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The Comparative Performance of Soil-Based Systems with Hydroponics

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Abstract

Conventional soil-based agriculture is resource-intensive, utilizing large amounts of land and water, thereby placing a strain on Earth's natural resources. Soil-based agricultural techniques create environmental issues such as soil degradation, deforestation, and groundwater pollution from the mass implementation of fertilizers and pesticides. Agricultural crop production using hydroponics has shown promise to be less resource intensive and provide a faster turnaround in crop production. Soilless cultivation using hydroponics promises to relieve some pressure on Earth's ecosystems and resources by utilizing lesser land and water footprint. The APS Laboratory for Sustainable Food at Florida Gulf Coast University (FGCU) compared the growth of Lettuce *Lactuca sativa* "Rex Butterhead" crop grown using soil and soilless methods to analyze the growth performance in each setting. Crops grown in the soil-based medium were raised in the FGCU Food Forest, used a mix of soil and potting mix, watered regularly, and followed standard Integrated Pest Management (IPM) practices. Crops grown hydroponically were grown in a thermally insulated grow tent with an artificial lighting source, ventilation, environmental controls, and the Deep-Water Culture (DWC) method. Lettuce plugs were grown for 15 days in controlled environments until two leaves after the cotyledons had developed and were ready for transplant. Plugs were transplanted into a 4 × 6 matrix at the FGCU Food Forest and the DWC growth system. Crops were grown to full bloom and ready for harvest in the soil (60 days) and soilless (30 days) based setups. We collected crop growth data, including wet weight (g), dry weight (g), leaf area (cm^2), and chlorophyll concentration ($\mu mol/m^2$). From the collected data, we derived the Specific Leaf Area (SLA, cm^2/g) and biomass productivity (kg/m^2). Descriptive statistics were used to describe the collected and derived data. We investigated the slopes of regression lines for each growth curve which derived the differences in biomass and productivity parameters between lettuce grown using soil and hydroponics. Both growing methods can grow lettuce crops to full bloom and to adequate harvest weight. The biomass parameters and productivity differ significantly between the growing methods. The lettuce crops grown using hydroponics increase in wet weight statistically and significantly faster than those grown in soil ($p < 0.0001$). Therefore, we determined that a hydroponic method of crop production may provide better crop output and biomass indicators measured than soil-based growth.

Keywords

Controlled Environment Agriculture, Hydroponics, Lettuce, Soilless Agriculture, Urban Agriculture

1. Introduction

Soil-based agriculture is a resource-intensive practice that can lead to the degradation of the environment. Land used for agricultural purposes consumes roughly forty-eight million square kilometers globally [1]. The United Nations estimates that 30% of the world's energy and 70% of the water used globally is consumed by agricultural practices [1]. The exacerbation of climate change continues to create additional pressures on agricultural productivity globally accompanied by the degradation of land and soil health and frequent and disastrous weather patterns [2]. The Food and Agriculture Organization (FAO) estimates that nearly one-third (33%) of the world's farmland is degraded to some degree [3]. Conventional soil-based agriculture can have negative impacts on the environment and food supply chain. Air, soil, and water pollution caused by excessive fertilizer and pesticide use, as well as the spread of pests, are a few of the potential threats [4].

The demand for food production is expected to increase to meet the needs of an expeditiously growing human population, however, it is faced with declining arable land per capita [5]. The human population is predicted to grow to nearly 11.2 billion people by 2100 [6]. The combination of declining land quality and the need to accommodate the growing population is limiting the space for agricultural production and will create difficulty in the future. According to the FAO, to meet the demands of a growing population, the world's annual agricultural production needs to increase 70% by 2050 [5]. Agriculture using controlled environments is a potential avenue for sustainable crop production. For example, the GREENBOX technology has been successful at demonstrating successful outcomes in producing healthy lettuce crops [7]-[13]. Controlled Environmental

Agricultural (CEA) technology has been able to achieve crop production past growing season by being able to control environmental parameters [14]. Sustainable crop production methods such as controlled environment agriculture through soilless cultivation techniques like hydroponics are emerging as a viable solution.

The term "hydroponics" originates from the Greek words "hydro", meaning water, and "ponons", meaning to work. Hydroponic growing techniques have been used for centuries dating back to the floating gardens of the Aztecs [15]. Today, hydroponics can be an indoor or outdoor agricultural practice where different crop growth variables can be changed if necessary, using a technology-based approach towards food production. Using hydroponics, environmental conditions, many of which affect plant growth, can be controlled to maintain optimal growing conditions till ready for harvest [16]. CEA allows crops to be grown out of season, along with the rate of crop production increases, making more food available; lettuce grown in hydroponics takes only 30 days to reach full growth and is ready to harvest where soil-based lettuce takes 45 - 75 days to grow to full bloom and ready for harvest [17] [18].

This study's overall objective was to evaluate the difference between soil and soilless methods of crop cultivation. We determined which methods, soil or soilless, can support optimal growth of lettuce *Lactuca sativa* "Rex Butterhead". We quantified the growth and productivity of the lettuce crop grown in the soil and soilless environment when grown to a healthy and ready-to-harvest crop and statistically evaluated the biomass output of both systems. Results from this study would help inform the comparative crop performance between conventional soil and soilless hydroponic crop cultivation methods.

2. Materials and Methods

2.1. Location

The experiments were held at Florida Gulf Coast University (FGCU) in Fort Myers, Florida. FGCU is in Southwest Florida and is approximately 6 m above sea level. Plug growth and Deep-Water Culture (DWC) hydroponics was held in the Aquarium room in the Water School Building (AB-9, #114) at FGCU. Soil-based growth was carried out on a plot of land at FGCU Food Forest.

Florida is in North America with the Gulf of Mexico residing on the west coast and the Atlantic Ocean on the east coast. Southwest Florida is known for its subtropical climate and having a wet season with an average rainfall of 1.2 m from April to October characterized by relatively high humidity and warm weather, and temperatures ranging from 23.9˚C - 32.2˚C [19]. In contrast, the dry season from November to March has an average rainfall 0.4 m with mild temperatures ranging from 23.9˚C - 27.2˚C, and drier air [19]. The wet season is correlated with the summer months as the dry season is with the winter months.

The Aquarium room dimensions are 8.4 × 10.2 m with an area of 85.65 m^2. The floor is slightly angled towards two larger drains on either side of the room.

FGCU's maintenance facility on campus grounds maintains the room's temperature via air conditioning units for consistent cooling and forces hot air for heating when needed year-round with ranging temperatures from 20.0˚C - 23.3˚C. We carried out soil-based growth at a 1 × 2 m plot of land at the FGCU Food Forest. This plot receives direct sunlight from 11:00 to 18:00 with recorded average temperatures between 16.9˚C and 20.5˚C as informed by the FGCU weather station.

2.2. Experimental Setup

Our DWC hydroponics setup consisted of environmental monitoring, grow tent, and lighting elements for hydroponic growth. We assembled one grow tent (The Original Gorilla Grow Tent® 5 × 5, Gorilla Inc., Santa Rosa, California) for plug cultivation and for the DWC system for lettuce crop production. The dimensions of the grow tent were 1.5 × 1.5 × 2.1 m weighing 30 kg consisting of a reflective thermal insulation made of 1680D canvas covering. The grow tent has three larger access points allowing various access points to tend to the lettuce crops along with multiple smaller openings for extended attachments.

The lighting element helped facilitate photosynthesis. Four LED lights (FREELICHT, Amazon Inc., Seattle, Washington) were used in the grow tent. The support of artificial lighting allows for plant growth to occur out of season and independent of the natural elements. The LED provided white light, rated 60 watts, and a luminous flux of 3000 lumens. The color temperature of the light was 3500 Kelvins. We positioned four rectangular LED lights parallel and equidistant from each other in the tent. These LED lights dimensions were 1.15 × 0.084 × 0.03 m and weighed 1.3 kg. A programmable outlet timer (BN-LINK Compact Outdoor Mechanical 24 Hour Programmable Dual Outlet Timer, Amazon Inc., Seattle, Washington) was used to set a 16-hour on and 8-hour off light cycle. The lighting element was rated 60 watts and had a luminous flux of 3000 lumens. The color temperature of the light was 3500 K.

Proper ventilation in the tent ensured adequate temperature and humidity by installing a duct fan (CLOUDLINE T6 Inline Duct Fan, AC Infinity Inc, Los Angeles, California) near the top of the grow tent and opened an air inlet at the bottom of the grow tent. A control panel attached to the fan-controlled fan speed, as well as an environmental sensor that was placed level with the LED lights to record temperature, relative humidity, and VPD. The fans' life expectancy was 67,000 hours. Its dimensions were 0.2 × 0.3 × 0.2 m with a 0.15 m duct size and weighing 3.3 kg. The total airflow was 11.4 m^3/min, and the voltage was 100 - 240 V with a current of 1.6 A.

The DWC nutrient delivery system consisted of a square 1.2 × 1.2 × 0.15 m tray (model number HGC707345, Hawthorne Hydroponics LLC, Vancouver, Washington) that was elevated on a stand. Four 0.61 × 0.61 m rafts made of polystyrene foam (Greenguard Project Panel 2' × 2', Kingspan Group, USA) were cut to fit evenly and float atop the nutrient solution. Six holes were cut with a

0.05 m radius leaving 0.15 m between each hole in all four of the foam boards. The horticubes were placed in a polypropylene aquaponics cup (Heavy Duty Net Cups Wide Lip Designed for Aquaponics, Amazon Inc., Seattle, Washington) and placed in each hole. For aeration, eight-cylinder shaped air stone filters were placed (4 × 2 Inch Large Air Stone Cylinder, Vivosun, Ontario, California) in the tray with the nutrient solution. Four air stones were connected to a pump (18 W - 600 GPH commercial air pump, AquaMiracle, Amazon Inc.) that was placed outside the tray on either side of the DWC system. An illustration of the experimental setup for the hydroponic system is presented in **Figure 1**.

We carried out soil-based growth on a plot of land at the FGCU Food Forest. The growth area had dimensions of 1 × 2 m and 0.15 m in depth and was cleared of any existing vegetation. An illustration of the experimental setup for the soil-based system is presented in **Figure 2**. To keep this controlled and for equal application of fertilizer, the existing soil was added with Miracle-Gro moisture control potting mix (Moisture Control Potting Mix, 16 qt., Miracle-Gro, The Scotts Company LLC, Marysville, Ohio). Soil based plugs were placed in Miracle-Gro moisture control potting mix containing 0.21% nitrogen, 0.11% phosphorus pentoxide, and 0.16% potassium oxide. Once the mixture of soil and potting mix was added, a weed barrier (Pro Garden Weed Barrier Landscape Fabric, 3 ft × 50 ft, ECOgardener, Amazon Inc., Seattle, Washington) was placed on top to reduce competition with other plant species. Twenty-four 0.038 m by 0.038 m square cut outs were made in 6 × 4 matrix 0.15 × 0.18 m apart from each other. To ensure protection in the FGCU Food Forest, a mesh garden

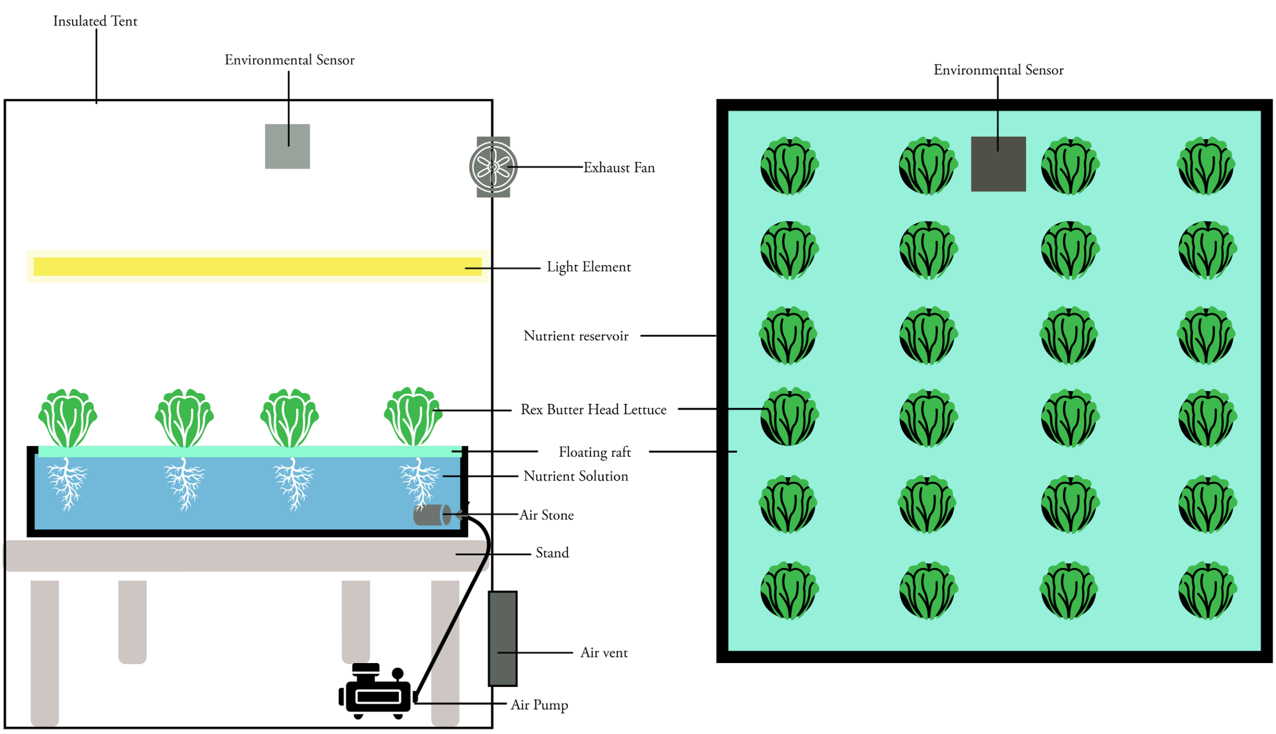

Figure 1. Illustration of Deep-Water Culture (DWC) experimental setup, front view (left), and the top view (right).

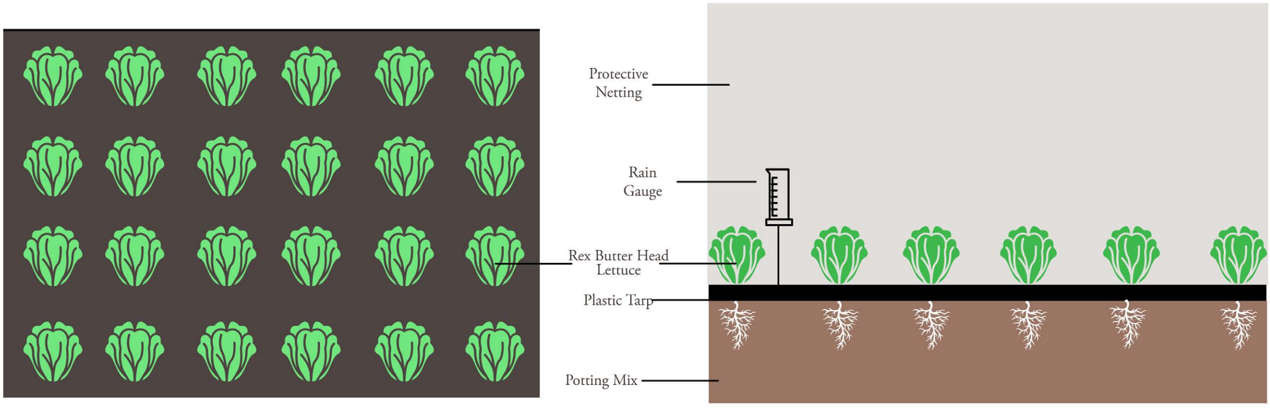

Figure 2. Illustration of the soil based experimental setup, top view (left) and front view (right).

netting kit (Garden Mesh Netting Kit, GMNKIT, Jantens, Amazon Inc., Seattle, Washington) surrounded the lettuce to keep out unwanted animals. A soil moisture gauge (VIVOSUN Soil Tester, 3-in-1 Plant Moisture Meter Light and PH Tester, VIVOSUN, City of Industry, California) was used to measure the moisture levels in the soil before every third watering event.

To limit the threat from diseases and pests, a trifecta crop control natural pesticide, insecticide, fungicide, and miticide (Trifecta Crop Control Ready to Use Maximum Strength Natural Pesticide, Fungicide, Miticide, Insecticide, 32 oz, Trifecta, Amazon Inc., Seattle, Washington) mix was used as needed. A rain gauge (Toiclebor® Rain Gauge 7" Capacity, Hanging or Ground Stake, Matte Black, Toiclebor, Amazon Inc., Seattle, Washington) was added to the site to measure any rainfall that occurred during the grow period.

2.3. Experimental Procedure

The growing cycles were held in the dry season in Florida, from January 5, 2023, to March 21, 2023. The first 15 days of the experiment consisted of seed germination until lettuce plugs were ready for transplant. This was followed by a 30-day growth cycle from January 20, 2023, to February 19, 2023, via DWC and a 60-day growth cycle from January 20, 2023, to March 21, 2023, via soil.

For this experiment, we used OASIS® Horticubes (104 count, OASIS® Grower Solutions, Kent, Ohio) which was placed in a black tray saturated in Reverse Osmosis (RO) water. One pelleted seed of Lettuce *Lactuca sativa* "Rex Butterhead" (Johnny's selected seeds, Fairfield, Maine) were placed in each recess. We covered the tray with newspaper and placed it in a dark grow tent for 48 hours for the beginning stages of germination. To promote the growth of the seeds, a starter solution was added to the hydroponic plugs. After 48 hours, the seeds were placed under the LED lights with a 16 hour on and 8 hours off light cycle, 06:00 - 22:00. The hydroponic plugs were given a starter solution for the first 15 days during the seedling stage to promote growth and soil plugs were given RO water.

The starter solution was a mixture of 3.6 g of "Jacks hydroponic 15.5-0-0" (calcium nitrate) and for every ten liters of water, 3.8 g of "Jacks hydroponic 5-12-26" was added. The starter solution on the hydroponic plugs was half the strength of the standard solution used in the DWC system. The starter solution and RO water was added daily to the plugs for the duration of the seedling stage.

We then transferred 24 hydroponic and soil plugs that were chosen randomly after 15 days when plugs showed two true leaves after the cotyledons and were placed in the 4 × 6 matrix in the DWC system and in the designated site in the FGCU Food Forest, 0.15 m by 0.18 m away from one another. The soil surrounding the lettuce must stay moist up to 0.5 m in depth to ensure proper growth. Watering every day, twice a day was necessary for proper soil moisture to decrease the chances of stress on the lettuce crops. Soil moisture was measured every third day. If the soil moisture gauge read three units or lower, more water was to be added to the next watering event.

The nutrient solutions pH and electrical conductivity (EC) were measured every three days and adjusted when necessary. The pH targeted was 5.8 standard units and if reading came back lower, we added an alkali (0.5 M NaOH), and if read high, we added an acid (0.5 M HCl). A dropper was used to administer the acid or alkali until the desired pH of 5.8 SU was met. If the EC was below 1.5 mS, fertilizer was added based on initial calculations. If the EC was below 2.0 mS, RO water was added to dilute the nutrient solution to decrease the EC.

Soil-based plugs were watered every day and twice a day when higher temperatures were recorded. For the first two weeks, 200 mL of water was added to each lettuce crop in the morning before getting any direct sunlight. Once the lettuce crops grew bigger, 400 mL of water was added before any direct sunlight and 100 mL of RO water was added after sundown. No additional fertilizer was added.

2.4. Data Acquisition

To obtain the biomass for each lettuce crop we randomly selected one lettuce head from the grow tent and from the FGCU Food Forest every five days for sampling. After the crop was harvested, the roots or any growing medium attached to the DWC crop were removed. To prevent the loss of moisture content, wet weight in grams was taken immediately after. Wet weight can be affected by waiting after harvest resulting in inaccurate measurements of biomass collected in the lettuce crop due to transpiration. The roots were not included in these weights because most were lost during harvesting.

We used a chlorophyll meter (CHL Plus Chlorophyll Meter, FT Green LLC, Wilmington, Delaware) to find the overall chlorophyll content of each sample. Four chlorophyll concentrations (μmol/m^2) were taken then averaged and converted into Soil Plant Analysis Development (SPAD) units. SPAD measures the difference between the transmittance infrared light (940 nm) and red light (640 nm).

The total leaf area was calculated by utilizing the Leafscan app [20] that can be downloaded through the app store on a mobile device (iPhone 14 Pro, Apple Inc., Cupertino, California). A reference sheet was used to calibrate the app with four black dots in a square shape 10.5 cm away from one another. We separated the leaves from the node, then placed them on the sheet and took a picture on the Leafscan app measuring in cm^2. The Leafscan app algorithim distinguishes between the white paper and the green leaf to generate the area with an accuracy of 0.01 cm^2. The data was downloaded and exported as a Comma Separated Value (CSV) file.

To obtain dry weight of lettuce crops, we placed the sampled crops in individual brown bags that were labeled and dated and placed them in a drying oven for 6 days at 65˚C. After six days the samples were removed from the drying oven and the weights were recorded.

2.5. Data Analysis

We utilized the collected data as described in the previous section to calculate the Specific Leaf Area (SLA) and chlorophyll content. SLA (cm^2/g) is the ratio of the total leaf area (cm^2) to the dry weight (g) of the crop. We derived the total chlorophyll content (mg/cm^2) from SPAD units as described in the previous section.

The data was processed using descriptive statistics to demonstrate our results and understand the difference in biomass output of the lettuce crops. Linear models were fitted to each growth curve to compare the rate of change in wet and dry weight for each growth method.

3. Results

The results from the growth cycles indicate that both DWC and soil-based crops are capable of growth to full bloom. We harvested Soil-based crops in 60 days when compared to DWC, which took 30 days to be ready for harvest. The disparity in time to be harvest ready indicates that DWC is a more efficient method of producing crops than traditional soil-based crop production, when it comes to the biomass produced.

We found that some of the lettuce crops had bolted in the soil, which is a vegetative state due to being exposed to elevated temperatures. In **Table 1**, the

Table 1. The average Wet Weight (g), average Dry Weight (g), average Specific Leaf Area (SLA) (cm^2/g), average Leaf Count (n), average and Total Chlorophyll Content ($\mu mol/m^2$) collected on the day of harvest.

Growth Method	Wet Weight (g/head)	Dry Weight (g/head)	SLA (cm^2/g)	Leaf Count (n)	Total Chlorophyll Content ($\mu mol/m^2$)
DWC	228.90	8.28	423.65	50	35.68
Soil	183.33	9.25	416.68	58	39.48

biomass of these crops was recorded on the day of harvest. It was noted that there was a significant difference in biomass between the crops grown in soil and those grown in DWC. The average wet weight of the soil-based crops was 45 g lower than the average DWC crops. However, the dry weight of both crops was similar, which can be attributed to the soil-based crops possessing a greater number of leaves.

The wet weight of the lettuce crops varied from 183.33 to 228.90 g. Soil-based crops grew at slower rate and produced crops lower in weight of 183.33 g at harvest which is statistically significantly lesser than DWC lettuce crops with a p-value of <0.0001. DWC lettuce crops had reached over 100 g by day 25 in the DWC system. On the 25th day of production in soil, crops reached a wet weight value of 32.3 g, which is drastically less than DWC. A lower wet weight value for soil grown crops indicates that DWC can produce crops with superior biomass when compared to soil-based production.

It has been observed that the dry weight of the crops showed a slight variance, ranging from 8.28 g to 9.25 g. The DWC crops exhibited a lower weight of 8.28 g, while the soil-based crops produced a higher dry weight of 9.25 g. It is worth noting that this indicates an increase in the structural and non-structural dry weight components, encompassing various elements such as cell walls, cytoplasm, glucose, sucrose, and starch. There was no statistically significant difference between the rate of dry weight values between DWC and soil-based growth ($p = 0.1592$).

The SLA varied from 416.68 to 423.65 cm^2/g, with DWC crops producing the greater value even though soil-based crops produced eight more leaves. Total chlorophyll content ranged from 35.68 to 39.48 ($\mu mol/m^2$) with soil-based crops producing the higher value. Our results demonstrated that the wet ($t = -14.4645$, $df = 8$, $p \leq 0.0001$) and dry ($t = 1.0345$, $df = 14$, $p = 0.1592$) weight increased significantly faster using DWC than soil. Figure 3 demonstrates the growth curve trends in wet and dry weight using both growing methods.

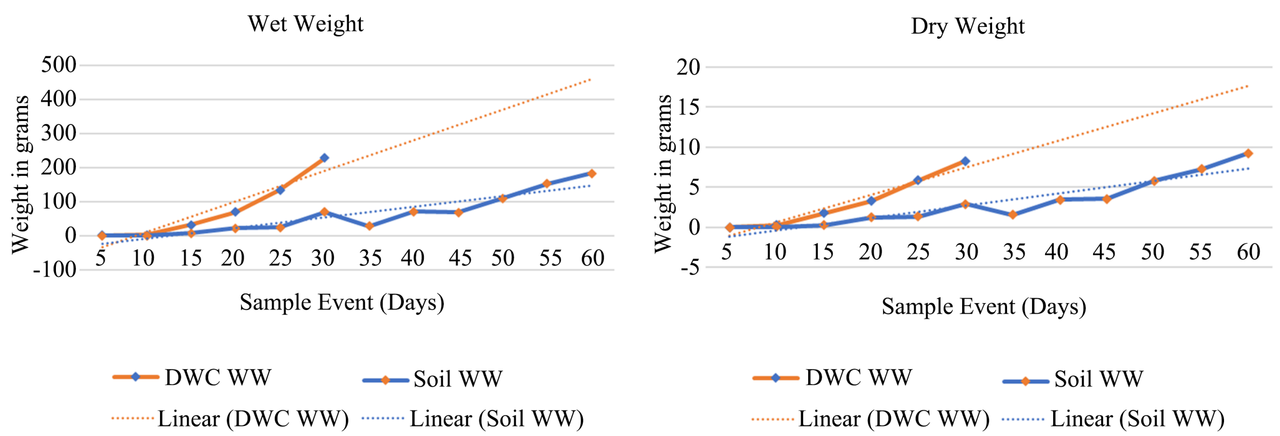

Figure 3. Wet weight (g) (top) and Dry Weight (g) (bottom) of the lettuce crop in both growing techniques from each sampling event. The dots along solid lines represent raw weight, and the dotted lines compare slopes of regression lines.

4. Conclusion

Our research aimed to examine the effectiveness between soilless methods of crop cultivation and conventional soil-based cultivation to produce lettuce crops. Specifically, we evaluated the growth and productivity of lettuce *Lactuca sativa* "Rex Butterhead" using DWC method hydroponic technology and soil-based method. Our findings indicate that hydroponic cultivation techniques can support optimal growth and yield of lettuce crops compared to traditional soil methods. In fact, the lettuce grown in the soilless environment showed statistically significant higher biomass output compared to the soil-grown lettuce. The use of hydroponic crop production methods, can therefore be a practical solution to enhance agricultural production and allow for a steady food supply chain, while minimizing the adverse environmental impact of conventional farming practices.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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