the economic feasibility of hydroponically-growing strawberries compared to soil-grown strawberries, the start-up costs, maintenance costs, and upkeep time were assessed. Hydroponic system displayed a higher start-up cost compared to the soil system. The initial higher investment could potentially be a barrier for the adaptation of hydroponic food production for business owners. Labor costs were another important consideration. Monitoring and adjusting the pH and nutrient levels of the solutions and monthly maintenance routines for changing and replacing nutrient solutions made the hydroponic system more labor-intensive.

The researchers suggest that at reasonable costs, growing strawberries in hydroponic systems, with higher yield and survival rate, could be a relatively feasible and more sustainable option in the long run compared to traditionally soil-grown systems (Treftz & T.Omaye, 2015). However, further research should be arranged to investigate economic and ecological feasibility as both systems have their advantages and drawbacks; and agricultural extensions must equip farmers and businesses with resources on the most suitable production method for their special circumstances in order to facilitate informed decision-making.

In an economic Analysis of soilless and Soil-based Greenhouse Cucumber Production in Turkey (Engindeniz & Gul, 2009), net return obtained from cucumbers grown in a mixture of perlite and zeolite was determined as 1.84 euro/m², whereas it was 1.48 euro/m² for conventional soil-based production due to higher yield in soilless system. Variable and fixed costs were 39.1% and 60.9% of the total costs of soilless production, whereas these figures constitute 45.9% and

54% of the total costs of soil-based systems which confirms the higher representation of set up costs and lower representation of annual running cost of the soilless system compared to the soil-based system. Although material costs and total costs were higher for soilless culture systems, adjusted cost and operating costs were generally lower and overall crop yield far exceeded the soil-based cultivation. The adjusted cost to produce 1 kg of cucumber in soil-based system was calculated as 12 euros/kg versus 11 euros/kg in soilless system. Overall, the researchers suggested soilless cucumber production as an economically viable alternative to soil-based cucumber production, while at the same acknowledging the potentials of soil-based productions by mentioning that previous studies conducted in the same regions reported even higher net returns (more than what they obtained from their own experiment on the soilless system) for organic soil-based greenhouse cucumber production under various fertilizer treatments (Tuzel et al., 2005).

Blok et al., (2017) stated that financial investments in hydroponics systems are to be met by a sufficient advantage in yield per unit area. Several Studies evaluated the economics of the soilless systems (Hansen, 1999; Blok & Vermeulen, 2012) concluded that investments in soilless systems require a 10-15% yield increase over soil grown chrysanthemum to become feasible.

Higher yields and higher resource use efficiencies are the result of obtaining advanced technologies (Marcelis & Heuvelink, 2019). On the flip side, the higher initial setup costs are inherent in hydroponic systems that are more complex and have higher level of precision in control measures. To put it in differently, higher yields and higher resource use efficiencies in high-tech systems comes at the cost of high initial investments and operating costs (Christie, 2014; Dorais et al., 2014; Torrellas et al., 2012b; Zhou et al., 2021). In determining the feasibility of soilless systems, an assessment can be done on a case-by-case basis whether the extra yield and higher

environmental benefits obtained through these additional investments justifies the higher production costs.

While hydroponic systems can be implemented in various setups, they typically require a controlled environment, such as a greenhouse or an indoor facility, and one can add the extra costs of building and maintaining a controlled environment on top of the already higher setup costs (Pahlavan et al, 2012; Engindeniz & Gul, 2009).

Because of the costs associated with hydroponic systems, it becomes imperative to select crops that hold a high market value to ensure financial feasibility. In many situations, hydroponic vegetable production is characterized by narrow profit margins, making it economically challenging. When it comes to traditional commodities like corn and wheat, the financial feasibility of hydroponics becomes even more questionable (Mendez Perez, 2014).

The economic feasibility of two lettuce production systems, soil cultivation (SC) and nutrient film technique (NFT) were analyzed under three supply scenarios, considering increasing desalinated seawater (DSW) availability. In the NFT system, the total cost, the revenue and the profit were 5.9, 5.7 and 3.5 times higher than the SC system, respectively. The financial assessment calculated the NFT system net present value (NPV) as 3.1 times higher than the SC system, which suggests the NFT as a more promising strategy. However, the internal rate of return in the SC system was 4 times higher, which shows the higher economic profitability of SC investments and the higher profitability risk of the NFT system. In this sense, the higher investment and operational costs in the NFT system led to a lower ratio of profit/total costs (0.079 versus 0.134), which, under non-limiting conditions, positions SC above the NFT system. Despite the higher investment and operational costs involved, the NFT system proved to be more

profitable thanks to its higher revenue, making it a viable choice for farmers with great purchasing capacity and well-established agronomic knowledge who displays a great resilience with respect to the high profitability risk of NFT systems (Maestre-Valero et al., 2018).

The low representation of the irrigation water and the fertilizers within the total costs made little differences in the total costs among scenarios, as other costs such as labor and plantlets were far more representative. Under a scenario of using 100% of DSW for irrigation of lettuce, water price thresholds of 1.1 €/m³ and 1.6 €/m³ are required in SC and NFT systems, respectively, for the investment to be feasible. Given the current water prices, only under a situation of lack of agricultural land or water availability and/or the need for the preservation of environmentally vulnerable areas, the NFT could be positioned over the SC system (Maestre-Valero et al., 2018).

According to WWF study in 2020 (WWF-US, 2020), lettuce grown in a greenhouse or vertical farm in St. Louise, USA remains more expensive than conventionally grown lettuce produced in California and shipped to St. Louis, even though the costs of the former have dropped significantly over the past decade. Transportation accounts for 67%-70% of costs for conventionally grown field lettuce shipped from Salinas, California, compared to just 12% for greenhouse and vertical farms. However, CEA farms face significant input costs. Labor and management, energy, and structures make up more than 80% of costs in greenhouse hydroponic farms. This is in line with the findings of Stein (2021) which proposes energy and labor as the two major factors contributing to the high costs of indoor and vertical farm operations. According to Gonnella and Renna (2011) the cost of energy accounts for 40% of the entire cost of greenhouse cultivation. Labor costs are high not only due to the lack of automation and higher wage rates in cities, but also because of the administrative staff needed for management and marketing. For large, established farms in California, less marketing is needed and management costs are spread

across a much larger quantity of lettuce (WWF-US, 2020). That is the reason why price for hydroponic products typically toward the high end and along the lines of pricing for organics which limits market penetration. Hydroponic production costs require growers to either identify consistent markets willing to pay a premium price, or produce at a great enough scale to realize cost economies while shipping large amounts of produce (Kaiser & Ernst, 2016).

“Right now, 60% of indoor farms in Japan are unprofitable, largely because of high energy use and cost. Most turn a profit because of government subsidies or by charging a premium to consumers for organic, fresh vegetables. “Japan government continue investing in technology that could change that curve, and is motivated to produce more of its own food” (WWF-US, 2020). According to the 2019 Global CEA Census Report only 15% of shipping container farms and 37% of indoor vertical farms were profitable (Stein, 2021).

Samangoei et al., (2016) confirms that soil-less systems are more productive per square meter, which increases the amount of locally grown, fresh produce available in urban areas; however, the production costs are higher and overall, soil-based system offers a more economically feasible option. At the city level, traditional farming can be done with virtually no economic resources, utilizing locally available planting materials, green manures, "live" fencing, and indigenous pest control techniques (Okemwa, 2015).

There are studies confirming that the profitability of hydroponic systems can be higher than that of soil-based systems. A case in point is Majid and colleagues (2021) study to determine whether hydroponic method presents a suitable and viable alternative to greenhouse soil-based lettuce cultivation in the temperate regions of northern India. Two hydroponic techniques viz. deep-water culture, and nutrient film technique were evaluated and compared to the conventional

soil-based cultivation method under protected conditions. Both hydroponic techniques performed better than the soil-based systems, having benefit-cost ratios greater than 2 which was higher than the average B/C ratio of 1.5 in conventional soil-based system. The NPV values and B/C ratios were higher for both crop cycles due to the comparatively lower cost of production and higher yields per picking (Majid et al., 2021). One must bear in mind that a single example does not establish a general pattern and profitability can actually vary depending on specific circumstances, scale of operation, local market dynamics, and individual farm management practices.

In a study to evaluate various cultivation techniques for roof top gardens in Bologna, Italy, Sanye-Mengual et al., (2015), grew lettuce using three techniques: nutrient film, floating hydroponic and soil cultivation. From the economic perspective, prices ranged between 0.13 and 1.95 €/kg⁻¹, with irrigation being the most contributing factor because of higher value of urban potable water than water in rural agrarian areas. Results showed a strong seasonality; during summer cycles, floating production exhibited the lowest environmental burdens and economic costs, primarily due to its reduced water consumption; while in winter cycles, soil production emerged as the most environmentally friendly and cost-effective option, owing to higher crop yields and shorter crop periods. Comparing lettuce production in summer, floating production showcased a per-kilogram environmental impact that was 60 to 85% lower and costs that were 25% cheaper than nutrient film technique. This disparity can be attributed to the lower crop yield, longer crop period (almost double, on average), electricity consumption by the recirculation pump, and higher water consumption in the nutrient film technique system (Sanye-Mengual et al., 2015).

While the above-mentioned conducted in Italy demonstrated that reducing water consumption can lead to cost savings, water costs in countries such as Iran or the United States

are not high enough to have a strong impact on system economics when compared to the costs of nutrients or energy (Christie, 2014). Although the ecological and societal benefits of water conservation should not be overlooked, it does not provide strong financial incentives for farmers to shift towards more efficient systems.

Fertilizer Consumption in Soil-based and Hydroponic Systems

Cultivation systems that accommodate more efficient use of nutrients allow farmers to optimize their fertilizer application, ensuring that crops receive the necessary nutrients without excessive or wasteful usage. This targeted approach satisfies both financial and environmental benefits (Foley et al., 2011; Bindraban et al., 2015). Hydroponic cultures require large quantities of water and essential nutrients to optimize plant production (Gagnon et al., 2010) and when wastewater released into the surroundings, it has the potential to percolate into the soil leading to contamination of groundwater and negatively affecting the surrounding ecosystems (Majid et al., 2021).

Literature frequently suggest that hydroponic systems potentially require less fertilizers, pesticides and herbicides and reduced reliance on these substances helps minimize the risk of environmental contamination from these chemicals (Blom et al., 2022; Maestre-valero et al., 2018; Okemwa, 2015; Bradley & Marulanda, 2001; Sheikh, 2006). This could be very beneficial when growing plants near sensitive water resources, including public drinking water source areas, the margins of waterways and estuaries and areas within the catchments of conservation valued wetlands (Qureshi, 2017).

Soil-less systems employ water in two different ways: either by continuously recirculating the water within the system or by running the nutrient solution through the system once and disposing of the water (run-to-waste). By circulating the nutrient solution in a closed system, hydroponics can achieve four times greater water efficiency compared to industrial field agriculture while still achieving the same yield (Astee & Kishnani, 2010; Abd-Elmoniem et al., 2006).

Soil-less systems, regardless of having recirculation or run-to-waste modus operandi, will eventually require the disposal of wastewater to prevent the accumulation of toxic ions and an excessive increase of electrical conductivity in the root area. If left untreated, waste solution can pose a threat to ecosystems and groundwater, necessitating proper treatment before it enters wastewater systems (Kumar & Cho, 2014).

The release of untreated effluent from hydroponic systems poses an environmental risk because of having high concentrations of nitrate and phosphate. These nutrients have the potential to trigger eutrophication in receiving water bodies, causing oxygen depletion and the release of toxins in water that can harm both animals and humans (Grewal et al., 2011). Nitrate leaching can result in the loss of essential cations like calcium and its movement into surface or groundwater, which can have implications for drinking water quality (Kumar & Cho, 2014).

Many river basins across Iran face pollution challenges related to nitrogen and phosphorus, caused by agricultural runoff and domestic wastewater. In certain areas like the southwestern and northern basins, nitrogen and phosphorus discharge levels exceed the natural diluting capacity of rivers by two to five times (Michel, 2017). This suggests that we are nearing or may have already exceeded the environmental thresholds regarding nitrogen and phosphorus pollution and any

expansion or adoption of cultivation methods should be approached with caution and prudent care with regard to their potential impact on the nitrogen and phosphorus cycles.

Tewolde et al., (2016) assessed the environmental impact of three hydroponic tomato production systems using life cycle assessment (LCA). The systems included two nutrient film technique (NFT) systems and one drip system utilizing granulated rockwool. Fertilizers used in production had the highest environmental impact, while water consumption had a lower impact across all systems. To minimize the impact of fertilizers, a proper irrigation schedule needs to be implemented, and further research is necessary to lower down the notable environmental implications associated with the discharge of nutrient solutions from hydroponic systems.

In terms of water usage and wastewater production, recirculating systems are more efficient and generate less wastewater, making them a more preferable choice (Samangooei et al., 2016). According to Stanghellini (2014) and Grewal et al., (2011), in greenhouse horticulture and certain high-value outdoor crops, the most effective approach to minimize the release of water, nutrients, and plant protection products into the environment is combining soilless cultivation methods with the recirculation of drainage solution in recirculating soilless systems.

In an analysis done by Rufi-Salis et al., (2020), three nutrient solution recycling options were analyzed: direct leachate recycling (DLR), chemical precipitation (CP), and membrane filtration (MF). All three alternatives showed lower eutrophication potential compared to conventional agriculture. By reusing wastewater and meeting crop nutrient needs sustainably, the DLR and MF processes can reduce global warming impacts by 44-52% compared to conventional cultivation.

In soil-based greenhouses, the most effective approach to reducing nitrogen (N) emissions is through the precise application of nutrients and water. However, it is highly improbable to completely eliminate N emissions in soil-based systems (Beerling et al, 2017). In principle, soilless methods have the potential to achieve zero emissions through 100% recirculation (Heuvelink & Marcelis, 2018; Putra & Yuilando, 2015; Rufi-Salis et al., 2020). As mentioned earlier, the top 20% of tomato growers in Netherland have nearly zero emissions (Heuvelink & Marcelis, 2018). In high-tech greenhouses with recirculation systems, the emission of nitrogen (N) is significantly lower compared to other systems, with values ranging from 64 to 107 kgN/ha.year (Zhou et al., 2021).

Unfortunately, collecting and reusing drain water is limited to high-tech greenhouses that employ soilless methods (Zhou et al., 2021). According to Soto et al., (2015), N emissions from low-tech greenhouses is about 2-4 times more than that of high-tech greenhouses with recirculation. High rates of nutrient solution recycling and limited emissions in countries like the Netherlands has been realized by higher financial resources available to farmers and the inspection and enforcement of regulation that oblige them to reduce discharge through implementation of advanced technology (Van Ruijven et al., 2017).

World Wildlife Fund (WWF-US, 2020) advocated three potential techniques for water recycling. The first approach is drainage water recycling, where the water is stored in fields and used for crop irrigation, taking advantage of its existing nutrient content. The USDA is leading this effort through their Transforming Drainage project (WWF-US, 2020). The second method is potable reuse, which involves treating the water to a level suitable for human consumption. Lastly, the Water Research Foundation is exploring the extraction of nutrients from wastewater (referred to as biosolids) and repurposing those nutrients for fertilizers or land applications. The later two

methods are costly and require additional infrastructure, making their adoption unviable for ordinary farmers in developing countries. Having less complications, the first approach can be easily applied by many farmers in various context. In ‘Result’ section, more excerpts from the literature have been provided regarding this method.

Growers also try to extend the lifespan of drainage water through disinfection by heating, UV irradiation, and chemical treatments such as hydrogen peroxide, ozone, and chlorine (Fussy & Papenbrock, 2022). The high concentration of saline ions in the irrigation water in arid and semi-arid areas poses further challenges for extending the lifespan of nutrient solution. Treating this water using reverse osmosis, although effective, can add to the complexity and cost of the hydroponic system (Gonnella & Renna, 2021; Heuvelink & Marcelis, 2016).

Despite the drawbacks of percolation, evaporation, and run-off associated with soil-based systems, the silver lining is the opportunity to utilize urban waste streams and incorporate composted food and green waste as a valuable source of nutrients to enrich soil (Grard et al., 2015). This approach not only addresses the issue of waste management but also holds significant implications for sustainable agriculture. With fertile soil resources being limited, the integration of soil-based systems utilizing urban compost can help replenishing essential nutrients and partially revive the natural nutrient cycle that disrupted with the expansion of urbanization after World War II. In the predominantly rural world of the past, plant nutrients were recycled as human and livestock wastes were returned to the land. But with the rapid growth of urban areas, this natural cycle was disrupted (Brown, 2004). It allows us to move closer to a circular model of nutrient utilization, mirroring the natural processes of nutrient cycling that has enabled life on Earth to sustainably exists and adapts for billions of years.

Energy Consumption in Soil-based and Hydroponic Systems

The energy requirements of conventional agriculture can vary depending on factors such as the scale of the operation, crop types, geographic location, and management practices. Although small plots of land could be managed with no or limited energy inputs, large-scale conventional agriculture relied on energy-intensive activities including operating machinery and equipment (e.g., tractors and combines) irrigation systems, and running processing facilities and transportation vehicles.

In controlled environment agriculture, energy is required (regardless of the nature of growing method) for heating, cooling, lighting, and ventilation in order to maintain optimal growing conditions throughout the year (Gonnella & Renna, 2021).

hydroponic systems, regardless of being implement in controlled environment or open field, rely on electricity; the irrigation system relies on a constant water flow generated by a pumping system which consumes electricity. In the event of power outages, costly generators are often required to ensure uninterrupted operation (Fussy & Papenbrock, 2022; Al-Shrouf, 2017). Christie (2014) brought up the fact that the energy used by the pump is significant, accounted for approximately 16% to 37% of the overall cost of lettuce production in her experiment which was focused on the topic of water and nutrient reuse within closed hydroponic systems. This aligns with Sanye-Mengual et al., (2015), report that nutrient film technique incurred the highest costs in lettuce production because of the significant energy consumption of the recirculation pump (76.8 ± 34.0 MJ/Kg) and the low crop yield (1.3 kg/m^2 , on average).

Given the current energy landscape, where a substantial portion of our energy is generated from fossil fuels, this could contribute hugely to carbon footprint and costs of running hydroponic systems (Fussy & Papenbrock, 2022). The use of fossil fuels for energy production has implications for water consumption. Thermal power plants that rely on fossil fuels to generate electricity require significant amounts of water for cooling. Back in 2004, in the United States, 48% of water withdrawals dedicated to thermal cooling, surpassing the 34% used for irrigation (Brown, 2004).

Further, as most hydroponic systems are set up in controlled environments, energy becomes indispensable because of environmental control (Fussy & Papenbrock, 2022; Christie, 2014). It has been calculated that the cost of energy accounts for 40% of the entire cost of greenhouse cultivation (Gonnella & Renna, 2021). According to a study done by Guilherme et al., (2015), the 11 ± 1.7 times more yields in greenhouse hydroponic system required 82 ± 11 times more energy as compared to open-field soil-based grown lettuce. Simply put, a portion of the water productivity gains from reduced water consumption and higher yields is negated by the hidden water consumption associated with energy inputs.

By incorporating energy-efficient technologies like solar or wind power and biomass energy, the environmental effects of greenhouse hydroponic systems can be reduced (Dorais et al., 2014). Additionally, taking a holistic approach to sustainability, considering the entire life cycle of the system, can guide informed decision-making about growing methods. Such comprehensive assessment must assess energy inputs of all the stages of each method life cycle, including but not limited to raw material extraction and production, setup, operation and disposal. By optimizing energy efficiency and adopting sustainable practices throughout the system's life cycle, the environmental impact of hydroponics can be minimized.

World Wildlife Fund (WWF-US, 2020) did a life-cycle assessment for five cultivation systems in 2020; conventional lettuce production in California, greenhouse hydroponic lettuce in St. Louis, and three other greenhouse methods (combination of vertical hydroponic and aquaponic systems) in St. Louis. Given the current technology efficiency, electricity sources, and natural resource availability, the assessment concluded that conventional lettuce produced in California and transported to St. Louis had the lowest overall environmental impact among the modeled agricultural systems. This was primarily due to its lower electricity footprint, the cleaner mix of electricity sources in California, and the fact that land had been cleared for conventional agriculture long ago in successful production areas.

Subsequent to conventional lettuce, greenhouse hydroponic lettuce grown in St. Louis and distributed locally had the next lowest environmental impact because of efficient land and water use. The higher electricity consumption of controlled environment agriculture (CEA) systems in the context of St. Louis' typical electricity mix (fossil fuels, nuclear power, and renewable energy), was the main reason behind their higher environmental impacts. They modeled a hypothetical scenario where all five systems exclusively relied on renewable energy sources like photovoltaic solar power or wind power. In this scenario, greenhouse hydroponic systems showed lower overall environmental impacts than conventional agriculture, with significantly reduced effects on human and ecosystem health (WWF-US, 2020). Romeo et al., (2018) also confirms that the source of electricity is a determining factor. When hydroponic systems utilize carbon-neutral sources like wind energy, they outperform soil-based cultivation because of their higher water efficiency and output, regardless of whether they are implemented in open-field or greenhouse settings.

In another study done by Blom et al., (2022), the carbon emissions associated with lettuce production were assessed in three different farming methods in the Netherlands: vertical farming

(VF), greenhouse horticulture [soil-based GH(s) and hydroponic GH(h)], and open-field farming (OF). The assessment considered the entire life cycle of the farm and the crop, from production to disposal. In the baseline scenario, the carbon footprint of vertical farming was found to be 16.7 times greater than OF, 6.8 times greater than GH(s) and 5.6 times greater than GH(h) (Blom et al., 2022). Electricity demand accounted for a significant portion of carbon footprint, representing 85% of the OF carbon footprint in the baseline scenario. Due to its higher dependence on electricity, hydroponics, under similar greenhouse conditions, would have a larger carbon footprint compared to its soil-based counterpart.

To enhance comparability, alternative scenarios were modeled for the lost carbon sequestration potential as a result of land use change (1), identical packaging for all farming systems (2), and the transition to renewable energy (3). Carbon footprint of vertical farming (VF) decreased to just 3.3 times higher than OF, 2.3 times higher than GH(s), and 2.4 times higher than GH(h). Even with the utilization of photovoltaic (PV) panels, electricity remained the primary contributor to the carbon footprint of vertical farming, accounting for 66% of its total emissions (Blom et al., 2022). Comparing the carbon footprints of greenhouse soil-based methods and hydroponic systems, the difference becomes insignificant, meaning that by transitioning to more renewable resource (e.g., solar or wind power), hydroponics can effectively compete with soil-based methods in terms of carbon emissions. However, vertical farms still have significant ground to cover, as far greater reductions in electricity inputs are required to make them a viable and sustainable option.

In the previous section, we discussed how high-tech greenhouses offer advantages in terms of water and fertilizer efficiency through the recirculation and recycling of nutrient solutions. However, the dilemma arises when considering the energy footprint. It has been found that low-

tech greenhouses exhibit much smaller energy use and CO₂ emissions compared to their high-tech counterparts. In fact, energy consumption in conventional low-tech systems can be about six times lower than in high-tech systems, as highlighted by Torrellas et al., (2012a). In Spain, organic low-tech greenhouses were estimated to have lower energy consumption compared to conventional low-tech systems due to the assumption that organic fertilizers require less energy to produce compared to synthetic fertilizers (Fadare et al., 2010). But when normalized by yield, the energy required to produce 1 kilogram of tomatoes in organic high-tech greenhouses was found to be approximately 20-40% higher than in conventional systems (Zhou et al., 2021).

In a comparative study conducted by Barbosa et al., (2015), the researchers examined the land, water, and energy requirements of a hypothetical greenhouse hydroponic system for lettuce production, comparing it to conventional agriculture in Yuma, Arizona. They found that an impressive hydroponic yield of 41 ± 6.1 kg/m² /y in a greenhouse unit came at a cost of energy demands amounted to $90,000 \pm 11,000$ kJ/kg/y. Conventional lettuce production yielded a lower average of 3.9 ± 0.21 kg/m² /y, with energy demands of 1100 ± 75 kJ/kg/y. The hydroponic method produces 11 times higher yields at the expense of consuming 82 times more energy than conventional open-field system.

The primary contributors to energy consumption in greenhouse hydroponic systems are the heating and cooling loads, accounting for approximately $74,000 \pm 10,000$ kJ/kg/y. This is followed by the energy required for supplemental artificial lighting, which amounts to $15,000 \pm 2100$ kJ/kg/y. The circulating pumps, on the other hand, contribute the least to the overall energy usage, totaling around 640 ± 120 kJ/kg/y. The significantly lower total energy use for conventional lettuce production in Arizona was split between fuel usage at 330 ± 20 kJ/kg/y and groundwater pumping at 760 ± 74 kJ/kg/y (Barbosa et al., 2015).

Embodied energy involved in crop cultivation brings added complexity to the energy input aspect. The energy hidden within pumped water and synthetic fertilizers contributes to the overall embodied energy of the crops. In a comparative life cycle assessment conducted by Emery and Brown (2016) on conventional lettuce production in California, irrigation emerged as a significant source of greenhouse gas emissions because of the region heavy reliance on irrigation water instead of rainfall. Pumping water for crop irrigation requires energy in the form of electricity (Emery & Brown, 2016).

The energy-intensive mining, refining and importing processes associated with manufacturing of synthetic nitrogen and phosphorus fertilizers also contribute to the embodied energy of crops (Samangooei et al., 2016). Regardless of the system employed, whether it is soil-based or hydroponic, the utilization of energy-intensive inputs (water, fertilizer, controlled environment, etc.) will result in higher embodied energy of crops and increased environmental impacts associated with crop production.

To conclude, hydroponic systems in its most basic forms, even when established in open fields, utilize electric pumps to aerate the water and circulate it to the plant roots. These systems depend on an energy source for their operation, thus producing crops with higher levels of embodied energy. On the other hand, soil-based systems have lower reliance on an external energy source for the survival of plants, require less energy in general, and do not necessitate backup power (Samangooei et al., 2016).

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Chapter 3: Material and Method

In 2022, an open field experiment was conducted to compare economic viability, and environmental impact of floating raft hydroponics and drip-irrigated soil growing methods for lettuce production in order to provide a solid ground for growers to make informed decisions about which method to use based on their available resources and environmental impact goals.

Most of the comparative studies performed within the global research community are confined to one particular aspect, such as economic feasibility, water consumption, and crop yield to name a few. Focusing on one aspect, such as yield, while ignoring others, can lead to narrow-minded or biased perspectives. In this research, it was tried to consider crop yield, economic viability and environmental impact in a context-sepecific study in order to provide a more comprehensive understanding of the strengths and weaknesses of each system. By considering a wide range of aspects, growers and researchers can make more balanced, informed and sustainable decisions that take into account the full range of benefits and drawbacks of each system.

Research Approach and Hypothesis

The main goal of this study was to conduct an integrated analysis of economic viability and environmental impact of two growing methods, namely, floating hydroponic and drip-irrigated soil in order to suggest the more sustainable option for growing vegetable, lettuce in particular.

Specific objectives

To compare plant growth, survival rate, yield, and production cost between the two systems.

To compare water consumption, electricity consumption and fertilizer consumption between the two systems.

Economic variables

Plant Growth Rate: 20 individual plants of each lettuce type were planted using each growing method, making up a total of 60 lettuce plant for each method. The height of the plants (PH) and the crown diameter (CD) were measured using a meter. Data was subjected to variance test (ANOVA) using Microsoft Excel.

Yield: For each system, the total yield, yield in grams per square meter, and the average head weight were measured at the time of harvest.

Plant survival rate: Plant losses due to biotic and abiotic stresses were numbered at the time of harvest and the rate was calculated based on the total number of seedlings planted in the first place.

Total production costs = Fixed costs + variable costs (Interest rates were included).

Fixed costs: Setup costs

Variable costs: labor, fertilizers, seedlings, electricity, water, etc.

Environmental variables

Water consumption: A tank with water-holding capacity of 1000 liter was used to measure the volume of water used in the drip-irrigated soil system. A 20 Liter plastic water container was used for adding water to hydroponic reservoir on a daily basis and to do a full change once in a while.

Electricity consumption: The energy consumed by submersible air pump and circulating pump were quantified by multiplying their respective power ratings by the duration of their operation in hours per day.

Fertilizer consumption: The quantity and type of fertilizers were compared between the two systems.

Study Area

The study area was located in Karaj, Alborz Province at easting 50°55'05.8", northing 35°49'21.1". With an average annual precipitation and evaporation of 247.3 mm and 2184 mm, and maximum and minimum temperature of 42 and -20 degree Celsius, Karaj experiences a semi-arid climate with hot summers and cold winters (Alborz Meteorological Department, 2023).

Timeline for the Study

The timeline for this research was for Winter 2022 to spring 2023. This included identifying research question and developing research proposal, conducting a literature review,

developing research design and methodology, setting up the study, collecting data, analyzing data, writing up results and draft report, and finalizing the draft report.

Experimental Design

Hydroponic and soil-based growing methods are two fundamentally different systems and their comparison, thus, unavoidably has several limitations. However, to control the experiment and make it as reliable as possible, both systems were built up in the same open field and at the same time in spring to ensure control variables, such as location, light level and temperature, remain consistent for both systems. Plants relied exclusively on sunlight as their source of light.

Land Plot Preparation

Four months prior to commencing the experimental trial, the designated soil plot subjected to ploughing using a shovel, wherein the plane tree fallen leaves from the surrounding area were collected and buried underneath the soil with the aim of gradually building up humus content over an extended period (Figure.1). The incorporation of plant material into soil can enhance soil fertility and plant growth by increasing the availability of nutrients and soil water retention capacity as well as improving soil structure and soil microbial community (Coulibaly et al, 2020; Chen et al, 2022). In addition, this strategy was expected to contribute positively to the overall productivity and sustainability of the land plot in the long run, particularly through carbon sequestration (Gerke, 2022).



Figure 1: Sheet Composting

A day prior to transplantation of lettuce seedlings, the topsoil was amended with decomposed livestock excreta, commonly known as ‘manure’, and vermicompost, a type of organic fertilizer produced by earthworms through the decomposition of organic matter. The addition of organic amendments to the topsoil provides an enriched nutrient content and improves soil physical properties.

Rotten manure is a good source of macronutrients such as nitrogen, phosphorus, and potassium, as well as micronutrients such as calcium, magnesium, and sulfur. The decomposition process of manure typically involves microbial activity which causes the break down and mineralization of organic matter and gradually increases the nutrient availability to plants. However, the use of fresh manure is not recommended as it can harbor viable weed seeds and harmful pathogens, such as E. coli, that can pose a risk to both human and plant health (University of Wisconsin-Madison, 2023).

Vermicompost is known for its high levels of humus, which improves the soil structure and water-holding capacity; it also contains beneficial microorganisms such as bacteria and fungi that enhance plant growth, increase the availability of oxygen, increase soil porosity, and improves nutrient content. Vermicompost is typically rich in plant-available nutrients such as nitrogen, phosphorus, and potassium, as well as trace elements such as iron, copper, and zinc (Rekha et al, 2018).

Layout of The Drip Irrigation Plot

The drip irrigation plot consisted of several components that work together to deliver water efficiently and precisely to the plants (The University of Rhode Island, 2023). The layout was designed according to the size and shape of the area to be irrigated.

A graduated tank with water-holding capacity of 1000 liter, filled with water from the municipal water supply was used as the water source. The location of the tank was considered in a way to be as close as possible to the field to minimize the length of the pipes and to reduce the cost of the system and allow for easy access to the tank for filling, maintenance, and cleaning. To

mitigate the risk of tank damage, careful consideration was given to the surroundings and to the stability of the foundation. The chosen area provides protection from external elements such as sunlight and extreme temperatures.

To increase the elevation difference between the tank and the field, the tank was put on cement blocks, positioned 120 cm above the level of the plants (Figure.2). A larger 5 cm diameter pipe was used for the mainline to further increase the water pressure and flow rate. The blocks were placed on a level and stable surface to prevent them from sinking or shifting over time.



Figure 2: Water tank

The mainline ran through the northern part of the field and connected the water source to the control valves. The valve regulated water flow from the mainline to the lateral lines which was set for manual control. A total of 21 valves were adopted on the mainline to support the lateral lines covering the entire land plot. 21 lateral lines, placed 40 cm apart, branched off from the mainline and distributed water to the individual plants. On each lateral line, there were 13 emitters

placed 30 cm apart, that delivered water to immediate proximity of each individual plant (Figure.3).

Although the entire plot was planted, the soil-based experimental unit consisted of five rows adjacent to the hydroponic reservoir, approximately 4 meters in length, with 0.4 m row spacing and 0.3 m in-row spacing containing 60 plants. Drip lines, with in-line emitters located 0.3 m apart, were placed adjacent to the plants.



Figure 3: Drip Irrigation Layout

Hydroponic System

Selection of Hydroponic System

Each type of hydroponic method has advantages and drawbacks, and the choice of method depends on factors such as the crop being grown, available resources, and growing conditions.

Our method was chosen for the simplicity of design and relatively low cost. The floating raft technique is an easy to setup hydroponic method that can be a good choice for a simple hydroponic experiment. Different hydroponic and soilless substrate systems have shown varying influences on plant growth due to differences in the distribution and availability of nutrients and water for plant uptake. Compared to some other hydroponic methods, such as NFT, this method required minimal equipment and is proved to enhance yield and resulted in a higher output. In Bologna, Italy, lettuce was grown using three techniques: nutrient film, floating hydroponic and soil cultivation in open air under similar conditions. Hydroponic lettuces grown in NFT system had a lower crop yield (1.3 Kg/m²) than lettuce production in soil (1.5 Kg/m²). In contrast, the floating system had the highest yield, having 46% more crop yield in comparison to NFT (Sanye-Mengual et al., 2015).

Doty (2020) showed the superiority of floating system for basil cultivation over their NFT and SAEF counterparts in terms of shoot yield. Research by Walters and Currey (2015) involving 35 different cultivars confirmed that plants grown in DFT systems had an average increase of 22.6 g in shoot dry mass compared to those grown in NFT systems. Another study conducted by Blok et al., (2017) observed faster growth rates in chrysanthemum plants cultivated using DFT rather

than NFT, suggesting that the thin film of solution supplied by NFT provided water and nutrients, including oxygen, at levels below the maximum capacity of root uptake.

Floating raft is one of the most common practices for growing lettuce (Kaiser and Erns, 2016) and it has also been highly recommended in some studies (Petropoulos et al, 2016; Sanye-Mengual et al, 2015). Floating systems provide roots with ample space to thrive and develop within a vast solution volume, thereby reducing the likelihood of root restriction and maximizing the absorption of vital nutrients and water.

Layout of the Floating (Raft) System

The floating system consisted of one rectangular reservoir measuring 100*370*16.2 cm which equaled to 600 Liters of water dug into the ground adjacent to the drip irrigated plot. Hollow clay bricks were used to reinforce the edges of the reservoir, ensuring stability and preventing any potential collapse of the reservoir walls. A sump was created within the reservoir to allow for easy removal of nutrient solution using a pump (Figure.4).



Figure 4: Floating Raft System Reservoir

A clear plastic sheeting was laid over the reservoir and bricks were used to hold the edges of the plastic sheeting in place (Figure.7). A submersible air pump and a circulating pump were used to oxygenate the nutrient solution and provide aeration to the roots (Figure. 5,6). The constant submergence of roots in a stagnant nutrient solution makes it necessary to rely on an auxiliary oxygen supply for adequate oxygenation. (Majid et al, 2012).



Figure 5: Submersible Air Pump



Figure 6: Submersible Air Pump



Figure 7: Floating Raft Reservoir and Plastic Sheeting

Three rafts measuring 100*123 cm made of Styrofoam were acquired to be floated on top of the nutrient solution (Figure.8). A total of 20 net pots were fit into holes drilled into the Styrofoam board at uniform interval from each other (Figure.9). Plants were fastened to these net pots with shoots above and roots descending into the nutrient solution. The crop density was in

line with the plant density of 24 plants per square meter. Kotsiras et al, (2016) have reported plant densities of 20-30 plants m⁻² for Butterhead, Lollo Rosso and Batavia lettuce types.

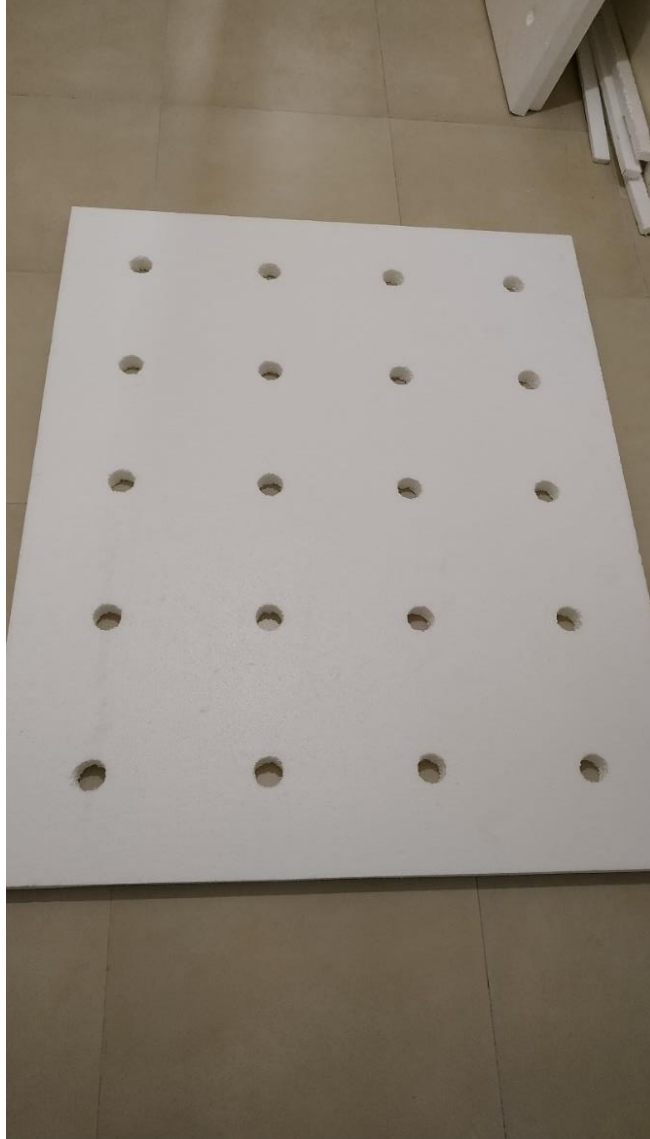


Figure 8: Styrofoam Board



Figure 9: Floating Rafts

Setting up Shade Cloth

Lettuce is a cool-season vegetable and prefers temperatures between 15-18°C for optimal growth. The loose-leaf varieties selected for this experiment are not adapted to high temperatures and direct sunlight. Due to its hot and arid climate, Karaj experiences high temperatures in late

spring and early summer. Since transplanting started slightly off-season and plants were exposed to rising temperatures in June, a 50% shade cloth was installed to protect plants from heat stress and dehydration and in order to extend the growing season by reducing light intensity and providing a cooler microclimate more conducive to plant growth (Kitta et al, 2012).

Shading is a simple, cost-effective passive cooling technology that can be simply implemented for open-air farming. Shade cloth is a type of fabric that is specifically designed to protect plants from excessive sunlight. It is typically made from a woven mesh material that allows air and water to pass through while blocking some of the sunlight. Shade cloth comes in various densities, ranging from 10% to 90% shade. The percentage refers to the amount of sunlight that is blocked by the cloth. For example, a 30% shade cloth will block 30% of the sunlight and allow 70% of it to pass through.

The wall fences were used to erect the shade cloth. The plot was rectangular in shape, with one side of its length and width enclosed by a wall fence. For the opposite length and width, two stakes were hammered firmly into the ground (one of the stakes served as corner post). A total of 8 grommets were used on the shade cloth to secure it to the support structure. Out of these, 5 grommets were fastened to the wall fence using ropes, two were tied to the stakes, and the last one was anchored to the ground using mosaic tiles as shown in figures (10) and (11).



Figure 10: Shade Cloth



Figure 11: Light intensity difference under the shade cloth

Selection of Lettuce Type

Lettuce is generally considered a good choice for hydroponic systems due to its relatively simple nutrient requirements and fast growth rate. In comparison to fruit-bearing vegetables, like

tomato, lettuce has simple requirements and can thrive with a standard nutrient solution. Tolerating a wide range of pH levels, it is easier to maintain a stable hydroponic environment for this vegetable.

However, the chosen varieties (types) can be more challenging to grow than more common lettuce types like Butterhead or Romaine lettuce, due to their sensitivity to fluctuations in temperature and humidity and because of requiring a more precise nutrient and pH levels in the growing medium. Despite these challenges, we selected *Lactuca Sativa* L. var Lollo Bionda, var Lollo Rosso and var Little Gem on the grounds that they are considered to be profitable. These varieties are high-end or luxury lettuce types in many parts of the world, including Iran, and are often used in fine dining restaurants and gourmet food markets because of their unique and attractive colors, textures, and flavors.

Nutrient Solution

Water Quality

Successful plant growth in a hydroponic system relies on several factors, including the quality and quantity of water. It is thus essential to analyze the chemical composition of water as it impacts the nutrient balance and pH level of the nutrient solution. By analyzing the water, growers can determine the levels of elements like calcium, nitrogen, phosphorous, and potassium, in their ionic form and adjust the nutrient solution accordingly. The chemical composition and pH of the water can also influence the overall pH level of the nutrient solution, impacting the availability of nutrients to the plants. (Qureshi, 2017). Moreover, the water needs to be tested for

contaminants, such as heavy metals, pesticides, and bacteria, which can adversely affect the entire system.

The microbial analysis was not conducted since the water source was potable (municipal) water. Though, doing the chemical analysis was essential because the quality of municipal water can vary depending on the source and treatment method used. Municipal water may contain high amounts of chlorine residuals, or other chemicals that are added to kill bacteria and other microorganisms. These chemicals can cause phytotoxicity and inhibit nutrient uptake (McGehee and Raudales, 2023). Chlorine residuals or other minerals and salts contained in municipal water when combined with the nutrient solution can contribute to nutrient imbalance and toxic ion buildup over time (Christie, 2014). A water sample was taken to a soil and water testing laboratory in Golshahr, Karaj to analyze the water's chemical composition and to adjust the nutrient solution accordingly.

Preparing Nutrient Solution

According to many studies, plants need an approximate of seventeen essential elements for proper growth, which are classified into macro-nutrients and micro-nutrients groups (Table.1).

Table 1: Summary of Nutrients for Hydroponic Crop Growth (Khan et al, 2017).

Type of Nutrients	Name of Nutrients	Functions in Plants
Macro	Nitrogen	Chlorophyll, amino acids and proteins synthesis
	Phosphorus	Photosynthesis and growth
	Potassium	Enzyme activity
	Hydrogen	Water formation
	Oxygen	Release of energy from sugar
	Carbon	Formation of organic compounds
	Calcium	Cell growth
	Magnesium	Enzyme activation
	Sulfur	Formation of amino acids and proteins
Micro	Iron	Used in photosynthesis
	Boron	Vital for reproduction
	Chlorine	Help roots growth
	Copper	Enzyme activation
	Manganese	Component of Chlorophyll
	Zinc	Component of enzymes
	Molybdenum	Nitrogen fixation
	Cobalt	Nitrogen fixation

Numerous nutrient solution recipes are available for hydroponic systems. Nutrients can be purchased as pre-formulated, ready-to-mix product or growers can prepare their own solutions based on a standard or modified formula. These formulas typically involve mixing together various salts and minerals in the correct proportions to provide the necessary nutrients for plant growth. Table (2), shows different nutrients used in the course of this experiment.

Table 2: List of Nutrient Used for This Experiment

Macro-nutrients	Micro-nutrients	Acids
Calcium Nitrate $\text{Ca}(\text{NO}_3)_2$	Fe chelated	Nitric acid HNO_3
Potassium Sulphate K_2SO_4	Manganese chelated	Hydrochloric acid HCl
Root P (Phosphorus Pentoxide P_2O_5)	Zinc chelated	Tartaric acid $\text{C}_4\text{H}_6\text{O}_6$
Potassium Nitrate KNO_3	Boron chelated	
Magnesium Sulphate $\text{MnSO}_4 \cdot 7\text{H}_2\text{O}$	Sodium Molybdate	
	Copper Sulphate	

The volume and frequency of nutrient solution application are dependent upon the hydroponic method, the vegetable species and their developmental stage, the size of the reservoir, and the prevailing climatic conditions (Sardare & Admane, 2013). The nutrient solutions were

prepared based on modified Hoagland solution (Jones, 2014), with consideration given to the above-mentioned determinants.

Water from municipal supply with EC = 529 $\mu\text{S}/\text{cm}$ and pH 7.18 was used to prepare the nutrient solution. Recommended by Saied Saheb-Fosuli, the agricultural consultant, the nutrient solution was changed four times during the experiment to maintain optimal growth conditions for the plants and to prevent the buildup of excess nutrients or other compounds that can interfere with plant growth. The frequency of nutrient solution replacement varies according to the growth and developmental stage of the plants, and it differs between floating systems and other hydroponic methods. Replacement intervals were comparable to those used in the experiment conducted by Majid et al., (2021).

The dates and amounts of nutrients used for preparing the nutrient solution were recorded for each replacement. Table (3) shows the date of the replacements and the corresponding quantities of dissolved nutrients (in 600 liters of water) in each round.

Table 3: Nutrient Solutions Formula

Initial Nutrient Solution		Replacement (1)	
16 May 2022		24 May 2022	
Nutrient	Amount	Nutrient	Amount
Calcium Nitrate $\text{Ca}(\text{NO}_3)_2$	225 g	Calcium Nitrate $\text{Ca}(\text{NO}_3)_2$	217 g
Potassium Sulphate K_2SO_4	107 g	Potassium Sulphate K_2SO_4	-
Root P (Phosphorus Pentoxide P_2O_5)	30 ml	Root P (Phosphorus Pentoxide P_2O_5)	42 ml
Potassium Nitrate KNO_3	19.5 g	Potassium Nitrate KNO_3	211 g
Magnesium Sulphate $\text{MnSO}_4 \cdot 7\text{H}_2\text{O}$	15 g	Magnesium Sulphate $\text{MnSO}_4 \cdot 7\text{H}_2\text{O}$	89.5 g
Fe chelated	18 g	Fe chelated	20 g
Manganese chelated	1.1 g	Manganese chelated	1 g
Zinc chelated	1.8 g	Zinc chelated	0.8 g
Boron chelated	3.6 g	Boron chelated	4 g
Sodium Molybdate	0.072 g	Sodium Molybdate	0.1 g
Copper Sulphate	0.4 g	Copper Sulphate	0.4 g
Replacement (2)		Replacement (3)	
6 June 2022		12 June 2022	
Nutrient	Amount	Nutrient	Amount
Calcium Nitrate $\text{Ca}(\text{NO}_3)_2$	486.5	Calcium Nitrate $\text{Ca}(\text{NO}_3)_2$	249 g
Potassium Sulphate K_2SO_4	-	Potassium Sulphate K_2SO_4	73 g
Root P (Phosphorus Pentoxide P_2O_5)	50 ml	Root P (Phosphorus Pentoxide P_2O_5)	54 ml
Potassium Nitrate KNO_3	155 g	Potassium Nitrate KNO_3	168 g
Magnesium Sulphate $\text{MnSO}_4 \cdot 7\text{H}_2\text{O}$	296 g	Magnesium Sulphate $\text{MnSO}_4 \cdot 7\text{H}_2\text{O}$	90 g
Fe chelated	25 g	Fe chelated	20 g
Manganese chelated	1.1 g	Manganese chelated	1 g
Zinc chelated	1.4 g	Zinc chelated	0.8 g
Boron chelated	1.6 g	Boron chelated	4 g
Sodium Molybdate	0.2 g	Sodium Molybdate	0.1 g
Copper Sulphate	0.2 g	Copper Sulphate	0.4 g
-	-	Nitric acid HNO_3	30 ml

Nutrient Solution Monitoring

Maintaining nutrient solution for optimal plant growth involves controlling two key parameters, pH and electrical conductivity (EC). The ideal pH range for the nutrient solution is 5.8 to 6.5, and a suitable EC range is 1.5 to 2.5 dS/m (Khan et al., 2018).

pH refers to the acidity or alkalinity of the solution. Too high or too low pH levels cause nutrient deficiencies or toxicities, which can stunt growth, reduce yields, and even kill the plants.

pH levels need to be monitored and adjusted regularly to ensure they remain within the optimal range.

EC is the measure of the nutrient concentration in the solution; As the concentration of nutrients increases, so does the EC value. It measures the ability of the solution to conduct an electrical current. Too high or too low nutrient concentration can also negatively affect plant growth and health.

Nutrient solutions do not possess the same buffering capacity as soil, and their pH level susceptible to fluctuations. It is thus essential to closely monitor and regulate the pH, oxygen levels, temperature, and soluble salts of the nutrient solution (Kaiser and Ernst, 2016). The nutrient solution pH level was regulated within a range of 5.8 to 6.2 by adding NaOH, HCL, nitric acid and tartaric acid as needed. The EC of all nutrient solutions was retained at the level of 150 to 181 $\mu\text{S}/\text{cm}$ throughout the experiment. EC and pH values were checking on a daily basis.

In order to protect the solution from extreme temperature fluctuations and sunlight, the reservoir was buried in the ground. The ground has a more stable temperature than the surrounding air and could keep the solution at a consistent temperature. The submersible air pump was found to be very effective in oxygenating the water and preventing waterlogging of the roots.

Calibration of EC and pH Meters

The floating system was monitored daily using two handheld meters, EZDO 6021 Conductivity Pocket Meter and EZDO 6011 pH Meter devices from Gondo Electronic Co., Ltd. in Taiwan. The devices were calibrated on a weekly basis, as recommended by Saied Saheb

Fosuli, the agricultural consultant. The EC meter was calibrating using a standard solution of HACH 5,000 μ S, and the pH meter was calibrating using pH 7.00 and pH 4.01 standard solutions in a two-point calibration process.

Transplanting

Lettuce seedlings were bought from a greenhouse proprietor and later transplanted for the experiment. A total of 120 seedlings were utilized, with 60 seedlings for each growing method (Floating and drip-irrigated soil methods). Each of the three lettuce species - Lollo Bionda, Lollo Rosso, and Little Gem - accounted for 20 seedlings in. The seedlings allocated for the floating system were transferred into net pots, which were then inserted into the floating system (Figure.12), and those utilized for the soil system were planted directly into the soil (Figure.13). Plants were monitored and treated throughout the experiment. At the end of the growth cycle, the final harvest was conducted, and total harvest were measured.



Figure 12: Newly Transplanted Seedlings - Floating System



Figure 13: Newly Transplanted Seedlings - Drip-irrigated Soil System

Pest Management

Integrated Pest Management (IPM) was adopted for both growing methods. IPM is a sustainable approach for managing pests that combines multiple control strategies to minimize their impact while reducing the use of pesticide.

Many definitions have been put forward for this concept. This study took the national coalition for IPM definition: “A sustainable approach to managing pests by combining biological, cultural, physical, and chemical tools in a way that minimizes economic, health, and environmental risks” (Jacobsen et al, 2004). The IPM components employed for this experiment is listed as follows:

- **Ploughing:** Four months prior to the start of this experiment, the land plot was ploughed deeply. Ploughing can turn over the soil and bury weed seeds and pests that are near the soil surface, reducing their chance of germination and emergence (Singh et al, 2023).
- **Decomposed manure and compost for soil fertilization:** The application of compost and decomposed manure to the soil was utilized with the intended purpose of eliminating the viability of weed seed and pest eggs to preclude their subsequent germination and hatching.
- **Sanitation:** As per the recommendation of the agricultural consultant, a hydrogen peroxide solution with a concentration of 2.5 milliliters per liter was applied to the soil prior to transplantation. Hydrogen peroxide can effectively serve as a soil sterilant, targeting a broad spectrum of microbial pathogens that could pose a threat to the newly transplanted crop. However, it is important to acknowledge that the utilization of hydrogen peroxide as a soil sterilant may impinge upon the beneficial soil microbiota that hold significance in the growth and development of plants. It should be administered prudently to minimize its possible adverse impact. Moreover, the effectiveness of hydrogen peroxide may vary depending on the soil type, moisture content, and other pertinent environmental factors, thereby warranting a case-by-case assessment.
- **Drip Irrigation:** Drip irrigation is recognized as an effective measure for mitigating pest challenges as it directly provides water to the root zone of the plant, thereby reducing surface moisture and creating an unsuitable environment for weed growth and pest oviposition and propagation (Singh et al, 2023).
- **Monitoring:** Pest populations and damage thresholds were monitored systematically for early detection of impending pest outbreaks. The data obtained from such monitoring

provides valuable insight into pest activity patterns and enables timely implementation of appropriate control measures (Singh et al, 2023).

- **Manual removing and handpicking:** It involved manually removing pests from plants, usually by picking them off by hand or using tools like tweezers for removing aphids (Singh et al, 2023).
- **Biological control using BT Biopesticide:** Liquid suspension of *Bacillus Thuringiensis* (BT) at the recommended dosage of 2 ml/L was sprayed onto both floating and soil systems to control citrus leafminer and aphid outbreak. BT is a naturally occurring soil bacterium that produces insecticidal proteins specifically toxic to certain insect species, including caterpillars, beetles, and mosquitoes (National Pesticide Information Center, nd). The proteins ingested by these insects cause gut rupture and subsequent mortality. BT possess the advantage of high specificity for the targeted insect pests while leaving beneficial insects such as pollinators unharmed. It also breaks down quickly in the environment and does not leave harmful residues (US Environmental Protection Agency (EPA), 1998).

Figure (14) depicts a close-up view of a Little Gem Lettuce that was infested with aphids. Nymphs undergo four molts as they develop towards adulthood, during which they shed their integument. The white flakes discernible on the lettuce leaves are the shed exoskeletons of the aphids (Cannon et al, 2017).



Figure 14: Aphids and their Shed Exoskeletons

Figure (15) shows a Lollo Bionda lettuce leaf infested by a leafminer, as evidenced by the visible winding, whitish tunnels created by the maggots (larvae) of leafminors as they feed between upper and lower surface of leaves (UC IPM, 2020).



Figure 15: Leafminer Winding Trails

- **Floating System Water Replacement:** After the first water replacement, algae began to colonize the hydroponic reservoir (Figure.16). Nutrient solution was replaced, reservoir was cleaned, and roots were washed with high-pressure water to remove algae.

Nutrient solution first replacement (Replacement (1) in Table.3) was performed using the water stored in the tank; while the initial nutrient solution, which didn't have a sign of algal growth, were formulated using the tap water. It is plausible to hypothesize a correlation between the use of stored water and the incidence of algal growth. It is possible that the water may have already been contaminated with algal spores prior to being transferred to the hydroponic reservoir. The storage of water in a tank for a prolonged period of time can increase exposure to sunlight, providing favorable conditions for algae spores to germinate and later grow and reproduce further in the reservoir.



Figure 16: Algal Growth on Roots and on the Below Surface of Styrofoam



Figure 17: Healthy Lollo Bionda Roots 16 days after removing algae Outbreak

Harvesting

Lettuce is typically harvested when the leaves reach their desired size and shape. This will vary depending on the variety of lettuce grown. For looseleaf lettuce (such as Lollo Rosso and Lollo Bionda varieties in this study) that does not form a compact head such as iceberg, harvesting process could begin once the outer leaves are grown to a length of approximately 7 to 10 centimeters (Marinelli et al, 1995; Meadowlark Journal, 2023). In general, the timing of the harvest is crucial, as leaving lettuce in the field for too long can result in the leaves becoming tough, bitter, or even bolted.

The final harvest took place 39 days after transplanting. Though hydroponic plants reached a marketable size, those grown in soil were smaller due to lower growth rate and had the potential

to grow larger if not harvested. However, since plants were subjected to increasing temperatures in June, to avoid premature bolting or drying out, plants were harvested earlier than planned.

Chapter 4: Data Collection and Statistical Analysis

Economic Analysis

The economic analysis of growing methods entailed doing a basic comparison between the two growing methods based on criteria such as plant growth, yield, plant survival rate, and total production costs. The objective is to provide insights into the relative productivity and costs associated with each method.

Growth Rate Analysis

The growth rate of various lettuce types cultivated in both floating and drip-irrigated soil systems were examined and compared. The growth rate of a plant directly impacts its yield, as plants with faster growth rates typically produce more biomass.

For both floating and soil systems, plant height (PH) and crown diameter (CD) were measured in situ using a meter at four different points during cultivation (1, 9, 29, and 39 days after transplanting). To combine PH and CD into a single metric determinant of plant growth, the volume of a hypothetical cylinder in which each plant could be fitted were calculated; with the plant height used to determine the height of the cylinder and the crown diameter used to calculate the radius. The cylinder volume, thus provide, an indication of each lettuce overall growth.

Leaf size or leaf number were not considered as additional criteria for assessing the growth rate to avoid potential damage to the delicate leaves of the plants. The focus was on minimizing any disruption to the growth cycle of the lettuce in order to grow high-quality produce. While

including these metrics could have provided a more comprehensive picture of the plant growth, the combination of plant height and crown diameter was deemed sufficient for the purpose of this study.

The statistical analysis of plant growth was conducted in two steps. In the first step, a one-way Analysis of Variance (ANOVA) was performed separately for each of the three lettuce varieties to determine if there were statistically significant differences in plant growth between the floating system and the drip-irrigated soil system. Thus, the null and the alternative hypothesis were:

H_0 = There's no significant difference in plant growth between the floating and drip-irrigated soil systems

H_1 = There's a significant difference in plant growth between the floating and drip-irrigated soil systems

The experiment's variables were classified as independent, dependent, and controlled (Table.4).

Table 4: List of Variables for One-way ANOVA

Independent Variables	Dependent Variables	Controlled Variables
Growing Method	Cylinder Volume (PH +CD)	- Temperature - Light

In the second step, the Two-way ANOVA was performed to determine whether the interaction effect between lettuce varieties and growing method is statistically significant (Laerd Statistics, 2018). This factorial design consisted of two independent variables (called factors): lettuce type and growing method. Lettuce type had three levels (Lollo Rosso, Lollo Bionda, Little Gem) and growing method had two levels (drip-irrigated soil system and floating system).

The hypotheses were:

H_0 = Lettuce type does not influence the relationship between plant growth and growing method.

H_1 = Lettuce type influence the relationship between plant growth and growing method.

Table 5: List of Variables for Two-way ANOVA

Independent Variables	Dependent Variables	Controlled Variables
• Lettuce Type • Growing Method	• Cylinder Volume (PH +CD)	• Temperature • Light

Yield

Yield refers to the amount of crops/vegetables produced per unit of land. It is an important component of economic analysis in agriculture and has a direct impact on generated revenue. 39 days after transplanting, the entire lettuce head were cut off at the base, roots were removed and harvest was weighted using a digital scale.

Plant Survival Rate

The percentage of plants that survived to the end of the experiment (39 days after transplanting) was measured. This criterion highlights some of the potentials and disadvantages of each growing method and provide insights into stress factors that may hinder plant growth and affect overall yield.

Production Costs

Production cost analysis was based on figures obtained from a 3 square meter plot for each growing method. The cost items were categorized into variable costs and fixed costs. The variable costs were inputs that were directly related to the production of lettuce, including labor, fertilizers, seedlings, electricity, and water consumption.

Fixed costs were further divided into investments and interests. Depreciation for initial investment was estimated using the straight-line method. Asset prices were divided by their useful life expectancies to determine annual costs for depreciation. The useful life for reservoir, shade cloth, EC and pH meter, and drip irrigation system were estimated to be 5, 5, 10, 10, and 10 years, respectively. Land rent was not included in this assessment. Land rent can be highly variable depending on the location of the parcel, soil types, and availability of water.

Interest on the total investment costs and interest on total variable costs were measured. Interest rates were categorized as part of the fixed costs. Interest is defined as the sum paid for the use of capital, expressed in terms of an annual rate or percentage of the capital involved (Engindeniz and Gul, 2009). The interest on total investment costs and total variable costs was calculated using a simple interest rate of 23%, set by Central Bank of Iran for 2023. The interest rate applied to one-half of total investment and variable costs as two crops per annum can be grown outdoor in Karaj. The total production costs were calculated by adding the fixed and variable costs.

Environmental Analysis

Crop Water Productivity

A graduated tank with water-holding capacity of 1000 liter was used to measure the volume of water used in drip-irrigated soil system after each irrigation. The total water consumption in floating system was calculated by adding up the amount of water used to fill in the reservoir during each replacement. The figures obtained are shown in table (6) and (7).

Table 6: Water Consumption in Floating System

Floating System	
Replacement Dates	Amount (L)
16 May 2022	600
24 May 2022	600
4 June 2022	600
12 June 2022	600
Total	2400

Table 7: Water Consumption in Drip-irrigated soil system

Drip-irrigated Soil System			
Irrigation Date	Amount (L)	Irrigation Date	Amount (L)
17 May 2022	44	8 June 2022	33
19 May 2022	33	10 June 2022	33
20 May 2022	33	12 June 2022	33
21 May 2022	33	14 June 2022	33
26 May 2022	33	16 June 2022	33
29 May 2022	33	18 June 2022	55
31 May 2022	33	20 June 2022	55
2 June 2022	33	22 June 2022	55
6 June 2022	33	Total	638

Crop water productivity (CWP) is commonly described as the correlation between the crop yield or crop value and a selected measure of water consumed (Wichelns, 2014). It can be calculated as the ratio of the yield produced to the amount of water utilized in the production process, or the value added to that amount of water. For the purpose of this study, CWP was measured in terms of yield return (Igbadun et al, 2006).

Yield Return: Water productivity with respect to yield return is measured as the amount of yield generated (in kg) per unit volume of water utilized (in m³).

CWP can also be assessed in terms of economic return, expressed as IRR/m³ (Igbadun et al, 2006). But given that the actual yield didn't meet the expected levels due to unfavorable weather conditions and pest infestation, measuring CWP in terms of economic return may result in biased and underestimated figures. This factor was, thus, left out to avoid erroneous conclusions regarding the effectiveness of growing methods under study.

Electricity and fertilizer Consumption

Since the experiment took place in an open field, no additional artificial lighting was utilized for either system. Consequently, the drip-irrigated soil system operated independently without requiring any external energy input. In contrast, the floating system incurred energy expenditure from the submersible air pump and the circulating pump. The energy consumed by the pumps was quantified by multiplying their respective power ratings by the duration of their operation in hours per day.

With regard to the fertilizer consumption, the drip-irrigated soil system was sustained exclusively by utilizing organic fertilizers, including rotten manure and vermicompost, while the floating system relied on synthetic fertilizers. The pros and cons of each alternative is discussed in the result section. The implications of this comparison will provide insights into the relative effectiveness of each alternative and their potential environmental impact.

Results and Analysis

Economic Analysis

Crop Growth Statistical Analysis

A combined total of 120 seedlings, evenly distributed, were used for floating and drip-irrigated soil systems. For each method, there were 60 samples, with 20 seedlings allocated to each of the three lettuce varieties: Lollo Bionda, Lollo Rosso, and Little Gem.

Plant height (PH) and the crown diameter (CD) were measured in situ using a meter at four different points during cultivation (1, 9, 29, and 39 days after transplanting). To combine PH and CD into a single metric determinant of plant growth, the volume of a hypothetical cylinder in which each plant could be fitted were calculated; with the plant height used to determine the height of the cylinder and the crown diameter used to calculate the radius. The data was derived by measuring the average increase in both plant height (PH) and crown diameter (CD) across 13 plants for each variety. Due to rising temperatures towards the end of the experiment, few plants were dried out, while others were affected by pest infestation. To ensure an equitable comparison and achieve accurate results, 7 plants from each variety were removed and the statistical analysis was carried out using a reduced sample size of 13 plants for each variety. Growth trends of each lettuce variety are illustrated for both floating and drip-irrigated soil systems (Figure.18).

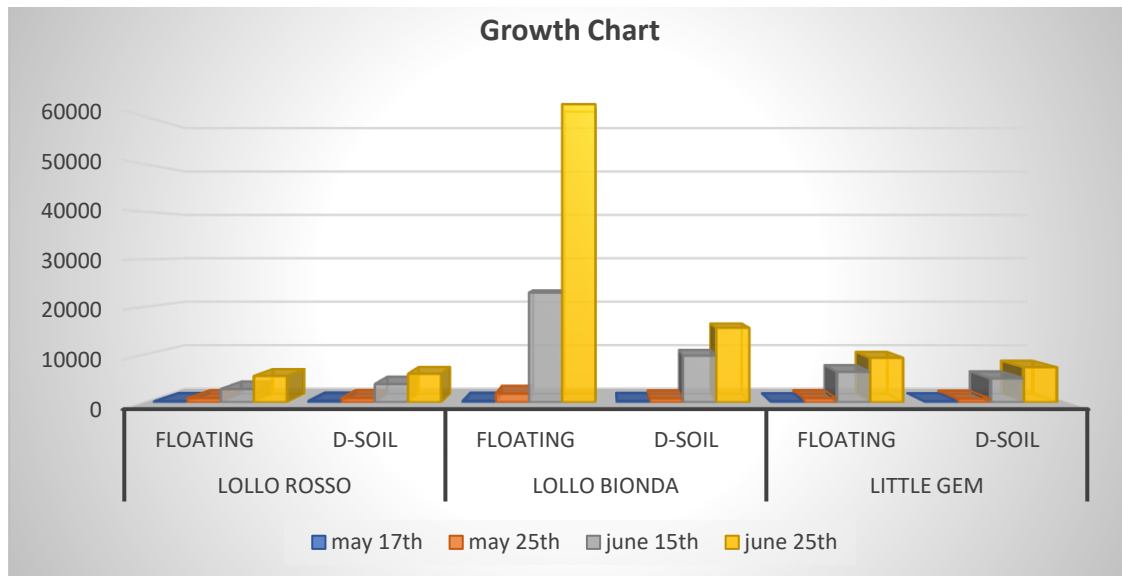


Figure 18: Plant Cylinder Volume (PH+CD) Growth for 38 Days

The picture below (Figure.19) was taken 15 days after transplanting. The overall better performance of the floating system is quite visible. The difference is particularly notable for the Lollo Bionda variety.



Figure 19: Plant Growth Visual Comparison in Floating and Drip-irrigated Soil Systems - Picture Was Captured 15 Days After Transplanting

The statistical analysis of plant growth was conducted in two steps. The one-way analysis of variance (ANOVA) was used to determine whether there were any statistically significant differences between the means of the plants grown in floating and drip-irrigated soil systems (Laerd Statistics, 2018). The test was performed separately for each lettuce type (variety).

ANOVA assumes that dependent variable is approximately normally distributed for each category of the independent variable and that there is homogeneity of variances. To make sure the results being accurate and unbiased, the homogeneity of variance for each combination of the groups of the two independent variables were tested using the Levene's test in Microsoft Excel. For all data sets analyzed, the obtained p-values were greater than the predetermined significance level of 0.05, which suggests that there is no significant violation of the assumption of homogeneity of variance. A normality test was performed using Microsoft Excel, and the obtained p-value ($p > 0.05$) confirmed that the data is normally distributed.

ANOVA results for three sets of data, one for each variety, are shown in tables (8), (9), and (10). An F-value > 4.26 and P-value < 0.05 indicates that there is a significant difference in plant growth between the floating system and drip-irrigated soil system.

Table 8: Lollo Rosso - ANOVA Results from Microsoft Excel for Volume Response

Lollo Rosso							
Summary	Groups	Count	Sum	Average	Variance		
	Floating	13	22990.83	1768.526	592632.8		
	D-Soil	13	24589.23	1891.479	485860.9		
ANOVA	Source of Variation	SS	df	MS	F	P-value	F crit
	Between Groups	98264.71	1	98264.71	0.182226	0.673272	4.259677
	Within Groups	12941925	24	539246.9			
	Total	13040189	25				

Table 9: Lollo Bionda - ANOVA Results from Microsoft Excel for Volume Response

Lollo Bionda								
Summary	Groups	Count	Sum		Average	Variance		
	Floating	13	269765.6		20751.2	3.56E+08		
	D-Soil	13	66687.07		5129.774	2501005		
ANOVA	Source of Variation	SS	df	MS	F	P-value	F crit	
	Between Groups	1.59E+09	1	1.59E+09	8.848527	0.006591	4.259677	Significant
	Within Groups	4.3E+09	24	1.79E+08				
	Total	5.89E+09	25					

Table 10: Little Gem - ANOVA Results from Microsoft Excel for Volume Response

Little Gem								
Summary	Groups	Count	Sum		Average	Variance		
	Floating	13	39800.8		3061.6	501265.5		
	D-Soil	13	31245.57		2403.505	670682		
ANOVA	Source of Variation	SS	df	MS	F	P-value	F crit	
	Between Groups	2815078	1	2815078	4.804102	0.038331	4.259677	Significant
	Within Groups	14063370	24	585973.7				
	Total	16878447	25					

The calculated p-value of 0.67 for Lollo Rosso implies that there is not enough evidence to suggest a meaningful difference in plant growth between the two systems for this variety. For Lollo Bionda the p-value (as computed from Microsoft Excel) is approximately 0.0066. This means that, the probability of obtaining the observed data under the assumption that the null hypothesis (no significant difference in plant growth between the floating and drip-irrigated soil systems) is true, is very low. In other words, the observed effect is unlikely to occur by chance alone and supports the notion that there is a meaningful difference in growth between the two systems.

An obtained p-value of 0.038 (smaller than the significance level of 0.05) for the Little Gem variety also suggest a significant difference in plant growth between the floating and drip-irrigated soil systems for this lettuce type. This means, if there were no significant difference between the two systems, there is only a 3.8% chance of obtaining a result as extreme as or more extreme than the one observed. Although the chance is higher than the 0.66% chance measured for Lollo Bionda, it still suggests that the observed difference in plant growth between the floating system and the drip-irrigated soil system is unlikely to be a random occurrence and provides evidence in support of a real and meaningful difference.

Comparing p-values for Little Gem (0.038) and Lollo Bionda (0.0066) conveys that there may be a stronger indication of a statistically significant difference for Lollo Bionda compared to Little Gem and that there is a higher likelihood of getting the observed differences in plant growth between the floating system and the drip-irrigated soil system for Lollo Bionda, compared to Little Gem, if the null hypothesis were true.

However, it's essential to acknowledge that part of the higher growth observed in Lollo Bionda, compared to Lollo Rosso, was influenced by the phenomenon of bolting (Figure.20). Bolting causes the plants to elongate rapidly, especially leading to increased plant height, which could falsely indicate higher growth rates. Therefore, this growth should not be entirely attributed to genuine positive growth but rather highlights that Lollo Bionda is more sensitive to temperature fluctuations. In more favorable environmental conditions, the difference in plant growth might not be as substantial.



Figure 20: Bolting Phenomenon in Lollo Bionda

Furthermore, we cannot definitively conclude whether the lower-than-usual growth in Lollo Rosso was solely due to unsuitable environmental conditions or not. This uncertainty could potentially impact the overall conclusion that "lettuce type influences the relationship between plant growth and growing method."

For the second phase of the statistical analysis, the interaction effect between the two categorical variables or factors (lettuce type and cultivation system) was examined using a two-way ANOVA (Table.11). Each factor has a finite number of possible values, which are known as levels. Lettuce variety (type) has three levels (Lollo Rosso, Lollo Bionda, Little Gem) and growing method has two levels (Drip-irrigated soil system and floating system).

Table 11: Two-way ANOVA from Microsoft Excel for Interaction Response

ANOVA: Two-factor with Replication						
Summary						
Floating	Lollo Rosso	Lollo Bionda	Little Gem	Total		
Count	13	13	13	39		
Sum	22990.83	269765.6	39800.8	332557.2		
Average	1768.526	20751.2	3061.6	8527.109		
Variance	592632.8	3.56E+08	501265.5	1.9E+08		
D-Soil	Lollo Rosso	Lollo Bionda	Little Gem	Total		
Count	13	13	13	39		
Sum	24589.23	66687.07	31245.57	122521.9		
Average	1891.479	5129.774	2403.505	3141.586		
Variance	485860.9	2501005	670682	3228318		
Total	Lollo Rosso	Lollo Bionda	Little Gem			
Count	26	26	26			
Sum	47580.07	336452.7	71046.37			
Average	1830.003	12940.49	2732.553			
Variance	521607.6	2.36E+08	675137.9			
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Growing Method	5.66E+08	1	5.66E+08	9.406114	0.003046	3.973897
Lettuce Type	1.98E+09	2	9.9E+08	16.4646	1.29E-06	3.123907
Interaction	1.02E+09	2	5.12E+08	8.511165	0.000481	3.123907
Within	4.33E+09	72	60128450			
Total	7.9E+09	77				

P-values measured for the growing method and lettuce type are less than the significant level of 0.05, which means these factors are statistically significant. These are the main effects in the model. The p-value of 0.00304565 suggests that the choice of growing method has a significant impact on the growth of the plants. The extremely small p-value of 1.29E-06 (or 0.00000129) indicates a highly significant effect of the lettuce type on plant growth.

Interaction effects determine that another variable influences the relationship between an independent and dependent variable. The extremely low P-value for the interaction effect suggests

that there is a statistically significant interaction effect between lettuce type and growing method on plant growth. To put it differently, the relationship between plant growth and growing method is not consistent and varies depending on the specific lettuce type being considered.

Taken together, the results indicate that the main effects of lettuce type and growing method, as well as their interaction effect, have a significant impact on plant growth. The null hypothesis (lettuce type does not influence the relationship between plant growth and growing method) is thus rejected based on the statistical evidence. The findings from the two-way ANOVA align with the results of the one-way ANOVA, which demonstrated a lack of sufficient evidence to support a significant difference in plant growth between the two methods for Lollo Rosso.

Yield

The yield in grams per square meter and the head weights were measured 39 days after transplanting. To determine the differences between soilless and soil-bound systems, expressing the yield in relation to the cultivation area is a more commonly used metric than the net total yield in grams or kilograms (Heuvelink and Marcelis, 2018). All the figures related to total harvest and total yield per unit area are added in tables (12) and (13) and the corresponding graphs can be found in figures (21) and (22).

The experimental plot was standardized to 1 square meter for both floating and drip-irrigated soil systems. While the actual area was larger in the soil system, it was treated as equal to the floating system based on the possibility of planting the seedlings with the same crop density. The spacing between the lateral lines and the emitters was wider than what would have been ideal

for lettuce cultivation because the drip irrigation system was initially designed to also accommodate larger-sized vegetables, such as tomatoes or beans, for practicing crop rotation.

Table 12: Total Harvest Obtained from Floating and Drip-irrigated Soil Systems

Total Harvest (g)	Lollo Rosso	Lollo Bionda	Little Gem	
	250	600	800	Soil-based
	300	2400	2000	Floating

Table 13: Total Yields Obtained from Floating and Drip-irrigated Soil Systems

	Lollo Rosso	Lollo Bionda	Little Gem	
Total Yield (g/m ²)	250	600	800	Soil-based
	300	2400	2000	Floating
Average head weight (g/m ²)	13.9	46.1	44.5	Soil-based
	17.64	120	100	Floating

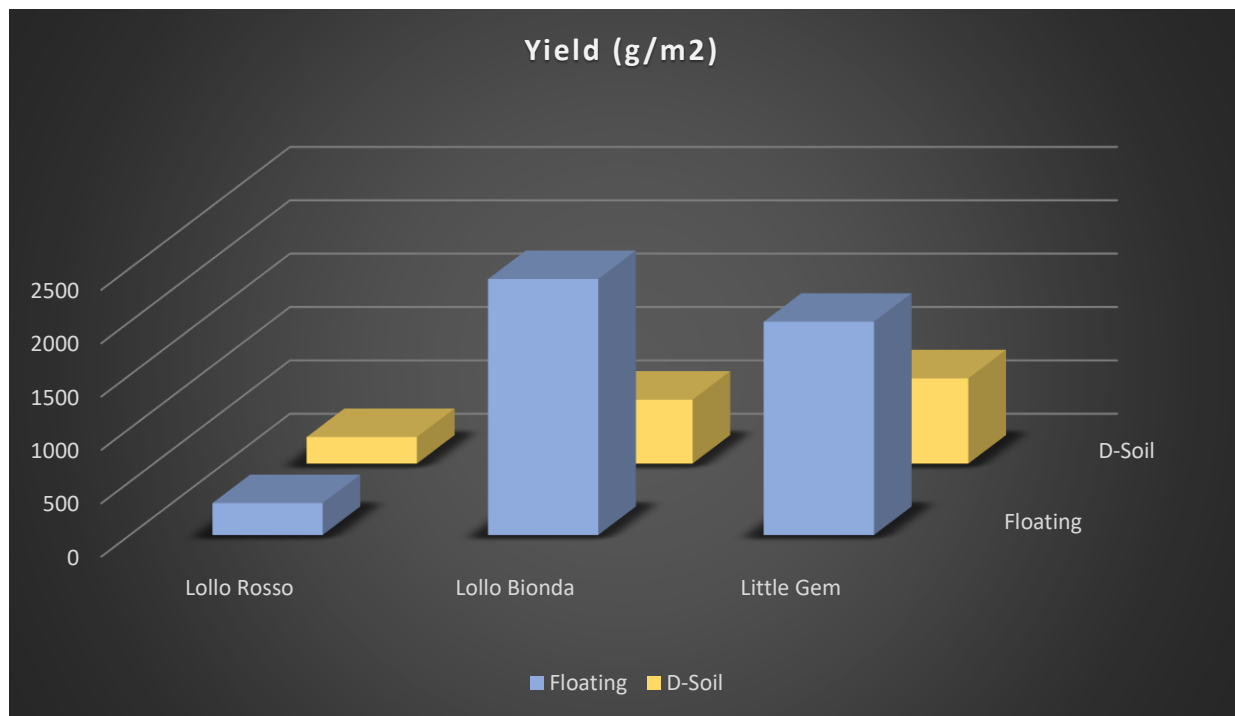


Figure 21: Yield (g/m²)

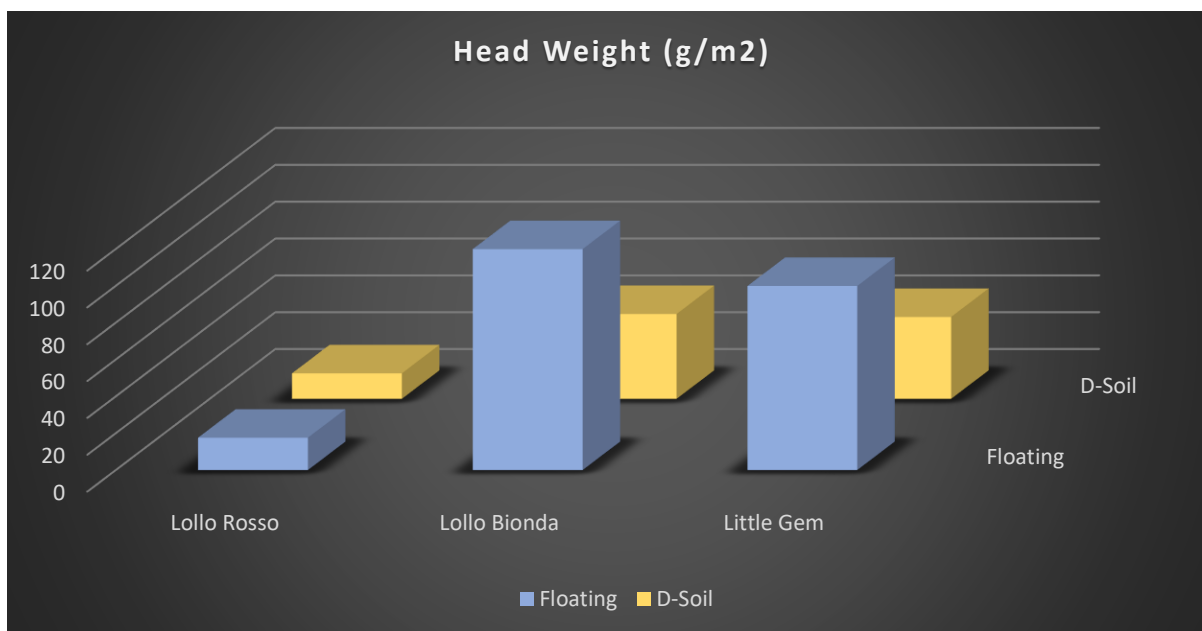


Figure 22: Head Weight (g/m²)

The yields for Lollo Rosso and Lollo Bionda varieties were found to be lower than expected. Madar et al, (2019) reported a head weight of 170.77 and 185.59 grams for Lollo Rosso and Lollo Bionda, respectively. Another study done by Matysiak et al (2022), reported a very high fresh weight of 240 and 350 grams for the Little Gem variety in a controlled environment. Our findings were also lower compared to the reported average of 150 grams for the same varieties cultivated in hydroponic greenhouses in Iran. (Fosuli, 2022). These lower-than-expected results highlights the importance of growing conditions (soil type, temperature and season, etc.).

Temperature was found to affect total yield and head weights of the three lettuce types, although the effect was more pronounced in drip-irrigated soil method. All varieties used for the purpose of this study are determined to be cool-season crops, with optimal daytime growth and development occurring at temperatures between 18 and 25°C, and nightly temperatures ranging

from 10 to 15°C (Lazo & Gonzabay, 2020). The effect of temperature was confirmed by the observation of ‘bolting’ in a few plants of Lollo Bionda type, a phenomenon in which the plant rapidly produces a tall, elongated stem instead of leaves. Bolting is a natural response to stress and is triggered by high temperatures, among other causes.

Given the nutrient solution content, the actual head weights can vary in hydroponic systems. Monteiro Filho et al (2016), examined the head weights of three varieties of curly lettuce under eight different nutrient solutions and reported mean weights ranged from 37 to 215 grams. Higher nitrogen concentrations in the nutrient solution could have been better conducive for achieving heavier head weights.

While it was expected that the drip-irrigated soil system would have a lower yield performance, the staggering yield increases of 150 to 300% observed for the Lollo Bionda and Little Gem varieties in the floating system highlighted the underperformance of the soil system. Under similar conditions as conventional soil systems, Heuvelink and Marcelis (2018) have reported yield improvements ranging from 15 to 40% in substrate cultures.

The lower-than-expected yield in the soil-based system could partially be justified by the organic approach employed; unlike the floating system, the soil system did not involve the application of any chemical pesticides or fertilizers. It is widely accepted that organically grown crops tend to have lower yields compared to conventional soil-based systems (De Ponti et al., 2012; Zhou et al., 2021). However, this explanation alone does not fully account for the abnormally low yield observed in drip-irrigated soil system. Other factors, such as adverse weather conditions and poor soil content, may have contributed to the underperformance of the drip-irrigated soil system.

Staggering higher yields have been reported for hydroponic systems in several studies. An 11-fold increase in lettuce production was reported by Barbosa et al, (2015) and Qureshi (2017) reported 8.35 times higher yield for hydroponic tomato production in Pakistan. However, these staggering yield differences were almost entirely the result of the optimal growth conditions and longer cultivation seasons in controlled environments, such as greenhouses (Heuvelink and Marcelis, 2018; Qureshi, 2017). When comparing a single growing period under similar conditions, the maximum yield improvements in hydroponic systems are generally observed to range from 15% to 40% (Heuvelink & Marcelis, 2018).

Plant Survival Rate

Hydroponic plants had a higher survival rate compared to the drip-irrigated soil-grown lettuces (Table.14), and this was account to a multitude of factors, including but not limited to pests. Despite the application of identical integrated pest management treatments for both growing methods, soil plants exhibited greater susceptibility to pest infestations. This can be explained by the greater abundance of beneficial bacteria and microbes that pests thrive on in soil conditions (Resh & Howards, 2012). This conclusion aligns with the findings of Treftz and T. Omaye (2015), who reported that growing strawberries in soil media can result in increased pest issues compared to hydroponics.

Table 14: Plant Survival Rate

	Lollo Rosso	Lollo Bionda	Little Gem	
Initial Number of Plants	20	20	20	Soil-based
	20	20	20	Floating
Number of Plants Survived	18	13	18	Soil-based
	17	20	20	Floating
Plant Survival Rate	90%	65%	90%	Soil-based
	85%	100%	100%	Floating

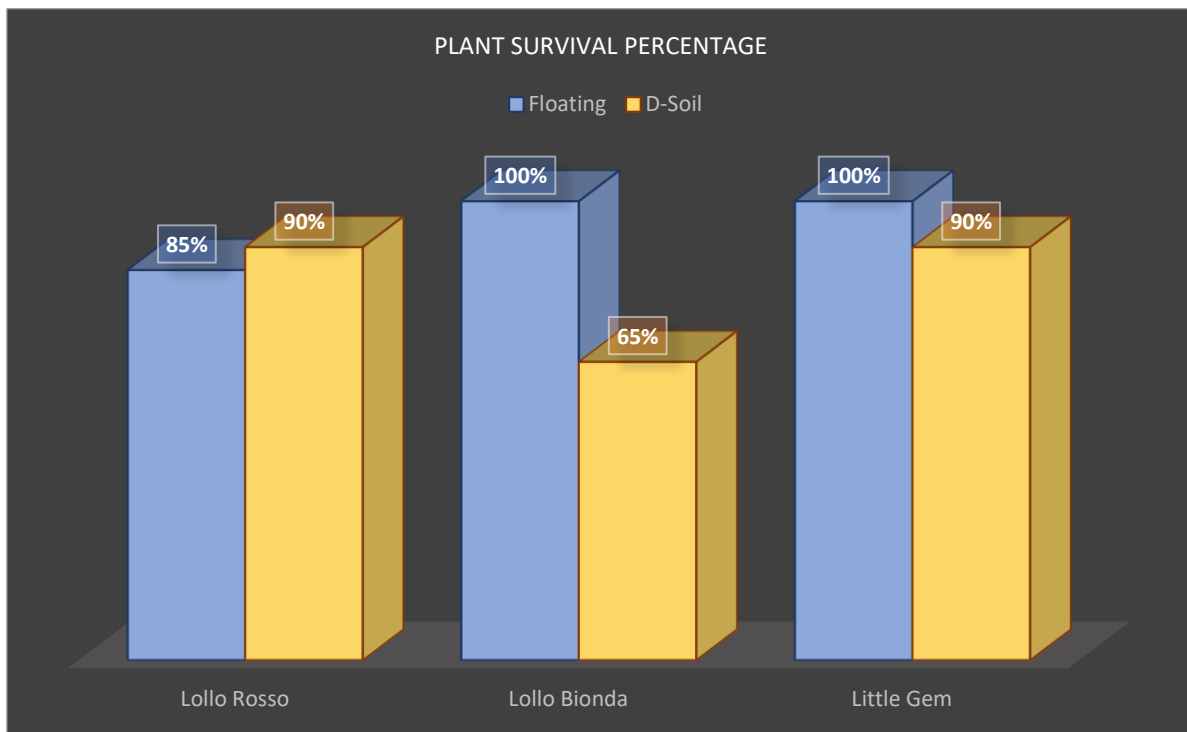


Figure 23: Plant survival rate in floating and drip-irrigated soil systems

The 85% plant survival rate observed in Lollo Rosso was due to the treatment method used to remove algae from floating roots after replacement (1). As an ultimate solution, the nutrient solution was replaced, reservoir was cleaned, and roots were washed using high-pressure water to eliminate algae. However, before attempting the washing treatment, a diluted solution of hydrogen

peroxide (2.5 milliliter per liter) was tested as a root dip for disinfection. A sample of three Lollo Rosso floating Lettuce plants was used to assess the effectiveness of this method. After being soaked and coated with the H₂O₂ solution, the entire plants turned white. Although their color eventually returned after being immersed in the nutrient solution again, the whole sample desiccated and withered after a few days. Had these three plants been treated in the same manner as the rest of the sample, Lollo Rosso would have achieved a 100% survival rate, similar to the other two varieties.

Temperature data was collected from Iran Meteorological Organization (IRIMO, 2022) and the trends are presented in Figure (24). Temperatures began surpassing 30°C in June, exceeding the optimal maximum diurnal temperature of 25°C. Lollo Bionda variety were found to be more vulnerable to temperature fluctuations and pest infestations, whereas Little Gem exhibited greater tolerance towards high temperatures.

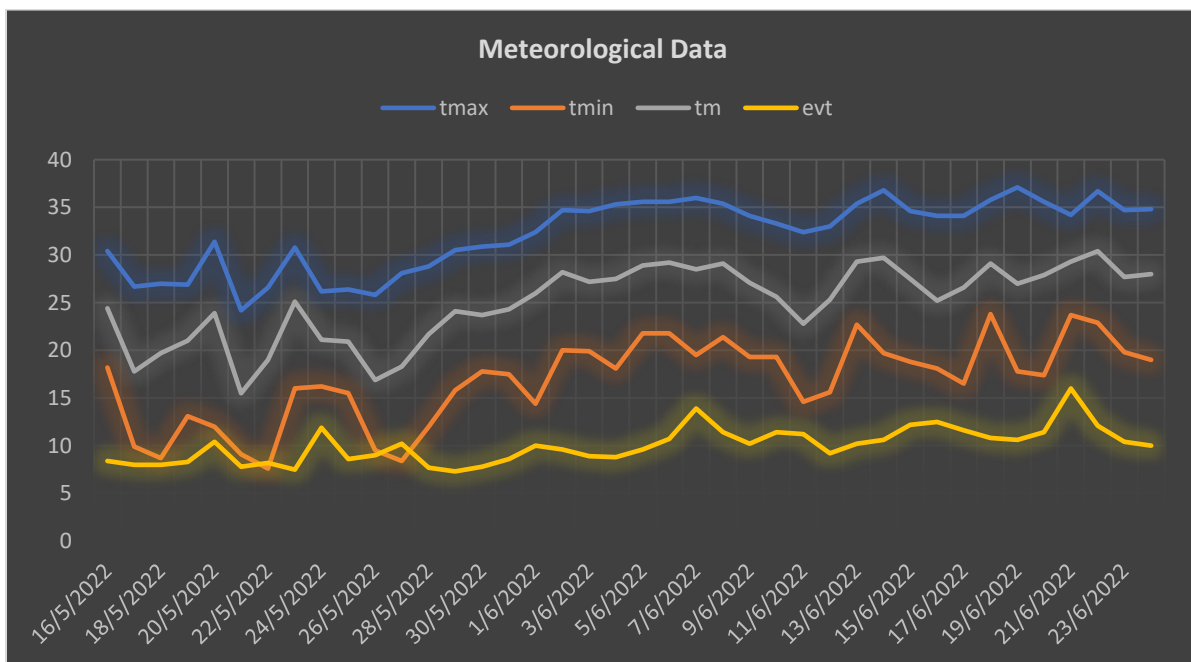


Figure 24: Meteorological Data (max, min, and mean temperature in °C + evapotranspiration rate)

The observations have confirmed that using a floating medium can offer plants a more favorable and stable growth environment, even when atmospheric conditions, such as temperature, are not within the optimal range. However, this doesn't mean that soil-based cultivations are inherently flawed. When atmospheric conditions and timing are appropriate, lettuce plants grown in soil can better resist biotic and abiotic stresses.

In addition to adverse climatic conditions, the spatial characteristics of the land plot posed additional challenges, making it generally less suitable for optimal lettuce growth compared to large-scale open-field agricultural plots. The experimental plot was surrounded by barriers (walls and trees), which restricted and altered soil temperature. Farmlands, on the other hand, have unobstructed and consistent wind flow, which aids in reducing soil temperature and creating a more favorable environment for lettuce growth, particularly during late spring when temperatures start to rise gradually.



Figure 25: Contrasting Quality of three lettuce Type: Healthy, Marketable vs. Dried, Pest-infected Specimen

Production Costs

This section provides an itemized breakdown of the expenses associated with the production of lettuce, as presented in Tables (15) through (19). Table (15) outlines the initial investment costs in Iranian Rial (IRR). The major portion of investment costs was attributed to the irrigation system for the soil-based system, while floating structure and nutrient solution monitoring devices had the major contribution towards the hydroponic system. Depreciation for initial investment was calculated using the straight-line method, whereby assets were divided by their expected useful life to determine annual depreciation costs. Given that two crops per annum can be produced in open-air settings in the region, the cost was split between the two.

Initial investment costs were estimated at IRR 450,000 for a $3m^2$ soil-based system and IRR 3,850,000 for the floating system. The drip irrigation system accounted for 50% of total initial investment costs for the soil-based system. Reservoir construction and the purchase of pH and EC meters made up 70% of initial investment costs for the floating system.

Table 15: Initial Investment Costs for Floating and Drip-irrigated Soil Systems (3 m²)

	Item	Initial Cost (IRR)	Useful Life Years	$\frac{\text{Annual Inv Cost}}{2}$ (IRR)	% of Cost
Soil-based System	Shade	1,000,000	5 years	100,000	22%
	Drip Irrigation System	4,500,000	10 years	225,000	50%
	Sprayer	2,000,000	8 years	125,000	28%
	Total (IRR)	7,500,000	-	450,000	100.0
Floating System	Reservoir Construction	5,000,000	5 years	500,000	13%
	Shade	1,000,000	5 years	100,000	2.6%
	pH Meter	22,250,000	10 years	1,112,500	28.9%
	EC Meter	22,250,000	10 years	1,112,500	28.9%
	Air Pump	3,000,000	5 years	300,000	7.8%
	Styrofoam	1,400,000	2 years	350,000	9%
	Net Pot	1,000,000	2 years	250,000	6.5%
	Sprayer	2,000,000	8 years	125,000	3.3%
	Total	-	-	3,850,000	100.0

Table (16) details variable costs associated with the materials. For the drip-irrigated soil system, these items were categorized as seedling, fertilizer, pesticide expenses, and water consumption. For the hydroponic system, they were further classified into seedling, fertilizer, and pesticide costs, water and electricity consumption, and the chemical analysis of water initially done in order to prepare the nutrient solution formula. The total variable costs for materials were found to be six times higher for the floating system, with the primary contributor being the higher costs of fertilizers and labor, as well as the expenses associated with conducting chemical water analyses.

Table 16: Variable Costs for Floating and Drip-irrigated Soil System (3 m²) - Materials

	Item	Total Cost (IRR)	% of Cost
Soil-based System	Seedling	300,000	28.4%
	Compost	384,615	36.5%
	Manure	153,846	14.6%
	Water	12,760	1.2%
	BT Pesticide	50,000	4.7%
	Hydrogen peroxide	153,846	14.6%
	Total	1,055,067	100.0
Floating System	Seedling	300,000	2.2%
	Electricity	100,000	0.7%
	Water	48,000	0.3%
	BT Pesticide	50,000	0.4%
	Water Analysis	6,000,000	45%
	Calcium Nitrate $\text{Ca}(\text{NO}_3)_2$	357,810	2.7%
	Potassium Sulphate K_2SO_4	84,600	0.6%
	Root P (Phosphorus Pentoxide P_2O_5)	335,000	2.5%
	Potassium Nitrate KNO_3	378,000	2.8%
	Magnesium Sulphate $\text{MnSO}_4 \cdot 7\text{H}_2\text{O}$	907,420	6.8%
	Fe Chelated	249,000	1.9%
	Manganese Chelated	569,830	4.3%
	Zinc Chelated	600,370	4.5%
	Boron Chelated	23,500	0.2%
	Sodium Molybdate	3,750	0.03%
	Copper Sulphate	2,130	0.02%
	Nitric acid HNO_3	200,000	1.5%
	Hydrochloric acid HCl	1,650,000	12.3%
	Tartaric acid $\text{C}_4\text{H}_6\text{O}_6$	1,500,000	11.2%
	Total	13,359,410	100.0

Table (17) outlines the variable costs related to labor for both drip-irrigated soil and floating systems. The cost of labor associated with weeding was non-existent in both systems as drip irrigation systems effectively minimizes weed growth. Notably, the daily management cost of the floating system was 2.5 times higher than that of the drip-irrigated soil system, mainly due to the reduced time required for weeding and irrigation. The amount of manual labor required in

hydroponic systems depends on the design's sophistication and the extent to which automation can be implemented. While hydroponic systems have the potential for complete automation, our simplified hydroponic system lacked automatic control measures, resulting in a higher level of manual work compared to the drip-irrigated soil system.

No one was hired for the labor work, but the time spent on labor was still taken into account for economic evaluation. For every hour of labor, 250,000 IRR (approximately 80 cents) were considered. It was based on the prevailing wage at the time, where a laborer working 8 hours would earn 2,000,000 IRR (approximately 6.6 dollars).

Table 17: Variable Costs for Floating and Drip-irrigated Soil-based System (3 m²) - Labor

	Item	Total Cost (IRR)	% of Cost
Soil-based System	Land Preparation	2,500,000	19%
	Shade Setup	1,000,000	7.5%
	Weeding	-	
	Planting	1,000,000	7.5%
	Pesticide Spraying	500,000	4%
	Harvesting	250,000	2%
	Daily Management	7,800,000	60%
	Total	13,050,000	100.0
Floating System	Making the Floating Raft Bed	1,000,000	4.5%
	Shade Setup	1,000,000	4.5%
	Planting	250,000	1%
	Pesticide Spraying	500,000	2%
	Harvesting	250,000	1%
	Daily Management	19,500,000	87%
	Total	22,500,000	100.0

Table (18) illustrates that labor costs account for the majority of the total variable costs, constituting over 60% of the total variable costs in both floating and drip-irrigated soil systems. Electricity and water costs, both show a low representation within the total variable costs. The under-representation of irrigation water in the total variable costs implies that the economic viability of the system is not significantly influenced by water consumption considerations. Rather,

it is suggested that the impact of water consumption should be evaluated within the context of environmental analysis, particularly in light of emerging concerns around water scarcity within the country and region.

Table 18: Variable Costs for Floating and Drip-irrigated Soil Systems (3 m²) – Materials + Labor

	Item	Total Cost (IRR)	% of Cost
Soil-based System	Seedling	300,000	2.1%
	Fertilizer and Pesticide	742,307	5.3%
	Water	12,760	0.1%
	Labor	13,050,000	92.5%
	Total	13,363,502	100.0
Floating System	Seedling	300,000	0.8%
	Fertilizer and Pesticide	6,961,410	19.4%
	Water Analysis	6,000,000	16.7%
	Water	48,000	0.2%
	Electricity	100,000	0.3%
	Labor	22,500,000	62.6%
	Total	35,909,410	100.0

Table (19) presents a comparative analysis of the total cost of producing lettuce in a 3 m³ floating and drip-irrigated soil system. The interest for total investment and variable costs were also included, which was calculated using a simple interest rate of 23%, set by the central bank of Iran for 2023. Since two crops can be grown annually in open-air, the interest rate was halved.

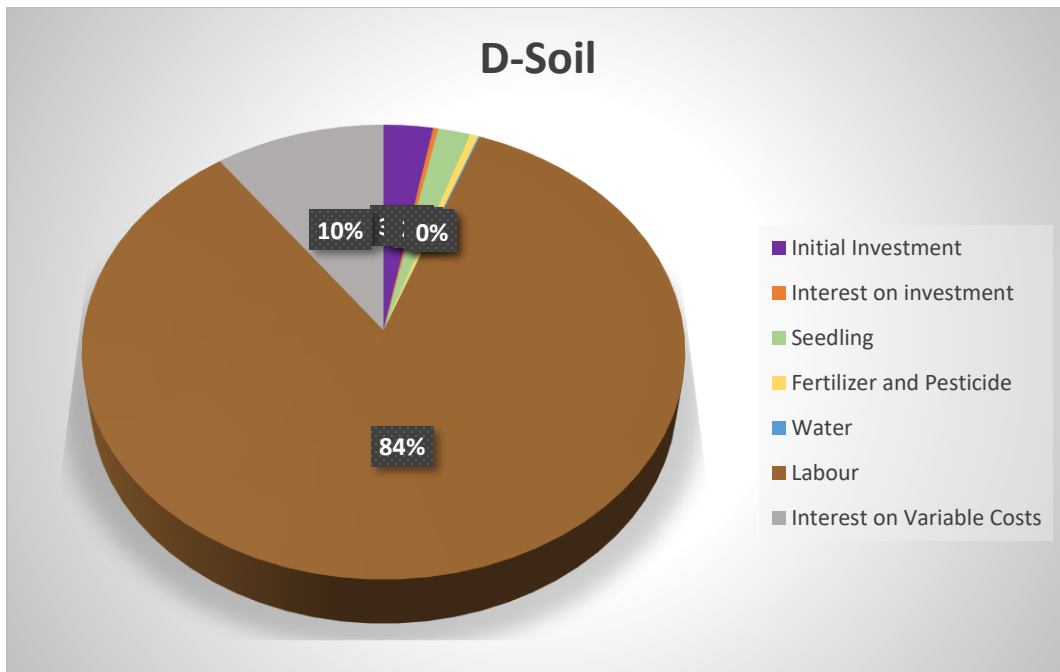


Figure 26: Cost Breakdown for Drip-irrigated Soil System

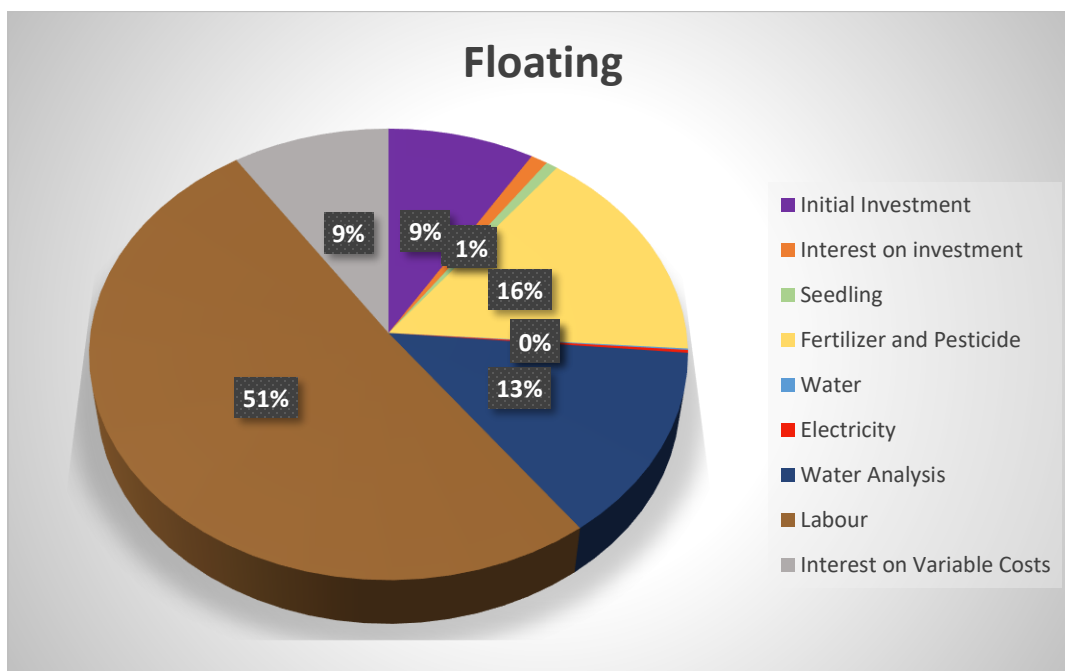


Figure 27: Cost Breakdown for Floating System

Interest rate is an important factor to be considered for countries experiencing slow economic growth, high inflation and volatility, the very characteristics of Iran's economy for the recent decade (Rome, 2022). Interest rate represents the opportunity cost of the invested money in agriculture. It signifies the potential earnings that could have been generated if the money had been invested in an alternative opportunity with the same level of risk.

High interest rates, hyperinflation and low economic growth erodes the value of money, killing investment returns, and making it challenging to sustain profitability and ensure a stable return on investment. Moreover, the uncertainty and volatility associated with hyperinflation make long-term planning in agriculture more challenging and less attractive compared to short-term business ventures that can adapt to rapidly changing market conditions, and allow for quicker turnover and faster realization of profits (FAO, nd). The interest rate could thus serve as a yardstick for comparing the potential returns of different investment opportunities.

Table 19: The Cost Comparison of Floating and Drip-irrigated Soil Systems (3 m²)

	Item	Soil-based System		Floating System	
		Total Cost	% of Cost	Total Cost	% of Cost
Fixed Costs (1)	Total $\frac{\text{Annual Inv Cost}}{2}$ (IRR)	450,000	2.9%	3,850,000	8.7%
	Interest on total $\frac{\text{Annual Inv Cost}}{2}$ (IRR)	51,750	0.3%	442,750	1%
	Total	501,750	3.2%	4,292,750	9.7%
Variable Costs (2)	Seedling	300,000	1.9%	300,000	0.7%
	Fertilizer and Pesticide	742,307	0.5%	6,961,410	15.7%
	Water	12,760	0.1%	48,000	0.1%
	Electricity	-		100,000	0.2%
	Water Analysis	-		6,000,000	13.5%
	Labor	13,050,000	84.3%	22,500,000	50.8%
	Interest on total Variable Costs (11.5%)	1,536,802	10%	4,129,582	9.3%
	Total	14,900,304	96.8%	40,038,992	90.3%
Total Costs (1+2)		15,402,054		44,331,742	
Cost per Head of Lettuce		256,701		738,682	
Cost per Kg of Lettuce		9,334,578		9,432,285	

The implementation of the floating system involves a notable increase in both the investment as well as the variable costs compared to the soil system. The total cost incurred by the floating system was 2.8 times higher than that of the drip-irrigated soil system. However, upon a closer examination of the production costs per kilogram of lettuce, the costs were found to be almost similar (Figure.28). This parity in costs stemmed from the substantial disparity in yield between the two systems, with the floating system having a 2.8 times higher yield, which effectively counterbalanced the 2.8-fold increase in production costs.

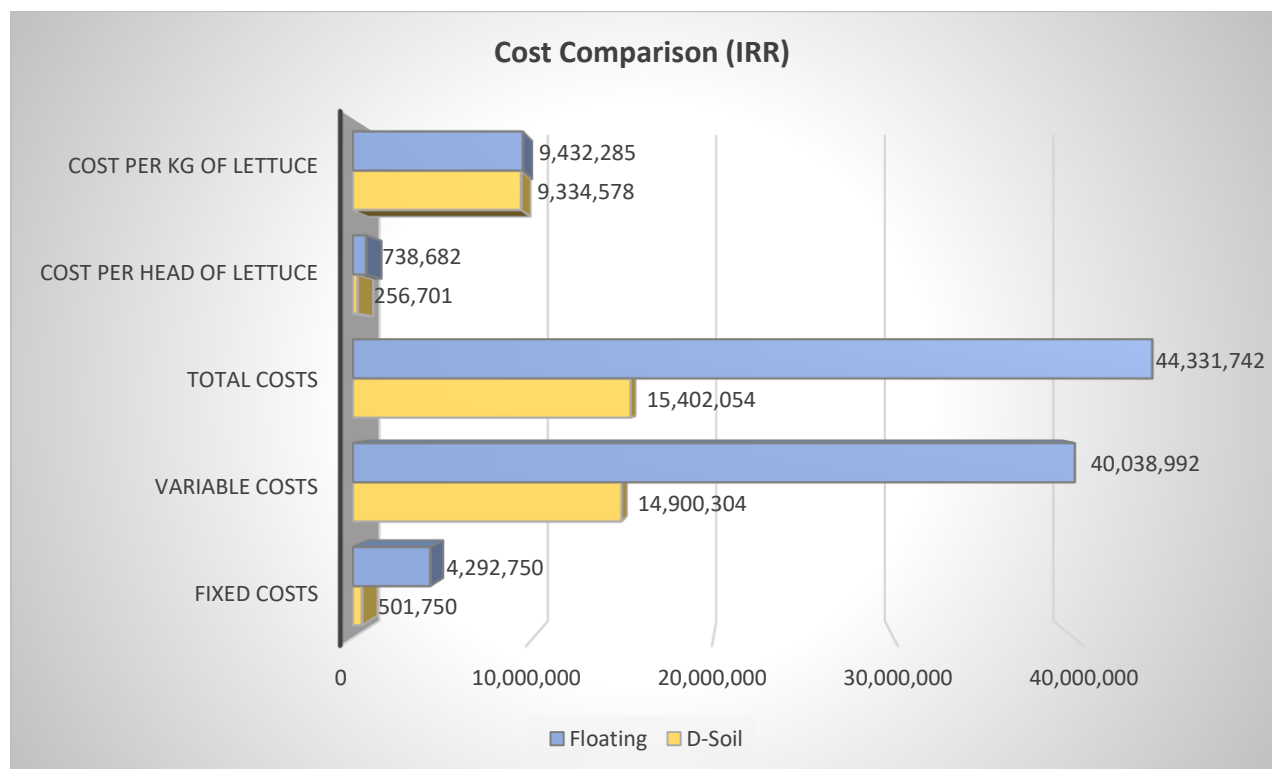


Figure 28: The Cost Comparison of Floating and Drip-irrigated Soil Systems (3 m²)

The obtained figures should be interpreted with caution since the experiment was carried out during the off-season, in which the higher temperature had a more pronounced effect on the soil-grown lettuces than on those in the floating system. It is possible that the differences in yield

between the two systems would not have been as pronounced if the experiment had been conducted during a cooler time of the year.

Calculating the revenue and profit was out of the scope of this study. Drawing conclusions about the overall profitability of agricultural production based on a small sample cause biased inference. To accurately assess profitability, economies of scale need to be considered. Economies of scale refers to the cost advantages that a business can achieve by increasing the scale or size of its production. For example, in larger hydroponic production systems, the cost of chemical water analysis comprises a much smaller proportion of the total costs, and the higher revenue resulting from increased production could more easily offset those costs; while in this study it comprised 17% of total variable costs and a good 45% of total variable costs for the materials. Also, in reality, the labor cost of managing a 50 m^2 and 200 m^2 ; or a 500 m^2 and 1000 m^2 greenhouse doesn't differ significantly. That is why greenhouse businesses smaller than 1000 m^2 doesn't justify the expenses incurred for labor, fertilizer, water, electricity, and other operational costs.

As the scale of production increases, the cost per unit of input, such as seeds, fertilizers, and equipment, may decrease due to bulk purchasing or leasing. The cost of hiring permanent workers for larger-scale production is lower than hiring daily wage workers, leading to further cost savings in labor which according to several studies reviewed in chapter (2) constitutes a good proportion of total costs. Furthermore, larger operations can invest in more advanced technology and equipment that can reduce labor costs and improve productivity.

On top of the limitations posed by the small plot of the experimental setup, the lower-than-expected yield of the products further undermines the reliability of revenue and profit calculations. Nevertheless, the comparison between the two systems can offer insights regarding their

respective economic costs. Though, in general, I found such a general comparison pertinent for a context-specific assessment to find out the more suitable method which provides a better cost-benefit tradeoff. When considered alongside other relevant environmental variables in the Iranian context, it can provide an insight on when and under what circumstances each system is most suitable.

Environmental Analysis

Water Consumption

Crop water productivity (CWP) of all lettuce types were compared in both methods. CWP is an important indicator of agricultural water use efficiency and is measured in terms of yield return (Igbadun et al., 2006) and as the amount of crop yield generated (in grams) per unit volume of water utilized (in m³).

Drip-irrigated soil system had higher CWP compared to the floating system. This could be ascribed to meticulous control over water application and reduced water loss due to run off or evaporation while using drip irrigation.

Table 20: CWP of Drip-Irrigated Soil and Floating Systems

Lollo Rosso					
	Marketable Plants	Total Yield (g)	Yield/Plant	Water Consumption/Plant (L)	CWP (g/L)
D-soil	18	250	13.9	10.6	1.31
Floating	17	300	17.6	40	0.4
Lollo Bionda					
	Marketable Plants	Total Yield (g)	Yield/Plant	Water Consumption/Plant (L)	CWP (g/L)
D-soil	13	600	46.2	10.6	4.4
Floating	20	2400	120	40	3

Little Gem					
	Marketable Plants	Total Yield (g)	Yield/Plant	Water Consumption/Plant (L)	CWP (g/L)
D-soil	18	800	44.4	10.6	4.2
Floating	20	2000	100	40	2.5

The total water consumption in floating system was approximately 3.8 times higher in comparison to the drip-irrigated soil system (Figure.29).

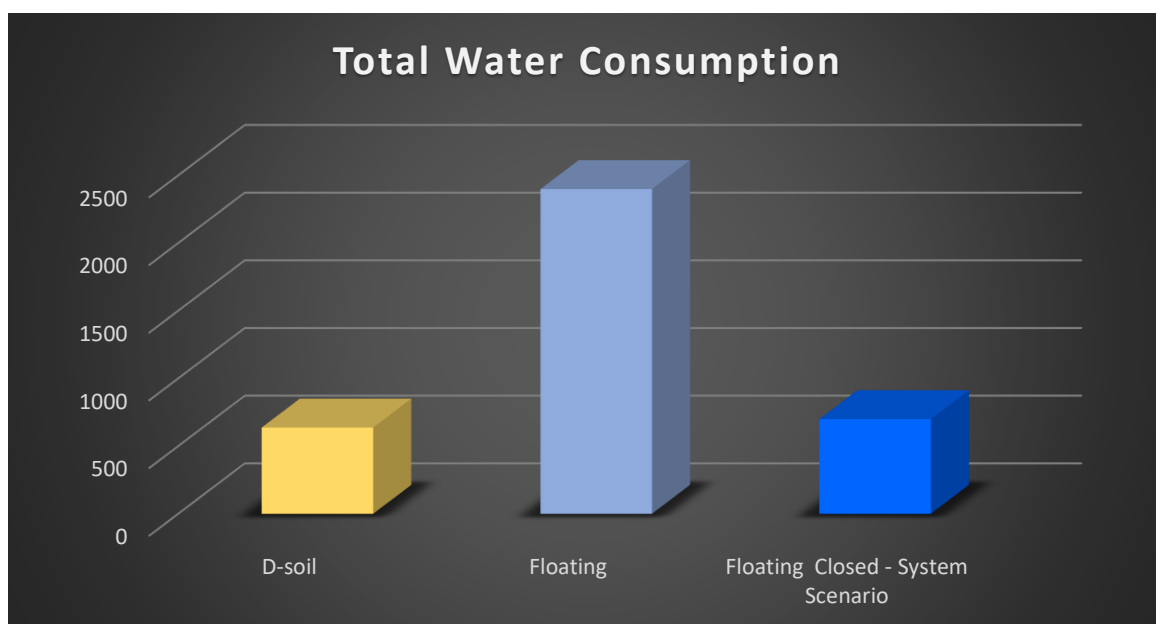


Figure 29: Total Water Consumption (in Liters)

Even when examining water usage in relation to yield, the drip-irrigated soil system still had better performance. The Crop Water Productivity (CWP) for Lollo Rosso, Lollo Bionda, and Little Gem varieties was 3.3, 1.5, and 1.7 times higher, respectively, in the drip-irrigated system (Figure.30).

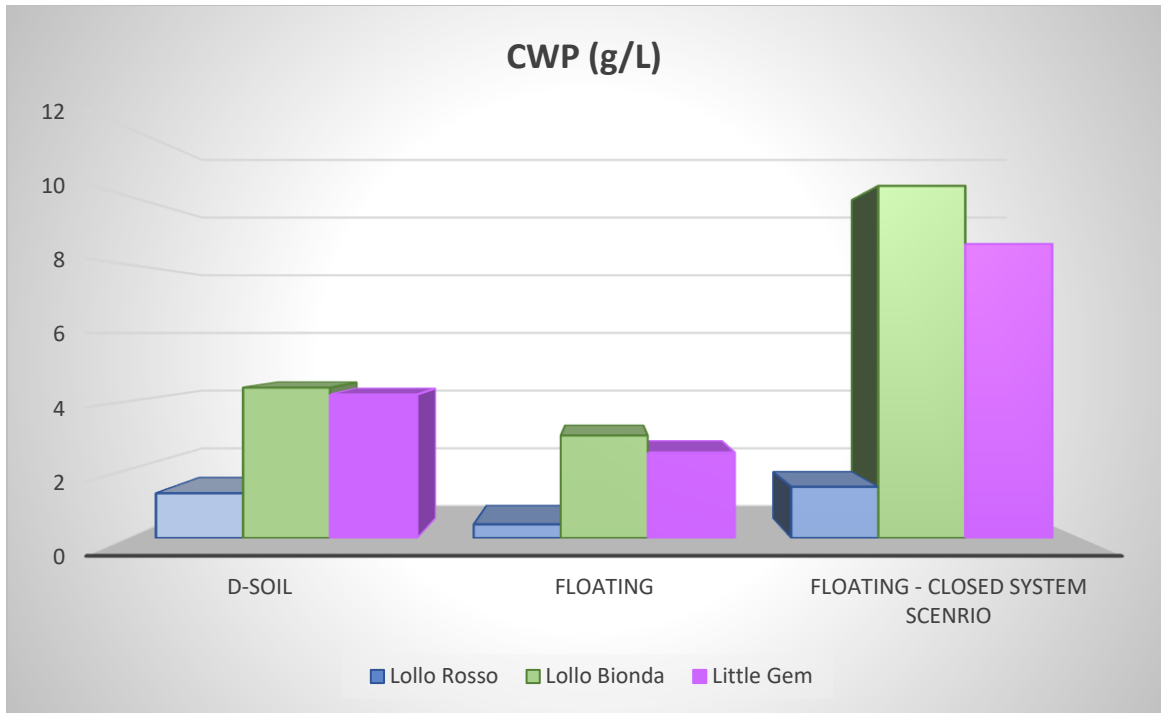


Figure 30: Crop Water Productivity (CWP) - (g/L)

The nutrient solution in floating system was replaced almost every other week, as per the recommendation of the agricultural consultant, Saied Saheb-Fosuli (2022). This practice was in line with the findings of Jones (2014), who reported that the nutrient solution undergoes physical and chemical changes on a daily basis. These changes occur due to factors such as plant root absorption, precipitation, microbial activities, as well as the addition of substances produced by the sloughing off of root material (root exudates). In short-term (less than 5 days), physical and chemical changes of nutrient solution is of little consequence, although volume restoration may be necessary. However, if the nutrient solution is to be used for an extended period of time, spent elements must be replenished and suspended particles filtered out to maintain its efficacy.

Many growers are now shifting towards semi-closed systems (Heuvelink & Marcelis, 2016), wherein the nutrient solution is reused by adding more water and nutrients instead of

replacing the entire solution, resulting in 20 to 40% less water and nutrient usage (Nederhoff & Stanghellini, 2010). In these systems, the nutrient solution is constantly monitored, adjusted and controlled to maintain proper nutrient ratios (Abd-Elmoniem et al., 2006). Conservation of water and nutrients in closed systems significantly reduces waste, which has both economic and environmental benefits. A range of savings have been reported by several studies, from 33% reduction in water consumption compared to open systems (Grewal et al., 2011; Christie, 2014), to 40% (Rufi-Salis et al., 2020) and even greater than 50% (Giuffrida & Lipri, 2003; Fayezizadeh et al., 2021; Rodriguez-Jurado et al., 2020). Bradley & Marulana (2001) reported that simplified hydroponic technology with recirculation reduces water use for crops by 90% compared to conventional soil-based systems for tomato production, while open soilless system saved about 65-70% of water applied by conventional farmers for tomato under plastic house (Fandi et al., 2008).

Assuming a closed system where nutrient solution is recycled until the end of the experiment, water consumption could have decreased to 700 liters, which was significantly lower than the 2400 liters used in the current arrangement. However, even with this improvement, the total water consumed by the floating system would still be higher than the 638 liters consumed by the drip-irrigated soil system (Figure.29). Nevertheless, the Crop Water Productivity (CWP) of the floating system would have been 2.3 times and 2 times higher for Lollo Bionda and Little Gem types than that of similar types grown in the soil system (Figure.30). Although, it would remain almost similar for the Lollo Rosso type, had the lettuces been planted under the same environmental conditions, resulting in a similar lower than expected yield.

Table 21: CWP of Floating System in Closed System Scenario

Lollo Rosso					
	Marketable Plants	Total Yield (g)	Yield/Plant	Water Consumption/Plant (L)	CWP (g/L)
Floating	17	300	17.6	11.6	1.5
Lollo Bionda					
	Marketable Plants	Total Yield (g)	Yield/Plant	Water Consumption/Plant (L)	CWP (g/L)
Floating	20	2400	120	11.6	10.3
Little Gem					
	Marketable Plants	Total Yield (g)	Yield/Plant	Water Consumption/Plant (L)	CWP (g/L)
Floating	20	2000	100	11.6	8.6

The financial benefits derived from minimizing the use of fertilizers in closed hydroponic systems cannot be overstated, with one study concluded that costs savings of 36% were achieved by using 23% less K₂POH, 57% less KNO₃, and 58% less MgSO₄ compared to open hydroponic systems for lettuce production (Christie, 2014). Similar findings were reported in a study by Tuzel and colleagues (Tuzel et al, 1999), which showed a 35% reduction in nutrient solution for cucumber. Recent studies have shown even greater cost savings associated with closed hydroponic systems. A study by Fayeizadeh et al, (2021) reported a staggering 97% reduction in fertilizer consumption in a closed system compared to an open system. Ruffi-Salis et al, (2020) concluded that closed hydroponic systems reduce nutrient consumption by 35% to 54% daily in green pea production. According to Mendez-Cifuentes (2020), 53 liters of nutrient solution were used to produce 1 kg of tomatoes in an open system, while only 22 liters were used in a closed system. Another study conducted in Ahvaz, Iran, by Alemzadeh Ansari and Darei (2022) demonstrated that the closed system increased crop yield, water productivity, and nutrient use efficiency by 22.63%, 80.81%, and 81.92%, respectively.

In the volatile economy landscape of Iran, cost savings can mean the difference between profitability and failure. Amir Hamidi (2022), a well-known hydroponic greenhouse grower in

Isfahan, a region grappling with water scarcity, brought up the fact that growers tend to reuse nutrient solutions for up to two crop cycles, which is primarily driven by economic incentives rather than simply conserving water. This corresponds with the findings of Christie's (2014) study on closed hydroponic systems, which concluded that lettuce can be grown for at least two consecutive runs (approximately 8-10 weeks) without discarding water or nutrient. Doing so, total water consumption for test systems was approximately 33% less than the total water consumption for control systems.

Considering an average weight gain of 150 grams per head for all 60 lettuce plants in our experiment, the water footprint for the irrigation system would amount to 70 liters per kilogram (L/kg), which falls below the conventional global water consumption footprint. However, it remains higher than the reported 20 ± 3.8 L/kg for hydroponically grown lettuce (Barbosa et al., 2015). Barbosa et al, (2015) considered 250 ± 25 L/kg for lettuce grown conventionally in southwestern Arizona. The global average water footprint of lettuce is 240 liter/kg. The figure is different from place to place. For example, in China and the USA, the two largest producing countries, lettuce has a water footprint of 290 and 110 liter/kg, respectively (Maestero-Valero et al., 2018).

Even when envisioning a scenario with 120 crops, each weighing an average of 150 grams, cultivated in two consecutive runs using the same nutrient solution in a floating system, the resulting water footprint would be 38 L/kg. Nevertheless, this figure still surpasses the suggested values by Barbosa et al, (2015). A difference that could be attributed to lettuce type and factoring in the average weight per head for different lettuce types, including heavier varieties like Romaine lettuce, which typically weigh between 200 to 450 grams per head.

Recycling nutrient solution presents its own challenges. To maintain a target electrical conductivity (EC) level in the recycling solution, growers often adjust EC using water and nutrients, assuming that this will provide sufficient nutrients to plants. However, this may not ensure optimal concentration of individual nutrients in the recycling solution as EC measurements doesn't give any clue regarding the levels of individual ions dissolved in the solution. It can be difficult to ensure the optimal levels of individual plant nutrients in the solution, and some nutrients may become excess or deficient over time, even if the EC is maintained at a target level (Miller et al., 2020).

Recycling nutrient solution made from tap water can be challenging (Miller et al., 2022). Such a nutrient solution may accumulate unwanted compounds or slowly consume nutrients over time, leading to an increase in solution EC and a reduction in the quantity of nutrients added during refill. This can lower tissue nutrient levels and cause reduced growth. To minimize the negative effects of recycling on plants, growers can either discard the old solution after two weeks, or use water filtered through reverse osmosis (RO) which has minimal levels of calcium (Ca), magnesium (Mg), and bicarbonate (HCO_3). In some large commercial operations, growers regularly analyze the recycling solution in a lab and use complex worksheets on computers to adjust the levels of individual nutrients. However, this method is expensive and technically challenging for growers and many prefer to discard the recycling solution instead.

Recycled nutrient solution might negatively affect growth and yield performance of several crops, including lettuce, strawberry, several leafy vegetables, and ornamentals. This is due to increased concentration of phytotoxic root exudates that cause allelochemical stress in plants, as reported in studies conducted on strawberry, tomato, and cucumber (Assaduzzaman et al.,

2020). Fayeizade et al., (2021) found the highest tomato plant height (248.00 cm) in open hydroponic system and the lowest height (206.33 cm) in closed hydroponic system.

Additionally, recycled nutrient solutions usually require sterilization to minimize pathogen loads. Growers often use chemicals and physical treatments such as hypochlorite, ozone, and UV-light for sterilization (Assaduzzaman et al., 2020), all of them are costly exercises making the adoption of closed system non-viable for regular growers.

Electricity Consumption

The electricity consumption of the floating system is measured in kilowatt-hours (kWh) using the following general formula:

Energy consumption (kWh) = (Power rating of submersible pump + Power rating of circulating pump) × Number of hours per day that the system is operating

The submersible air pump had a power rating of 6 Watt-hour and the circulating pump had a power rating of 35 Watt-hour, and the system was operating for 24 hours per day.

$$Energy\ consumption\ (kWh) = \frac{(6W + 35W) \times (24)}{1000} \approx 38.38\ kWh$$

The cumulative electrical consumption of the floating system over the entire duration of the experiment was determined to be 38.38 kilowatt-hours.

Fertilizer Consumption

The quantities of fertilizers applied in the floating and drip-irrigated soil systems are presented in Table (22); the breakdown of nutrients consumed in the floating system is also depicted in a pie chart (Figure.31). The drip-irrigated soil system was maintained solely on the application of organic fertilizer (rotten animal waste and vermicompost), whereas the floating system was exclusively relied on synthetic fertilizers.

Table 22: Fertilizer Used in Floating and Soil-based Systems

Floating System		Soil-based	
Fertilizer	Amount	Fertilizer	Amount
Calcium Nitrate $\text{Ca}(\text{NO}_3)_2$	1178 g	Rotten Manure	9.5 kg
Potassium Sulphate K_2SO_4	180 g	Vermicompost	9.5 kg
Root P (Phosphorus Pentoxide P_2O_5)	176 ml		
Potassium Nitrate KNO_3	553.5 g		
Magnesium Sulphate $\text{MnSO}_4 \cdot 7\text{H}_2\text{O}$	490.5 g		
Fe Chelated	83 g		
Manganese Chelated	4.2 g		
Zinc Chelated	4.8 g		
Boron Chelated	13.2 g		
Sodium Molybdate	0.47 g		
Copper Sulphate	1.4 g		

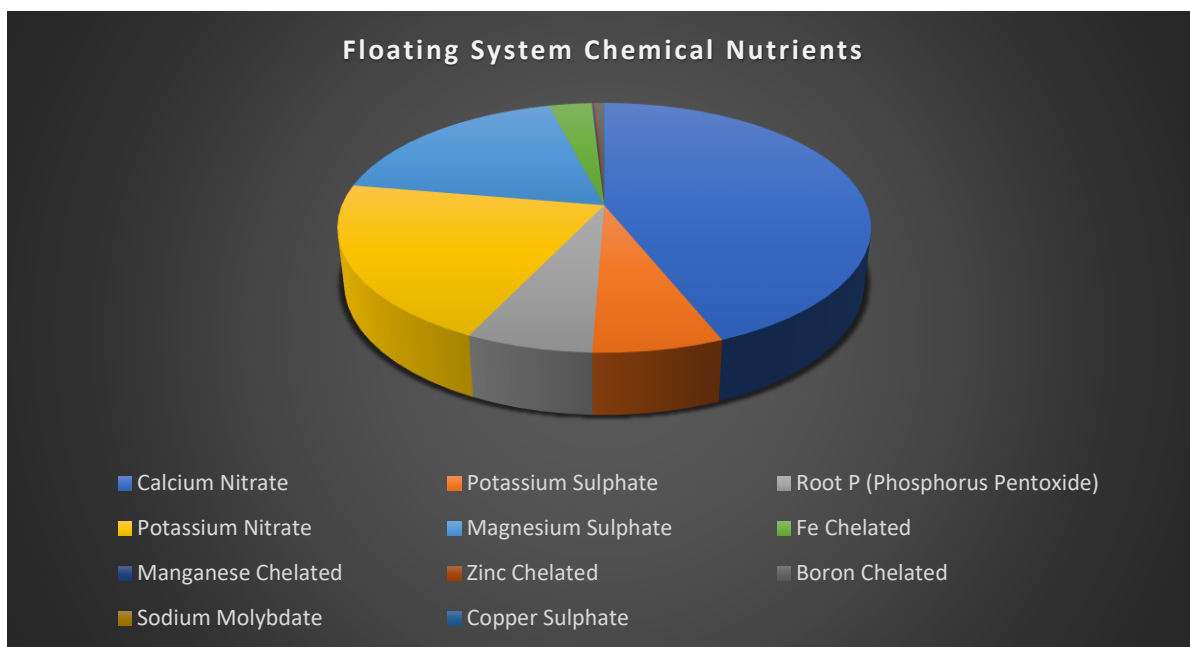


Figure 31: Chemical Nutrients Breakdown for Floating System

The manufacturing of synthetic and organic fertilizers stems from distinct industrial systems. While synthetic fertilizers are produced by global mining and chemical industries, compost and organic fertilizers involve the recycling of valuable nutrients that would otherwise be wasted in landfills (Emery & Brown, 2016).

The process of manufacturing nitrogen fertilizer involves converting nitrogen gas into ammonia, a method that is energy-intensive and emits approximately 4 kg CO₂ per kg of N converted into fertilizer. The production of phosphorus fertilizer also requires energy and involves converting phosphate rock into plant-available form through industrial processes, emitting around 2 kg CO₂ for every kg of Phosphorus (Emery & Brown, 2016).

In contrast, compost production is typically associated with carbon sequestration, through the diversion of feedstocks from waste materials and their transformation into soil amendments. By preventing methane production from food waste and biosolids in landfills, a substantial

greenhouse gas benefit is achieved for lettuce cultivation, amounting to 0.37 kg CO₂ equivalent per kg of lettuce (Emery & Brown, 2016).

Aside from reliance on fossil fuel, the discharge of hydroponic wastewater into the environment lead to groundwater contamination and consequent ecological repercussions (Majid et al., 2021; Kumar & Cho, 2014). Plants can absorb only a portion of the chemical fertilizers in hydroponic nutrient solution, with the remaining components losses in the wastewater. On May 24th, a sample of the nutrient solution was collected from the first replacement discharge and taken to the laboratory. The analysis (Table.23) confirm that a portion of the nutrients are not absorbed by the plants and are instead lost to the environment.

Table 23: Initial Nutrient Solution Chemical Analysis

Parameter	Result	Method
Calcium (Ca)	116 mg/l	S.M. 2017.3500-Ca. B
Magnesium (Mg)	28.8 mg/l	S.M. 2017.3500-Mg. B
Potassium (K)	63.9 mg/l	S.M. 2017.3500-K. B
Nitrogen (N)	14.06 mg/l	HACH Method 8039
Phosphorus (P)	17.53 mg/l	HACH Method 8048
Iron (Fe)	3.17 mg/l	S.M.3111 B

As maintained by Prystay and Lo (2001), Hydroponic Waste Solution (HWS) contains concentrated nitrate and phosphorus which is considered a leading cause of point-source pollution. Nitrate and phosphate levels in the wastewater trigger eutrophication in sensitive aquatic ecosystems such as wetlands and estuaries. Algal blooms deplete oxygen levels in water bodies and release toxins that harm humans and animals. Loss of essential cations, like calcium, is one of the repercussions of nitrate leaching into soil ecosystems. Soil's nutrient imbalance and the

consequent limited uptake of other essential nutrients and soil acidity are other ramifications of reckless discharge of nutrient solution (Wang et al, 2018).

To maximize the use of nutrient wastewater, it was utilized for irrigation purposes on other crops and plants in the surrounding area that were not part of the experiment. Jensen and Collins (1985) confirmed that the discharged solution can be reused for irrigation without causing additional environmental pollution. Similarly, Qureshi (2017) noted that the wastewater contains valuable nutrients that can be utilized to improve soil fertility. Leaf lettuce (*L. sativa* L) was successfully cultivated in discharged nutrient solution by Lee et al, (1999) and an increase in growth and yield of red pepper were reported by Park et al, (2005). In another study, Zhang et al, (2010), used non-recycled HWS for growing paprika. Their study concluded that the growth, total yield, and the number of paprika fruits were higher in the plants grown in HWS. A study conducted by Hong et al, (2009), suggested that the waste nutrient solution can be used as an alternate water resource for cultivating Chinese Cabbage. Kim et al, (2000), also found that the reuse of waste nutrient solution from rose hydroponic cultures enhances the growth of *Euphorbia pulcherrima*, a commercially important plant species, also known as poinsettias.

In addition to controlling point-source pollution, reusing HWS` can be implemented as a strategy to address water crisis in arid or semiarid regions like Middle East. In the experiment done by Park and his colleagues (2005), they determined that the amount of HWS produced by experimental greenhouse facilities, which was 2880 liters per hectare per day, could have been used for irrigating 409.86 m², to offset the water loss caused by evapotranspiration (Park et al., 2005).

It is important to acknowledge that organic fertilizers have lower nutrient content and a slower rate of releasing nutrients into the soil. In contrast, synthetic fertilizers do not require direct decomposition, possess high nutrient content, and rapidly release nutrients that can be readily absorbed by plants (Sharma, 2017). Ergo, inorganic fertilizers generally increase plant growth rate and the overall productivity more rapidly and in the short-term. This can partially explain the higher yields observed in the floating systems.

Chapter 5: Discussion

Table (24) summarizes the scores on criteria for the two growing methods. Based on the data analysis for each criterion, the system that had the best performance for this criterion was labelled with a plus symbol (+). The systems that obtain ‘+’ across most criteria is considered to perform best.

Table 24: Criteria for Drip-irrigated Soil-based and Floating Systems Evaluation

Criterion	Drip-irrigated Soil-based	Floating
Plant Growth		+
Yield (g/m ²)		+
Plant Survival Rate		+
Length of Harvest Season (Crop Period)		+
Setup Cost	+	
Production Cost (Per head and Per Kg)	+	
Maintenance Cost	+	
Energy Use	+	
Reliance on Back-up Energy Supply in case of Power Outage	+	
Total Water Use	+	
Water Productivity (g/l)	+	
Ease of using organic fertilizer from urban and rural waste stream	+	
N and P Emission to Surrounding Environment	+	
Eutrophication Potential	+	
Waste Generation	+	
Suitable for Diverse Environments		+
Suitable for All Types of Crops	+	
Pesticide Use		+
Pest Management Difficulty		+ (If root zone affected)
Reliance on Technical Knowledge	+	
Total Number of Obtained Best Scores	13	7

While the growth and yield variance in the Lollo Rosso lettuce type may have been minimal, the floating system exhibited a remarkable advantage in overall yield compared to the

drip-irrigated soil system. Specifically, the floating system yielded approximately three times and two times more in the case of Lollo Bionda and Little Gem type, respectively. While many studies have indeed validated the higher growth rate and yield in hydroponic systems, the notable discrepancy observed in this particular experiment can be ascribed to a few contributing factors.

Firstly, planting lettuce slightly off-season rendered soil lettuce more susceptible to vulnerability. The growth and viability of plants are strongly tied with climate, and the impact of the Karaj climate on lettuce grown in an open-field without environmental controls is an important contributing factor to consider when interpreting the results of this research. Temperatures over 27°C inhibit lettuce growth (Smith et al., 2011).

Moreover, the physical characteristics of the experimental cultivation plot employed in this study differed from expansive open-field agricultural plots. Enveloped by surrounding walls and trees, the experimental plot experienced altered air circulation patterns and fluctuations in soil temperature. In contrast, agricultural farmlands benefit from unhindered wind flow, which lower down soil temperature and establishing an environment more conducive to lettuce growth during the late spring when temperature begin to rise gradually.

Poor soil quality, combined with utilization of organic farming practices (omission of chemical fertilizers and pesticides) should also be regarded as significant factors influencing the subpar plant growth and reduced yields observed in the drip-irrigated soil system. It is widely recognized that organic agricultural methods result in lower yields compared to conventional approaches. Coronel et al., (2009) reported that the yield of the crop was the lowest for lettuce grown organically (44.50 g/plant) compared to hydroponic (220.75 g/plant) or conventional (63.50 g/plant) lettuce.

Our prediction was that by ensuring appropriate timing, planting in fertile soil, and providing a combination of organic manure and alternative nutrient sources, the significant disparity in yield would not be as pronounced.

The floating lettuce showcased a higher survival rate compared to their soil-grown counterparts, with pest-related issues being just one facet of the equation. Despite implementing identical integrated pest management strategies for both growing methods, the soil-grown plants exhibited a heightened vulnerability to pest infestations. Additionally, as the month of June progressed, temperatures soared beyond the optimal diurnal threshold of 25°C, surpassing the 30°C marks. Consequently, some losses occurred as the plants became desiccated during the latter stages of the experiment. Floating systems necessitate diligent monitoring for the growth of algae and microbial organisms, as an infection of this nature proved very challenging to control and could have resulted in widespread damage to the entire crop.

The initial investment costs for the floating system were approximately 2 times greater than the drip-irrigated soil system. The drip irrigation system accounted for 50% of total initial investment costs for the soil system, while reservoir construction and the purchase of pH and EC meters made up 70% of initial investment costs for the floating system. The total variable costs for materials were found to be six times higher for the floating system, with the primary contributor being the higher costs of fertilizers and labor, and the conduct of chemical water analyses. Labor costs account for the majority of the total variable costs, constituting over 60% of the total variable costs in both the floating and drip-irrigated soil systems. The daily management cost of the floating system stood at 2.5 times than that of the drip-irrigated soil system. The amount of manual labor required in hydroponic systems depends on the its design and the extent to which automation can be implemented. While hydroponic systems have the potential for complete

automation, our simplified hydroponic system lacked automatic control measures, resulting in a higher level of manual work compared to the drip-irrigated soil system. Also, as depicted in table (25), hydroponic systems, in general, necessitate a certain level of technical expertise and knowledge.

Electricity and water costs both show a low representation within the total variable costs. The under-representation of irrigation water in the total variable costs implies that the economic viability of the system is not significantly influenced by water consumption considerations. Rather, it is suggested that the impact of water consumption should be evaluated within the context of environmental analysis, particularly in light of emerging concerns around water scarcity within the country and region.

The production costs per kilogram of lettuce in both systems were found to be almost similar. This was due to the significant difference in yield between the two systems, with the floating system exhibiting a 2.8 times higher yield, which effectively counterbalanced the 2.8-fold increase in production costs. Nevertheless, under improved growing conditions such as cooler temperatures, richer soil quality, and a controlled environment, the substantial disparity in plant growth and yield between the two systems would diminish and the higher initial investment and maintenance expenses associated with the hydroponic system would become more discernible when considering costs per kilogram of lettuce.

Calculating the revenue and profit was out of the scope of this study. Drawing conclusions about the overall profitability of agricultural production based on a small sample cause biased inference. The idea was to do a general comparison and observe the overall amounts in relation to each other without delving into precise figures that might be misleading for someone

considering starting an agriculture or greenhouse business. To accurately assess profitability, economies of scale need to be considered.

The stagnant economy and soaring inflation rates in Iran have pushed the country perilously close to economic collapse, making it difficult to justify initiating new ventures across various economic sectors. Particularly in the realm of agriculture, where the prices of agricultural products fall significantly short of production costs, embarking on agricultural business endeavors lacks profitability, even in its most rudimentary forms.

Investing in advanced hydroponic production within sophisticated greenhouses may remain a viable option for a select group of affluent farmers who had initially entered the industry during more prosperous times. These early entrants benefited from subsidies provided by the Ministry of Agriculture, Jihad (World Food Programme (WFP),2016), including support for fertilizers, agricultural water, electricity, seeds, pesticides, as well as generous loans to acquire land and construct greenhouses. However, for newcomers and many long-standing practitioners in the field, the prospect of investing in more efficient technologies fails to justify the higher financial commitments.

Total water consumption has been approximately 3.8 times lower for the drip-irrigated system. Even when examining water usage in relation to yield, the drip-irrigated soil system still had better performance. The Crop Water Productivity (CWP) for Lollo Rosso, Lollo Bionda, and Little Gem varieties was 3.3, 1.5, and 1.7 times higher, respectively, in the drip-irrigated system.

In the floating system, the nutrient solution underwent replacement approximately every other week. By transitioning towards more closed systems, the floating system could potentially achieve higher water efficiency. As put forward in the literature review, in the open field

conditions of California's San Joaquin Valley, WUE for tomato production ranged from 19 to 25 kg/m³ for drip irrigation, while closed irrigated hydroponic greenhouses in the Netherlands achieved a WUE of 66 kg/m³, and warmer climates such as Spain and Italy reached 25 to 30 kg/m³ (Al-Shrouf, 2017). However, realizing this potential hinge upon factors such as the irrigation strategy, implementation of recirculation practices, and the quality of the irrigation water. In reality, collecting and reusing drain water can only be applied in high-tech, hydroponic greenhouses (Zhou et al, 2021) which make it financially not feasible for many growers.

Ensuring an appropriate concentration of essential nutrients in the solution is vital for the effectiveness of recirculating systems. Continuous monitoring of specific nutrient ion concentrations would be ideal, but it can be costly for certain ions and not currently possible for others. However, the EC of the nutrient solution can be used to approximately monitor nutrient status in an indirect way (Christie, 2014). To maintain consistent and dependable electrical conductivity (EC) and pH measures throughout the process, the water should be purified in a reverse osmosis (R.O.) unit or a similar filtration device but this process is financially demanding (Christie, 2014). Moreover, in arid regions, additional complexities may arise due to the high concentration of soluble ions in both surface and underground water sources.

Even by putting all these measures into place, over time it is anticipated that most closed hydroponic systems will develop some type of microbial community (Ehret et al. 2001). If left uncontrolled, these communities have the potential to negatively impact plant health through infection or competition for nutrients (Garland, 1994; Ehret et al., 2001). Within industry this would normally be controlled through either discarding or treating (e.g., by UV radiation, Ozone, or heating) the nutrient solution which are costly and energy intensive (Christie, 2014).

Overall, the implementation of recycling and recirculating systems for hydroponic systems requires additional investment which seems not feasible at the current challenging economic landscape and the limited probability of securing substantial funding for this venture. However, exploring the semi-closed alternative seems worthwhile. When compared to the costs of nutrients, water costs in Iran are not high enough to motivate farmers to shift towards semi-closed systems. Many growers in Iran are now utilizing nutrient solution up to two consecutive runs only to reduce costs associated with fertilizers. The ecological and environmental benefits for reducing water consumption have entirely been overlooked.

Floating and other hydroponic systems rely on a continuous supply of energy to circulate and oxygenate the nutrient solution. If there is a power outage and no backup energy source is available, the entire harvest can be affected. Good news is, plants are very resilient and can often recover even if the power is disrupted for up to 24 hours. To safeguard hydroponic farm against such setbacks, there are reliable methods to prevent power outages, including utilizing off-grid power solutions like solar energy and employing generators equipped with redundancies. This study did not delve into the assessment of the embodied energy of water and fertilizer consumption, as it fell beyond the scope of its investigation.

Drip-irrigated soil system was maintained solely on the application of organic fertilizer (rotten animal waste and vermicompost), whereas the floating system was exclusively relied on synthetic fertilizers. The production processes for synthetic and organic fertilizers differ significantly. Synthetic fertilizers are manufactured by large-scale mining and chemical industries, whereas compost and organic fertilizers are produced through the recycling of valuable nutrients that would otherwise go to waste in landfills (Emery & Brown, 2016). This contributes to a more circular nutrient management system.

Aside from reliance on fossil fuel, the discharge of hydroponic waste solution (HWS) into the environment lead to groundwater contamination and consequent ecological repercussions (Majid et al, 2021; Kumar & Cho, 2014). When released into water bodies, concentrated nitrate and phosphate in HWS can trigger a process called eutrophication, causing excessive growth of algae. This unchecked algal growth can deplete oxygen levels in the water, posing a threat to aquatic organisms, and release harmful toxins that can negatively impact both humans and animals. Nitrate leaching can disrupt the balance of essential nutrients in the soil, leading to soil acidity and inhibiting the uptake of other vital nutrients (Wang et al, 2018).

For soil-based greenhouses, the most effective way of reducing nutrient emissions is to apply nutrients and water with more precision. While, in hydroponic greenhouses zero emission of nutrient and pesticide can be achieved through 100% re-use of drain water (Zhou et al, 2021). However, this potential can only be realized in high-tech, hydroponic greenhouses (Zhou et al, 2007) which without the presence of regulatory frameworks and government subsidies, make it financially not feasible for many growers.

To conclude, using the scoring system, drip-irrigated soil systems emerged as the more advantageous choice for vegetable cultivation for the current economic and socio-political conditions of Iran, offering a practically viable approach that balances environmental considerations and economic feasibility.

Floating or other hydroponic systems are practical only in situations where the producer is having a well-established agronomic knowledge in hydroponic system management and is able to invest large sums of money in production facilities, which is not the case for many farmers. Unless the soil presents particular challenges, the initial costs for a complex, automated

hydroponic system is prohibitively high for small-scale producers and many commercial farmers. However, there are certain scenarios where the perspective of hydroponic systems becomes more favorable. Under a situation of food insecurity, lack of fertile soil, or water availability in the future or when the country recovers from the economic hardship and more government subsidies and investments will be available to be provided against the initial cost of hydroponic infrastructure system, the hydroponic (floating) could be positioned over the soil-based system. Or, there are places that are short of fertile soil and water, but they have energy, like southern provinces, where hydroponic greenhouses could become a viable alternative if adequate funding for initial implementation is accessible.

At large scale, particularly when having a recycling/recirculating design, hydroponic systems hold the potential to alleviate the strains on land, biodiversity, and natural resources, yet the industry encounters challenges that impede its expansion beyond the realm of high-end leafy greens. Overcoming financial obstacles requires collective support and concerted efforts to propel the industry towards progress.

The system will be specifically more appealing to city planners (Qureshi, 2017; Barbosa et al., 2015), particularly as population increases and arable land declines due to poor land management or encroaching urban sprawl. In Tokyo, where land is valuable due to a burgeoning population, hydroponic rice production has emerged as a solution to sustainably feed the city residents while preserving precious land resources. The rice is harvested in subterranean vaults, completely eliminating the need for soil. By maintaining precise environmental control, the system enables four harvest cycles per year, a remarkable departure from the conventional single harvest season (Sardare & Admane, 2013).

There is a promising prospect that, over time, the cost of hydroponic systems may come down, as with any technology. The environmental impact of high energy consumption can be addressed by improving efficiency and utilizing cost-effective renewable energy sources like solar energy which is very promising in Iran due to the high number of peak sun hours experienced across the majority of its geographical regions.

Further, if electricity is sourced from renewable energy like solar instead of the standard fossil fuels, greenhouse farms would have lower environmental impacts than open-field conventional agriculture (WWF-US, 2020). If soil cultivation is done in controlled environments, such as a greenhouse, the plant growth, yield and plant survival weaknesses of the soil system could be significantly mitigated. Under controlled environment, the yield is up to 10 times higher per unit area compared to field production (Heuvelink et al, 2020). As outlined in the literature review, the reported higher yields of hydroponics are to a great extent the result of meticulous control of environmental factors within the hydroponic greenhouse, which allow for continuous production year-round. These conditions also promote a reduction in the number of days required for each harvest cycle in the soil system, partially lowering the gap observed in this experiment for the crop period.

Greenhouse horticulture delivers the world's highest ever agricultural resource use efficiencies for water and nutrients (Stanghellini, 2014). Drip-irrigated soil system under a controlled environment has the potential to have higher water efficiency compared to open hydroponic systems. In addition to the advanced drip irrigation technique, the potential for higher efficiency comes by 1- Reduced potential evaporation (less sun radiation; less wind and higher humidity), and 2- increased production (better control of pathologies; better control of climate factors). A research study conducted in Florida, USA, revealed notable water and nutrient savings

in greenhouse cucumber cultivation compared to field-grown cucumber crops. Specifically, the greenhouse method utilized only one third of the water, 28% less nitrogen, and 23% less potassium per kilogram of fruit in comparison to traditional field cultivation (Jovicich et al., 2007).

In soil-based systems water loss by drainage is usually high. However, providing water in a more precise approach based on tensiometer measurements of soil water content can improve the water use efficiency. Valenzano et al., (2008) conducted trials on tomato cultivation and found that irrigation management practices utilizing tensiometers in soil-based systems yielded higher water use efficiency compared to the average results obtained from hydroponic systems such as nutrient film technique (NFT) and open-loop mineral wool substrate culture. This result is rarely achieved in common greenhouse farms, due to excessive, and often haphazard, use of water and fertilizers (Heuvelink and Marcelis, 2016).

It is important to acknowledge that higher yields and survival rate, year-round production and increased water efficiency in controlled environment come at the cost of higher economic expenditure and greater energy consumption. Environmental impacts of energy consumption could be lowered down by shifting towards renewable energy but more economic expenditures will remain as an indispensable component of controlled environment agriculture (CEA).

In light of the prevailing socio-political and economic conditions in Iran, and the current status of natural resources, the general finding of this study suggests that the drip-irrigated soil system holds a distinct advantage over the floating (hydroponic) system. The potential and drawback of each system has been discussed and the significant scope for improvement within soil systems under controlled environments has been underscored in the last few paragraphs to emphasize that many of the observed shortcomings of the soil-based system in this study could

be effectively mitigated or overcome under more favorable environmental and economic conditions. The focus of this research lies with introducing the system that can provide a balanced mixture of economic and environmental benefits while the technological changes and intervention is kept at minimum. Modernity views high-tech capital-intensive technology as development and progress while according to Levins (1986) “this view is a very nineteenth century one, a thermodynamic model in which vast amounts of energy are used to move vast amounts of material”. While the alternative knowledge- and thought-intensive models are in favor of achieving the highest outcomes with the least intervention and capital expenditures. This viewpoint can be likened to the impact of hormones; tiny molecules that can trigger significant effects in the larger organism, or the way in which meager amounts of energy in nerve impulses can propel the entire body into motion. Drip-irrigated soil system can better satisfy this viewpoint and could be implemented with less intervention, less expenditure and sustain the comparable benefits to hydroponic systems even when applied in open field.

While the findings of this study hold relevance for the broader Iranian context, it is strongly recommended to approach each specific region with meticulous attention to its unique characteristics. Given the versatility of these systems, it is necessary to know the advantages and disadvantages of the individual systems with regard to unique characteristics of each location to understand their applicability. In a study arranged by Christie (2014), farmers were approached via email, seeking their input on water consumption, nutrient consumption, and production quantities. “No two hydroponic systems were identical and many subtle changes between them in both construction and set-up potentially impacted their function and efficiency”.

To put it differently, not all systems are equally efficient, nor can they be applied in all areas and locations. Likewise, not all plant species are equally suited for cultivation in hydroponic

systems. Some crops are not as productive in hydroponic systems than others and thus do not make financial sense to grow in a hydroponic system (Samangooei et al., 2016). The economic aspect cannot be overlooked either. By considering the interplay between crop type, economic viability, and environmental sustainability, we can ascertain whether and when the adoption of hydroponic techniques becomes truly worthwhile. (Fussy & Papenbrock, 2022).

Chapter 6: Conclusion

Although scarcity of freshwater resources is the reality of Iran, intensive projects in groundwater extraction, dam construction, and interbasin water transfers has created the illusion of abundance (Madani et al., 2016). High return from oil sales, instead of being invested in development of the country, improving the efficiency of agriculture and industry, have fueled a wave in technocratic populism.

Technocratic populism merges the belief in expertise with a populist political appeal that resonates with ordinary citizens. It offers promises of expert-driven solutions aimed at benefiting the common people (Bustikova & Guasti, 2019). In Iran, this ideology has been intertwined with the advantages enjoyed by contracting companies and construction material supply chains (many of which operate as branches of the Revolutionary Guard Corps), the gains accruing to the state bureaucracy through construction projects, and the prevalent public perception which gauges the effectiveness of state governance primarily through the lens of construction endeavors. This prevailing narrative has tilted the state's priorities more towards construction rather than effective governance and policy-making (Fazeli, 2020).

The management of water resources stands out as a prominent illustration of this phenomenon. Hundreds of dams and thousands of water projects have been erected at exorbitant prices. However, the adoption of low-cost yet socially impactful strategies, such as water governance, stakeholder engagement in sustainable water resource management, and making proper investments in the industrial and agricultural sectors to enhance water use efficiency are significantly lagging behind (Fazeli, 2020). Such low-cost strategies necessitate consensus-

building, aligning with stakeholders' interests, and delegating authority which are not only more complex but also incompatible with the political desires of autocratic leaders.

The result has been building numerous water intake and diversion structures in a country located in an arid and semi-arid climate, putting into place subsidy for water, energy, and food, skewing perceptions of water availability and drying up the whole Iranian Plateau and diverting every ounce of the available freshwater to unsustainable and inefficient agricultural, industrial and domestic practices (Akhani, 2021).

Relying excessively on oil production and sales for a significant portion of government revenue has rendered the country susceptible to the perils of the "curse of oil." This predicament gives rise to a paradoxical situation, often referred to as the "paradox of plenty," as described by social scientist Terry Lynn Karl. In this scenario, the remarkable success of the energy export sector hampers overall economic growth, causing unequal development and the infamous "Dutch Disease" phenomenon (Karl, 1997; Brew, 2022). To put it differently, governing the country primarily through oil revenues without resorting to taxation has paved the way for the rise of technocratic populism, corruption, and political instability, as the government has little incentive to be accountable, responsive, or efficient (OECD, 2008).

In an effort to gradually lower down the government expenditures on subsidies, the first phase of the Targeted Subsidy Reform (TSR) was enforced in December 2010 to replace the indirect subsidies of key staples (petroleum, water, electricity, and bread) with direct cash transfer to targeted households. The quick implementation of the first phase of the reform, intertwined with sanctions, had unintentional consequences, among others, two-digit inflation rates. As the

inflation caused a decline in real prices, energy and water prices are still heavily subsidized and far from the target (World Food Programme, 2016).

Despite the dire condition with the state of natural resources, farmers have no incentive to preserve natural resources as water and electricity costs are far less representative in total production cost. Devouring the country natural resources, pouring them into large-scale construction projects that has weakened our natural capital base, coupled with corruption and lack of consideration for national benefits in external policy, has led to a situation of economic bankruptcy, that the farmers and government potential to invest in agricultural efficiency has been lowered down while at the same time the wrong policies and incorrect subsidies has unincentivized farmers to factor in natural resource conservation while planning for their growing methods.

Within this context, approaching for the low-laying fruits seems like the most logical way forward. Systems which with the lowest level of investment could bring about the most efficiency in yield, water, fertilizer, and energy consumption can be the best options for the foreseeable future.

This study examined and compared two cultivation systems, namely the drip-irrigated soil system and the hydroponic floating system against both economic and environmental criteria. The economic evaluation encompassed plant growth, yield, plant survival, and production cost, while the environmental assessment focused on water consumption, electricity consumption, and fertilizer consumption. Within the specific context of Iran, the drip-irrigated soil-based system emerged as the superior choice. This conclusion is supported by its lower production cost and its ability to achieve higher environmental efficiency in terms of total water consumption (3.8 times

lower), as well as electricity, and fertilizer consumption. These findings underscore the potential of drip-irrigated soil system as one of the examples of low-laying fruits described in the above paragraph.

On another note, it is worth mentioning that the introduction or recommendation of alternative growing methods represents only one facet within the complex and intricate landscape of food security. Increasing food security means more than simply boosting food production; it is often rooted in economic and political factors rather than geography or technology alone. Trade, accessibility and consumption challenges needs to be dealt with within the context of global markets, governmental policies, and social attitudes. Wandering through an autocratic illusionary reverie of national food self-sufficiency, the Iranian government has lost precious opportunities to amend its hostile external policy and its unstable national economic policies, which has made food unaffordable for many. The number of people experiencing hunger in Iran has surged in recent years, in part because the government cannot control currency inflation, sometimes doubling the cost of food overnight. While technology holds the potential to boost food production, it cannot guarantee its realization or the equitable distribution of food where it is most needed. In both impoverished and affluent nations, the paradox of some individuals having plenty of food while others suffer from starvation persists. Undernourishment remains a concern even in wealthy countries. For everyone on Earth to be adequately fed today and, in the future, we must strive for both increased production and improved distribution. These efforts must span within individual countries and across nations (Dahlman et al., 2011).

As a final note, it should be emphasized that the focus of this research was on conventional agricultural practices; however, when it comes to exploring less resource-intensive agricultural practices, future researches can also focus on whole-system design approaches like permaculture

and agroforestry, which their ethics and practices are still alive in some rural communities in Iran. Less planet-damaging practices of traditional methods of agriculture, nomadic sheep grazing and integrated animal husbandry continue to be practiced in certain areas, though in some places abandoned in favor of modern destructive practices like monocultural farms, pesticides, CAFOs, and GMOs, among others. Iran has a rich history of permaculture and agroforestry, which hasn't received sufficient attention from scientific literature. There is ample room for research in this area, and promoting these traditional practices could offer a path to restore ecosystems and revitalize abandoned and degraded rural communities which historically have been the primary producers of agricultural resources in Iranian plateau.

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Appendix: Supplemental Materials and Methods

Research Data for Plant Growth:

Lollo Rosso					
17 May 2022					
D-Soil			Floating		
PH (cm)	CD (cm)	C. Volume (G1)	PH (cm)	CD (cm)	C. Volume (G1)
5	7.5	220.9	7	6	197.9
8	8	402.1	5	5	98.2
4.5	6.5	149.3	5	8	251.3
5.5	7	211.7	6	7	230.9
6.5	7.5	287.2	5.5	8	276.5
6.5	8.5	368.8	5	8	251.3
4.5	8.5	255.4	5.5	7	211.7
7.5	8.5	425.6	4.5	7.5	198.8
6	6	169.6	5.5	7	211.7
7.5	9.5	531.6	6.5	7	250.1
6.5	6.5	215.7	5	9.5	354.4
7.5	8.5	425.6	4	7	153.9
6	10.5	519.5	6.5	7.5	287.2
Average		321.8	Average		228.8

Lollo Rosso					
25 May 2022					
D-Soil			Floating		
PH	CD	C. Volume (G2)	PH	CD	C. Volume (G2)
5.5	12	662	7.5	13	995.5
9.5	14.5	1568.7	6.5	11	617.7
6	11	570.2	5.5	10.5	476.2
8	14	1231.5	6.5	13	862.8
7	10	549.8	6.5	14	1000.6
7.5	13	995.5	5	10.5	433
5.5	11.5	571.3	6	15	1060.3
8.5	13	1128.2	5	8.5	283.7
7.5	12	848.2	6.5	13	862.8
10	12.5	1227.2	7.5	16	1508
7	11	665.2	6	14	923.6
10	10	785.4	6	10.5	519.5
7	12.5	859	7	17	1588.9
Average		894	Average		856.4

Lollo Rosso					
15 June 2022					
D-Soil			Floating		
PH	CD	C. Volume (G3)	PH	CD	C. Volume (G3)
8	20	2513.3	10.5	18	2671.9
10.5	20	3298.7	10	18	2544.7
9	21	3117.2	10	16.5	2138.2
11	26	5840.2	12	19	3402.3
8.5	19.5	2538.5	12	20	3769.9
11	22	4181.5	9	14	1385.4
11	18	2799.2	11	18	2799.2
12	23	4985.7	8	16.5	1710.6
12	22	4561.6	10	19	2835.3
12	22	4561.6	12	20	3769.9
10.5	22	3991.4	10.5	20	3298.7
11	19	3118.8	9.5	16.5	2031.3
12.5	21	4329.5	12	20	3769.9
Average		3833.6	Average		2779

Lollo Rosso					
25 June 2022					
D-Soil			Floating		
PH	CD	C. Volume (G4)	PH	CD	C. Volume (G4)
14	20	4398.2	11	18	2799.2
14	20	4398.2	11	20	3455.8
11	21	3810	13	22	4941.7
16	28	9852	12	20	3769.9
10	18	2544.7	15	28	9236.3
14	23	5816.7	11	19	3118.8
15	23	6232.1	12	23	4985.7
15	26	7963.9	12	22	4561.6
14	28	8620.5	14	21	4849
15	22	5702	14	25	6872.2
13	23	5401.2	14	25	6872.2
15	21	5195.4	13	24	5881.1
14	27	8015.8	15	30	10602.9
Average		5996.2	Average		5534.3

Lollo Bionda					
17 May 2022					
D-Soil			Floating		
PH	CD	C. Volume (G1)	PH	CD	C. Volume (G1)
9	9	572.6	8	9.5	567.1
7	8.5	397.2	9	7.5	397.6
8	6	226.2	7	8	351.9
5.5	5.5	130.7	6	6	169.6
6	5.5	142.5	6.5	7	250.1
6	5.5	142.5	7	6.5	232.3
8.5	5.5	201.9	9.5	9.5	673.4
6.5	7	250.1	8	6	226.2
6	5.5	142.5	4.5	6.5	149.3
6	5	117.8	6	7	230.9
8.5	6.5	282.1	6.5	6	183.8
6.5	7.5	287.2	6.5	7	250.1
7	7	269.4	8	7	307.9
Average		243.3	Average		306.9

Lollo Bionda					
25 May 2022					
D-Soil			Floating		
PH	CD	C. Volume (G2)	PH	CD	C. Volume (G2)
9	14.5	1486.2	8.5	18.5	2284.8
7	10	549.8	9	20.5	2970.6
8	11	760.3	7	15	1237
9	13.5	1288.2	7	13.5	1002
6	10	471.2	7.5	14.5	1238.5
9	11	855.3	7	15.5	1320.8
8.5	14	1308.5	9.5	21.5	3449
6.5	11	617.7	8	17.5	1924.2
7	11	665.2	6	13.5	858.8
8.5	10.5	736	6	16.5	1282.9
8.5	11	807.8	10	16	2010.6
6.5	11	617.7	8	15.5	1509.5
7	9	445.3	8	20.5	2640.5
Average		816.1	Average		1825.3

Lollo Bionda					
15 June 2022					
D-Soil			Floating		
PH	CD	C. Volume (G3)	PH	CD	C. Volume (G3)
21	31	15850.1	29	35	27901.3
18	24	8143	27	41	35646.9
22	26	11680.4	21	30	14844
19	28	11699.3	17.5	26	9291.3
16	17.5	3848.5	24	30	16964.6
17	28	10467.8	26	30	18378.3
17	27	9733.4	32	40	40212.4
18	30	12723.5	30	38	34023.4
21	24	9500.2	15	25	7363.1
23	27	13168.8	24	28	14778.1
16	25	7854	26	34	23605.9
16	24.5	7543	27	32	21714.7
14	21	4849	26	41	34326.6
Average		9773.9	Average		23003.9

Lollo Bionda					
25 June 2022					
D-Soil			Floating		
PH	CD	C. Volume (G4)	PH	CD	C. Volume (G4)
26	32	2910.4	46	38	52169.3
25	22	9503.3	48	40	60318.6
31	25.5	15831.9	42	36	42750.8
21	28	12930.8	29	29	19155.1
19	22	7222.5	45	32	36191.1
20	30	14137.2	38	45	60436.4
33	27	18894.3	62	70	238604
25	35	24052.8	45	45	71569.4
29	26	15396.9	21	23	8725
34	26	18051.6	40	35	38484.5
24	28	14778.1	47	47	81542.4
21	35	20204.4	42	34	38132.7
25	24	11309.7	41	45	
Average		15632.6	Average		62560.5

Little Gem					
17 May 2022					
D-Soil			Floating		
PH	CD	C. Volume (G1)	PH	CD	C. Volume (G1)
7	5.5	166.3	6	5	117.8
6	5	117.8	3.5	7	134.7
7	4.5	111.3	6	6.5	199.1
6	4.5	95.4	5.5	4	69.1
7	8	351.9	7	5.5	166.3
8	4	100.5	6	6	169.6
7	7	269.4	6	4	75.4
7.5	4	94.2	4	5.5	95
9.5	6	268.6	6.5	6.5	215.7
7.5	5.5	178.2	5.5	6.5	182.5
8	4	100.5	5	5.5	118.8
9	5	176.7	7	8.5	397.2
7	4	88	5	6	141.4
Average		163	Average		160.2

Little Gem					
25 May 2022					
D-Soil			Floating		
PH	CD	C. Volume (G2)	PH	CD	C. Volume (G2)
7	11	665.2	7	14	1077.6
6.5	8.5	368.8	6	11.5	623.2
7	10	549.8	3.5	8	175.9
6	17	1361.9	5.5	11	522.7
7	10.5	606.1	7	14	1077.6
8.5	12	961.3	7	13	929.1
9.5	7.5	419.7	6.5	13.5	930.4
7.5	10.5	649.4	6	11	570.2
10.5	10.5	909.2	7.5	15	1325.4
9	10.5	779.3	8	14	1231.5
8	9	508.9	5.5	12.5	675
10	11	950.3	7	15.5	1320.8
9	12	1017.9	6	12.5	736.3
Average		749.8	Average		861.2

Little Gem					
15 June 2022					
D-Soil			Floating		
PH	CD	C. Volume (G3)	PH	CD	C. Volume (G3)
15	25	7363.1	19.5	21	6754
15	18	3817	17	22	6462.3
14	19	3969.4	11.5	18	2926.4
11	14	1693.3	16.5	21.5	5990.3
16	23	6647.6	18	26	9556.7
16	23	6647.6	17.5	22	6652.3
13	19	3685.9	17	21	5888.1
16	23	6647.6	19.5	24	8821.6
14	18	3562.6	16	23	6647.6
12	20	3769.9	17.5	20	5497.8
12	20	3769.9	17	20.5	5611.1
15	24	6785.8	18.5	20	5811.9
16.5	23	6855.3	19	21	6580.9
Average		5016.5	Average		6400.1

Little Gem					
25 June 2022					
D-Soil			Floating		
PH	CD	C. Volume (G4)	PH	CD	C. Volume (G4)
21	28	12930.8	20	26	10618.6
15.5	24	7012	17	27	9733.4
18	22	6842.4	16	19	4536.5
17	17	3858.7	17	22	6462.3
16	23	6647.6	20	28	12315
18	25	8835.7	20	23	8309.5
15	22	5702	19	28	11699.3
21	24	9500.2	19.5	25	9572
20	18	5089.4	20	25	9817.5
15	20	4712.4	21	24	9500.2
21	21	7273.6	18	24	8143
19	23	7894	20	27	11451.1
18	26	9556.7	19	25	9326.6
Average		7373.5	Average		9345

Lollo Rosso Growth Data				
D-Soil				
G2 – G1	G3 – G2	G4 – G3	Average Growth	Total Average Growth
401.1	1891.3	1884.9	1392.433	1891.479
1166.6	1730	1099.5	1332.033	
420.9	2547	692.8	1220.233	
1019.8	4608.7	4011.8	3213.433	
262.6	1988.7	6.2	752.5	
626.7	3186	1635.2	1815.966	
315.9	2227.9	3432.9	1992.233	
702.6	3857.5	2978.2	2512.766	
678.6	3713.4	4058.9	2816.966	
695.6	3334.4	1140.4	1723.466	
449.5	3326.2	1409.8	1728.5	
359.8	2333.4	2076.6	1589.933	
339.5	3470.5	3686.3	2498.766	
Floating				
G2 – G1	G3 – G2	G4 – G3	Average Growth	Total Average Growth
797.6	1676.4	127.3	867.1	1768.526
519.5	1927	911.1	1119.2	
224.9	1662	2803.5	1563.466	
631.9	2539.5	367.6	1179.666	
724.1	2769.3	5466.4	2986.6	
181.7	952.4	1733.4	955.833	
848.6	1738.9	2186.5	1591.333	
84.9	1426.9	2851	1454.266	
651.1	1972.5	2013.7	1545.766	
1257.9	2261.9	3102.3	2207.366	
569.2	2375.1	3573.5	2172.6	
365.6	1511.8	3849.8	1909.066	
1301.7	2181	6833	3438.566	

Lollo Bionda Growth Data				
D-Soil				
G2 – G1	G3 – G2	G4 – G3	Average Growth	Total Average Growth
913.6	14363.9	5060.3	6779.266	5129.774
152.6	7593.2	1360.3	3035.366	
534.1	10920.1	4151.5	5201.9	
1157.5	10411.1	1231.5	4266.7	
328.7	3377.3	3374	2360	
712.8	9612.5	3669.4	4664.9	
1106.6	8424.9	9160.9	6230.8	
367.6	12105.8	11329.3	7934.233	
522.7	8835	5896.7	5084.8	
618.2	12432.8	4882.8	5977.933	
525.7	7046.2	6924.1	4832	
330.5	6925.3	12661.4	6639.066	
175.9	4403.7	6460.7	3680.1	
Floating				
G2 – G1	G3 – G2	G4 – G3	Average Growth	Total Average Growth
1717.7	25616.5	24268	17200.733	20751.2
2573	32676.3	24671.7	19973.667	
885.1	13607	27906.8	14132.967	
832.4	8289.3	9863.8	6328.5	
988.4	15726.1	19226.5	11980.333	
1088.5	17057.5	42058.1	20068.033	
2775.6	36763.4	198391.6	79310.2	
1698	32099.2	37546	23781.067	
709.5	6504.3	1361.9	2858.5667	
1052	13495.2	23706.4	12751.2	
1826.8	21595.3	57936.5	27119.533	
1259.4	20205.2	16418	12627.533	
2332.6	31686.1	30881.1	21633.267	

Little Gem Growth Data				
D-Soil				
G2 – G1	G3 – G2	G4 – G3	Average Growth	Total Average Growth
498.9	6697.9	5567.7	4254.833	2403.505
251	3448.2	3195	2298.066	
438.5	3419.6	2873	2243.7	
1266.5	331.4	2165.4	1254.433	
254.2	6041.5	0	2098.566	
860.8	5686.3	2188.1	2911.733	
150.3	3266.2	2016.1	1810.866	
555.2	5998.2	2852.6	3135.333	
640.6	2653.4	1526.8	1606.933	
601.1	2990.6	942.5	1511.4	
408.4	3261	3503.7	2391.033	
773.6	5835.5	1108.2	2572.433	
929.9	5837.4	2701.4	3156.233	
Floating				
G2 – G1	G3 – G2	G4 – G3	Average Growth	Total Average Growth
959.8	5676.4	3864.6	3500.266	3061.6
488.5	5839.1	3271.1	3199.566	
-23.2	2750.5	1610.1	1445.8	
453.6	5467.6	472	2131.066	
911.3	8479.1	2758.3	4049.566	
759.5	5723.2	1657.2	2713.3	
855	4957.7	5811.2	3874.633	
475.2	8251.4	750.4	3159	
1109.7	5322.2	3169.9	3200.6	
1049	4266.3	4002.4	3105.9	
556.2	4936.1	2531.9	2674.733	
923.6	4491.1	5639.2	3684.633	
594.9	5844.6	2745.7	3061.733	

Temperature Data:

Data	Tmax	Tmin	Tm	EVT
16/5/2022	30.4	18.2	24.4	8.4
17/5/2022	26.7	9.9	17.8	8
18/5/2022	27	8.7	19.7	8
19/5/2022	26.9	13.1	21	8.3
20/5/2022	31.4	12	23.9	10.4
21/5/2022	24.2	9.1	15.5	7.8
22/5/2022	26.6	7.6	19	8.2
23/5/2022	30.8	16	25.1	7.5
24/5/2022	26.2	16.2	21.1	11.9
25/5/2022	26.4	15.5	20.9	8.6
26/5/2022	25.8	9.5	16.9	9
27/5/2022	28.1	8.4	18.3	10.2
28/5/2022	28.8	12	21.7	7.7
29/5/2022	30.5	15.8	24.1	7.3
30/5/2022	30.9	17.8	23.7	7.8
31/5/2022	31.1	17.5	24.3	8.6
1/6/2022	32.4	14.4	26	10
2/6/2022	34.7	20	28.2	9.6
3/6/2022	34.6	19.9	27.2	8.9
4/6/2022	35.3	18.1	27.5	8.8
5/6/2022	35.6	21.8	28.9	9.6
6/6/2022	35.6	21.8	29.2	10.7
7/6/2022	36	19.5	28.5	13.9
8/6/2022	35.4	21.4	29.1	11.4
9/6/2022	34.1	19.3	27.1	10.2
10/6/2022	33.3	19.3	25.6	11.4
11/6/2022	32.4	14.6	22.8	11.2
12/6/2022	33	15.6	25.3	9.2
13/6/2022	35.4	22.7	29.3	10.2
14/6/2022	36.8	19.7	29.7	10.6
15/6/2022	34.6	18.8	27.5	12.2
16/6/2022	34.1	18.1	25.2	12.5
17/6/2022	34.1	16.5	26.6	11.6
18/6/2022	35.8	23.8	29.1	10.8
19/6/2022	37.1	17.8	27	10.6
20/6/2022	35.6	17.4	27.9	11.4
21/6/2022	34.2	23.7	29.3	16
22/6/2022	36.7	22.9	30.4	12.1
23/6/2022	34.7	19.8	27.7	10.4
24/6/2022	34.8	19	28	10