Scientific Research Publishing

Agricultural Sciences, 2023, 14, 1108-1120
https://www.scirp.org/journal/as
ISSN Online: 2156-8561
ISSN Print: 2156-8553

The Comparative Performance of Nutrient-Film Technique and Deep-Water Culture Method of Hydroponics for GREENBOX Technology

Mya Alexandria Catherine Griffith[1], George Paul Buss[2], Paige Ann Carroll[1], Xiusheng Yang[3], John L. Griffis Jr.[2], Galen Papkov[4], Sarah Bauer[5], Kathryn Jackson[6], Ankit Kumar Singh[1]

[1]Department of Ecology and Environmental Studies, The Water School, Florida Gulf Coast University, Fort Myers, FL, USA
[2]Department of Marine and Earth Sciences, The Water School, Florida Gulf Coast University, Fort Myers, FL, USA
[3]Department of Natural Resources, University of Connecticut, Storrs, CT, USA
[4]Department of Mathematics, Florida Gulf Coast University, Fort Myers, FL, USA
[5]Department of Environmental and Civil Engineering, Mercer University, Macon, GA, USA
[6]Independent Researcher, Alexandria, VA, USA

Email: mgriffith@fgcu.edu, gbuss@fgcu.edu, pcarroll@fgcu.edu, xiusheng.yang@uconn.edu, jgriffis@fgcu.edu, gpapkov@fgcu.edu, bauer_sk@mercer.edu, kgn816@gmail.com, asingh@fgcu.edu

How to cite this paper: Griffith, M.A.C., Buss, G.P., Carroll, P.A., Yang, X.S., Griffis Jr., J.L., Papkov, G., Bauer, S., Jackson, K. and Singh, A.K. (2023) The Comparative Performance of Nutrient-Film Technique and Deep-Water Culture Method of Hydroponics for GREENBOX Technology. *Agricultural Sciences*, **14**, 1108-1120.
https://doi.org/10.4236/as.2023.148074

Received: June 1, 2023
Accepted: August 27, 2023
Published: August 30, 2023

Abstract

With the rising pressures on food security, GREENBOX technology was developed as an avenue for fresh leafy vegetable crop production in urban settings. GREENBOX units were designed to be thermally insulated and climate controlled, with an artificial lighting source that utilized soilless cultivation techniques. Previous studies conducted on GREENBOX technology used the Nutrient Film Technique (NFT); however, various hydroponic methods exist, such as the Deep-Water Culture (DWC) method being the most used. The APS Laboratory for Sustainable Food at Florida Gulf Coast University (FGCU) compared the crop growth performance between DWC and NFT systems using GREENBOX technology. The following study monitored environmental conditions and compared productivity and biomass data of Rex Butterhead Lettuce crops between DWC and NFT systems. We assembled two GREENBOX units using commercially available materials and the standard nutrient solution for fertigation. The crops grown in DWC and NFT were in a 4 × 6 configuration. The DWC and NFT systems were used to grow Lettuce *Lactuca sativa* "Rex Butterhead" over 30 days to full bloom from prepared plugs grown for 14 days. We collected environmental data including Photosynthetic Photon Flux Density (PPFD, μmol/m^2·s), Daily Light Integral (DLI, mol/m^2·d), temperature (˚C), relative humidity (%), and Vapor Pressure Deficit (VPD, kPa). We collected lettuce crop growth data, which included wet weight (g), dry weight (g), leaf area (cm^2), and chlorophyll concentration (μmol/m^2).

We derived data, including the Specific Leaf Area (SLA, cm^2/g) and biomass productivity (kg/m^2), from previously collected data. We used descriptive statistics to present the collected data. A paired t-test was performed to understand the differences in biomass and productivity parameters between the DWC and NFT-grown lettuce crops. Both the DWC and NFT-grown crops could grow lettuce crops to harvest weight at full bloom. Observed data demonstrated that the biomass parameters and productivity did not differ significantly between the two hydroponics techniques. Therefore, we believe both hydroponic methods may be similar in growth performance and may be used in future iterations of GREENBOX design and prove suitable for fresh vegetable crop production in urban settings.

Keywords

Controlled Environment Agriculture, Food Insecurity, GREENBOX, Hydroponics, Lettuce

1. Introduction

The human population continues to proliferate, as does the demand for food production. The global population is projected to reach 11.2 billion, nearing 2100, significantly higher than 2.5 billion in 1950 [1]. As urbanization continues to expand to meet the needs of a rapidly growing population, the amount of arable land and resources needed to carry out successful crop production are dwindling. Agriculture currently consumes an area of forty-eight million square kilometers globally [2]. Conventional soil-based agriculture is resource intensive and requires large amounts of land, water, energy, and time to maintain. Agricultural land is often vulnerable to external factors such as soil, air, and water pollution, soil salinization, desertification, climate change-induced droughts, extreme variation in temperatures, extreme variation in solar radiation, and the spread of pests, which may result in environmental degradation [3]. Additionally, increasing instances of food deserts and food shortages across the globe are only being exacerbated by global conflicts such as the Ukraine War. With Russia and Ukraine being global producers in the agriculture industry, global agricultural markets will suffer major disruption due to the Ukraine War [4].

Hydroponics provides an avenue for sustainable crop production. Although there has been a recent newfound interest in hydroponics, the techniques have been around for centuries, dating back to the hanging gardens of Babylon and the floating gardens of the Aztecs [5]. The word "hydroponics" is derived from the Greek words "hydro", meaning water, and "ponos", meaning labor [5]. Hydroponics is a soilless cultivation method using a continuous flow of water and nutrient solution that plants usually get from traditional farming soil [6]. Soilless agriculture requires less space, water, and time resulting in a net increase in crop production rate with the capability to help solve food scarcity issues [6]. Using simple hydroponic techniques reduces crops' land needs and requirements by more than 75% and the water required for irrigation by 90%, with the more negligible environmental impact [7]. Controlled Environment Agriculture (CEA) using hydroponics consists of growing spaces that are closed or semi-closed, thereby protecting them from harmful insects and pests, which adds to the consistency and predictability of food production [8]. Due to improved space, energy, material, and resource utilization, soilless culture techniques are increasingly becoming more relevant [9].

There are two main types of hydroponic systems, open and closed. An open system refers to a system where the nutrient solution only completes one passage through the system, whereas a closed system refers to a system where the nutrient solution is recirculated through the system continuously [10]. There are various hydroponic methods, including Nutrient Film Technique (NFT), Deep-Water Culture (DWC), Ebb and Flow systems, Drip systems, Deep Flow Technique (DFT), Aquaponics, and Aeroponics, with the NFT and DWC being the most used. NFT allows nutrients and water to flow continuously through a channel along the crop's roots as a thin film. The solution is then deposited in a reservoir and recycled through the NFT system, making it closed. NFT channels are designed with a flow rate of 0.2 l/min and a slope of 1.5% for ideal lettuce production [11]. Similarly, DWC stores a large amount of nutrient solution in a basin while continuously aerating it. The crops are on top of a foam raft that rises and falls with the solution level, leaving the roots saturated in the nutrient solution. The floating raft technique allows for appropriate monitoring of minerals in solution and plant uptake for leafy greens [12].

GREENBOX technology was developed at the University of Connecticut in 2017 [13] [14] [15] [16] [17]. GREENBOX technology is an avenue for fresh leafy vegetable crop production, using a controlled environment system with optimal environmental conditions, enhanced through artificial lighting, environmental sensors, ventilation systems, and nutrient delivery systems [18]. GREENBOX technology was designed to be used in urban warehouse settings as an avenue for urban agriculture for localized crop production. Prior studies have conducted technical feasibility studies, comparative studies with greenhouse, and a financial analysis which found that GREENBOX technology was technically and financially viable for lettuce crop production [14]-[20]. Previous studies on GREENBOX technology utilized NFT systems for the soilless technique and did not consider other soilless cultivation methods.

The main objective of this study was to conduct a comparative analysis between crops grown using NFT systems and DWC systems using GREENBOX technology. We monitored the environmental conditions and measured the biomass and productivity of crops grown in each technique to determine if there were any significant differences. Descriptive statistics were reported, and statistical analysis using a paired t-test were used to understand the differences in biomass parameters between DWC-grown and NFT-grown lettuce crops. The results from these experiments will inform us about the technical feasibility of utilizing different soilless cultivation methods using GREENBOX technology, which may be considered for future design iterations.

2. Materials and Methods

2.1. Location

The experiments were conducted in the Aquarium Room (Academic Building 9, #114) at Florida Gulf Coast University (FGCU) in Fort Myers, Florida, United States of America. Fort Myers is in Southwest Florida along the Gulf of Mexico, resulting in a generally subtropical climate consisting predominantly of hot, humid summers and moderately cold winters lasting only a few weeks. The summer months are April through October, with an average temperature between 23.9˚C - 32.2˚C [21]. The winter months are November through March, with average temperatures between 23.9˚C - 27.2˚C [21].

2.2. Experimental Setup

We assembled two GREENBOX units for lettuce crop production using NFT and DWC systems. The GREENBOX units were equipped with an artificial LED lighting element, environmental monitoring control modules, and soilless cultivation systems of hydroponics similar to the experimental setup used in previous studies [14] [15] [16]. The two GREENBOX units were equipped with different hydroponic methods. An illustration of the NFT and DWC systems in the GREENBOX units is presented in **Figure 1**.

We procured two grow tents (The Original Gorilla Grow Tent® 5 × 5, Gorilla Inc., Santa Rosa, California) for the setup of GREENBOX units. The dimensions of the grow tents were 1.5 × 1.5 × 2 m. The tents were made of 1680D canvas covered with a reflective diamond surface for internal thermal insulation. Industrial-grade zippers and dual-cinching ports were included to maximize containment. The tent included two access points, a variety of ports for enhanced accessibility, additional extensions, and weighed 39.9 kg.

Four rectangular LED lights (FREELICHT, Amazon Inc., Seattle, Washington) induced photosynthesis in each grow tent. Supplemental lighting supports the growth of the crop because it allows access to consistent, quality light throughout the growth cycle, regardless of the season and time of day, independent of the sun. The dimensions of these lights were 0.8 × 0.03 × 1.15 m and weighed 1.2 kg. The lighting element was rated 60 watts with a luminous flux of 3000 lumens. The color temperature of the light was 3500 Kelvins. We positioned the LED lights parallel and equidistant from each other in each tent. A programmable outlet timer (BN-LINK Compact Outdoor Mechanical 24-Hour Programmable Dual Outlet Timer, Amazon Inc., Seattle, Washington) was used to time the lights as they were turned on and off at a specific time of day.

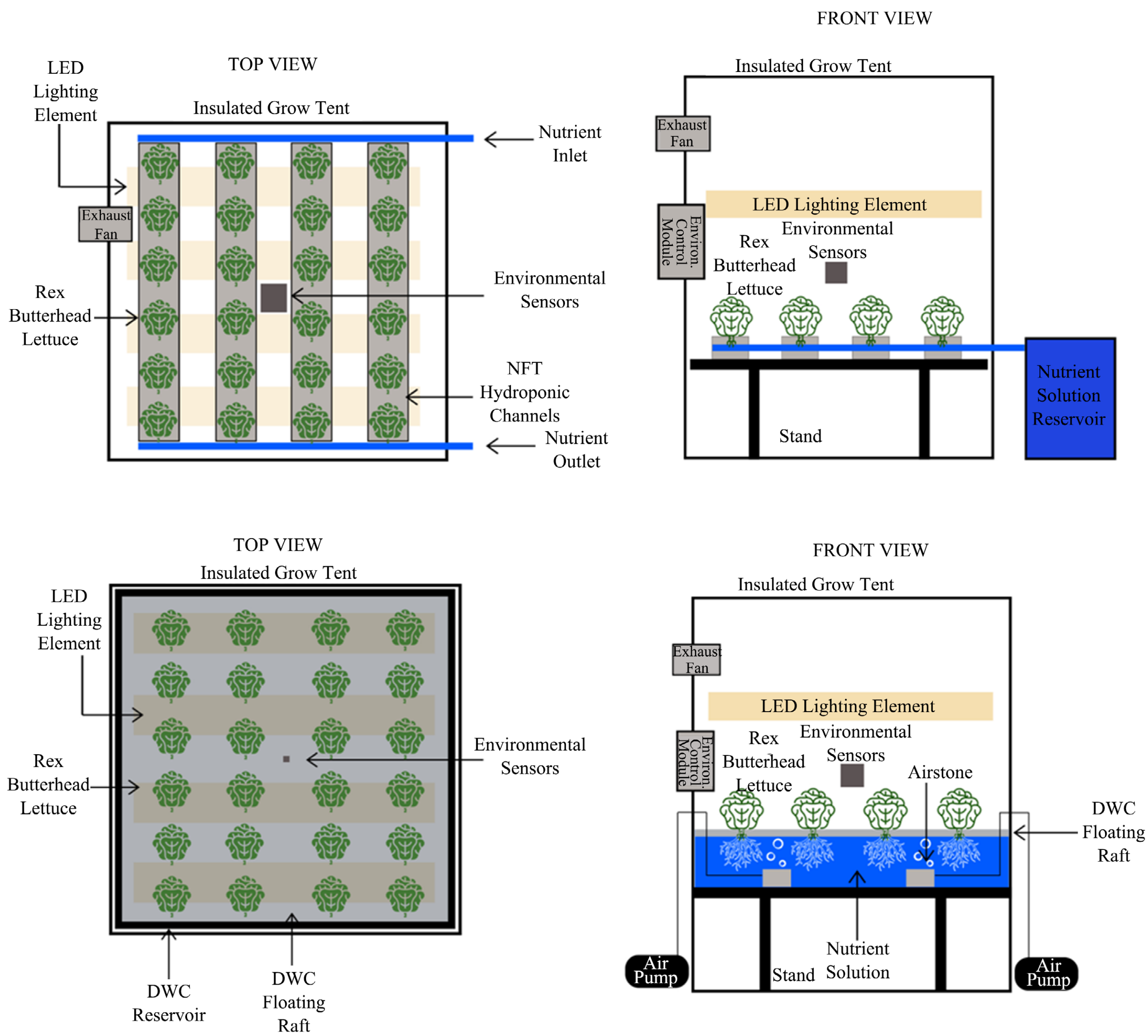

Figure 1. Illustrations of the experimental NFT setup (top) and DWC setup (bottom) in the GREENBOX units. The GREENBOX units are shown in a horizontal top view and a front cross-sectional view.

A duct fan (CLOUDLINE T6 Inline Duct Fan, AC Infinity Inc, Los Angeles, California) was installed in each system to ventilate and help control the environmental conditions during the growth cycle. The fan dimensions were 0.20 × 0.32 × 0.21 m with a 0.15 m duct size and a weight of 3.3 kg. The total airflow was 11.4 m^3/min. The voltage was 100 - 240 V with a current of 1.67 A. The life expectancy of the fan was 67,000 hours. The fan was positioned at the top of each tent with open inlets at the bottom for recirculation. A controller was provided with the fan to control the fan speed and an environmental sensor to monitor the temperature, relative humidity, and Vapor Pressure Deficit (VPD). The sensor was placed at crop level and represented the growing conditions the crops were exposed to.

A light meter (FH-100 Light Meter PAR Meter, Amazon Inc., Seattle, Washington) was used to measure the PPFD and DLI inside the grow tents. The measuring range is 400,000 lx and 6000 (μmol/m^2·s). PPFD measurements are automatically converted into DLI using the TUYA app, connected to a mobile device using Bluetooth.

A pH and Electrical Conductivity (EC) meter (High Accuracy Lab PH/EC Tester Digital Kit, Amazon Inc., Seattle, Washington) were used to monitor the nutrient solution every three days. The EC meter had a measuring range of 0 - 9990 μs/cm for conductivity with ±2% accuracy. The pH meter measured a 0.00 - 14.00 pH with a ±0.05 pH accuracy.

The main components for the NFT system were the four NFT channels (HydroCycle 4" Pro NFT Series 5'L Lid w/1" Square Holes, FarmTek, Dyersville, Iowa) were placed on a stand (4' × 4' Fast Fit Grow Tray Stands, Hydrobuilder.com, Chico, California) in GREENBOX unit 1. The NFT Channels were made with UV-stabilized plastics. The dimensions were 1.2 × 0.15 × 0.05 m. Square holes of 0.03 m were positioned every 0.15 m. The channels were set at a slight angle to allow the nutrient solution to flow through the delivery system. The nutrient delivery system comprised a 20 L reservoir to store the nutrient solution, a submersible pump (model number AAPW400, Hydrofarm LLC, Petaluma, California), and opaque piping material. The pump had a 1515 L/h capacity and a 24-watt usage. It cost about $400 to assemble one NFT system.

The DWC setup included a square 1.2 × 1.2 m tray (model number HGC707345, Hawthorne Hydroponics LLC, Vancouver, Washington) placed in a stand identical to the GREENBOX units with an NFT setup. The DWC tray dimensions were 1.23 × 1.23 × 0.15 m, weighing 6.8 kg. Floating rafts to support crops were made of foam boards (Greenguard Project Panel 2' × 2', Kingspan Group, Atlanta, Georgia) and were fitted to float along the water level. Six holes were cut in each board, maintaining 0.15 m on each side to allow room for each lettuce crop to grow. A 4 × 6 grid of polypropylene aquaponics cup (Heavy Duty Net Cups Wide Lip Designed for Aquaponics, Amazon Inc., Seattle, Washington) was placed in each hole to support the lettuce plugs in place until ready for harvest. Eight cylinder-shaped air stones (4 × 2 inch Large Air Stone Cylinder, Vivosun, Ontario, California) were placed inside the tray for oxygenation of the nutrient reservoir. Two air pumps (18 W - 600 GPH commercial air pump, AquaMiracle, Amazon Inc., Seattle, Washington) were connected to four air stones for aeration. The pump dimensions were 0.14 × 0.08 × 0.09 m, weighing 0.9 kg. The airflow capacity was 2271 LPH with a maximum pressure of 20 kilopascals. In this setup, it cost about $550 to assemble one DWC system.

Chlorophyll concentration was taken using an at LEAF CHL Blue chlorophyll meter (at LEAF CHL Blue chlorophyll meter, Wilmington, Delaware). It is a handheld device that noninvasively measures the chlorophyll content of green-leaf plants. Optical density measurements were taken at two different wavelengths (640 nm and 940 nm). The chlorophyll meter is powered by 2 AA (1.5 V) batteries, lasting 5000 - 30,000 measures, depending on use and battery type.

2.3. Experimental Procedure

Lettuce crop production lasted 44 days over January and February 2023. The first 14 days consisted of plug preparation and 30 days of growth to maturity. On day 14, the lettuce plugs were transplanted into the NFT and DWC hydroponic systems. The pelleted Lettuce *Lactuca sativa* "Rex Butterhead" (Johnny's selected seeds, Fairfield, Maine) seeds were sown by placing one seed in each hole of the OASIS® Horticubes (104 counts, OASIS® Grower Solutions, Kent, Ohio). We chose lettuce as it is an agriculturally crucial leafy vegetable due to worldwide demand [22]. The horticubes were then placed in a black tray (20" × 10", Perfect Garden Seed Starter Grow Trays, Amazon Inc., Seattle, Washington), saturated with Reverse Osmosis (RO) water, and covered with newspaper. The covered seeds were placed in the dark grow tent for 24 to 48 hours to facilitate germination. Following the germination period, the seeds were placed under artificial LED lighting. The lights were programmed to provide 16 continuous hours of light per day between 06:00-22:00.

The seedlings were provided with a starter nutrient solution to promote growth. The starter solution was prepared by mixing 3.6 grams of "Jack's hydroponic 15-0-0" (calcium nitrate) (Jacks Nutrients, JR Peters, Inc., Allentown, Pennsylvania) and 3.8 grams of "Jack's hydroponic 5-12-26" (Jacks Nutrients, JR Peters, Inc., Allentown, Pennsylvania) for every 10 L of water. A starter solution was administered daily to ensure complete saturation of the horticubes throughout the seedling stage. The plugs were ready for transplant into the NFT and DWC systems after fourteen days when two true leaves after the cotyledons had developed. A nutrient solution was prepared for both the NFT and DWC systems using 9 grams of "Jack's hydroponic 15-0-0" (calcium nitrate) (Jacks Nutrients, JR Peters, Inc., Allentown, Pennsylvania) and 9.4 grams of "Jack's hydroponic 5-12-26" (Jacks Nutrients, JR Peters, Inc., Allentown, Pennsylvania) for every 10 L of water.

Due to the nutrient uptake by plants during growth, the elemental composition of the nutrient solution is altered in a closed-loop system. Therefore, monitoring the composition of the nutrient solution regularly is essential. The optimal temperatures to grow lettuce are 17˚C - 28˚C, and the optimum pH is 5.8 Standard Units (SU) and EC of 1.5 [23]. The nutrient solution was maintained with a target pH of 5.8 Standard Units and a targeted EC of 1.5 - 2.0 mS. The pH and EC of the nutrient solution were measured every three days and adjusted accordingly. If the pH was below the target pH of 5.8 SU, we increased the pH by adding an alkali (0.05 M NaOH), and if the pH was above the target pH of 5.8 SU, we added an acid (0.05 M HCl). We administered dosing using a dropper and added acid or alkali until we reached the target pH of 5.8 SU. If the EC was below the target EC of 1.5 mS, we increased it by adding fertilizer based on initial calculations. If the EC exceeded the target of 2.0 mS, we decreased the EC by increasing the water content through dilution with RO water.

2.4. Data Acquisition

We collected environmental data such as temperature (˚C), relative humidity (%), and VPD (kPa). The amount of water vapor in the air can be described by relative humidity (RH) or vapor pressure deficit (VPD). The VPD is defined as the difference between the actual water vapor pressure and saturation water vapor pressure at a given temperature. Comma Separated Values (CSV) data was downloaded weekly from the environmental module. An environmental sensor connected to each grow tent's fans monitored temperature and relative humidity. Environmental sensors were calibrated regularly following manufacturers' recommendations. Light intensity was monitored using a PPFD light sensor. Three PPFD (μmol/m^2) and DLI (μmol/m^2·d) light measurements were taken daily from different points in the GREENBOX units.

The biomass data of each lettuce head was monitored by destructive sampling every five days. A lettuce head was chosen randomly from each grow tent. The growing medium and roots were removed. Wet weight (g) was taken immediately after harvest from NFT and DWC systems to retain maximum moisture content. Waiting to measure wet weight could lead to a loss of mass due to evapotranspiration and lead to inaccurate data. The dry weight (g) was also recorded for each sample by placing all the leaves in a brown paper bag and left in a convection oven set at 65˚C for six days. The roots were not considered in these measurements.

Using a mobile device (iPhone 12 mini, Apple Inc., Cupertino, California), the leaf area was measured using the Leafscan app [24]. First, a reference measurement was made by drawing four dots on a blank piece of paper in the shape of a square. Then, each leaf was placed inside the square and photographed in the Leafscan app. The leafscan app measured the leaf area in square centimeters (cm^2) with an accuracy of 0.01 cm^2. The data was collected and exported as CSV file.

Four chlorophyll concentrations (μmol/m^2) measurements per sample were taken using an atLEAF CHL Blue chlorophyll meter (atLEAF CHL Blue chlorophyll meter, Wilmington, Delaware). Plant relative chlorophyll concentration is measured by inserting a leaf into the device aperture. Green leaves of up to 3 mm thickness can be measured. Measurements were later converted into Soil Plant Analysis Development (SPAD) measurements which measure the difference between the transmittance of a red (640 nm) and an infrared (940 nm) light through the leaf. The total chlorophyll content of a crop is calculated by converting the at LEAF CHL values into SPAD and considering the relationship between them [25].

2.5. Data Processing and Statistical Analysis

Using collected variables described in the previous section, we derived SLA (cm^2/g), which is the ratio of total leaf area to dry weight of the crop, SPAD, and productivity (kg/m^2). Descriptive statistics were used to represent biomass data. The wet and dry weights were displayed graphically to represent the growth trend. Over the growth cycle, dry weight, wet weight, total leaf area, SLA, and productivity of lettuce crop in each hydroponic setting are presented in the following section. Statistical analysis using a paired t-test were used to understand the differences in biomass parameters between NFT and DWC grown lettuce crops. Statistical analysis was conducted using R statistical software [26] at the 5% level of significance.

3. Results

Results from the growth cycle of NFT and DWC grown crops using GREENBOX technology demonstrate the "Rex Butterhead" lettuce was exposed to the optimal environmental conditions required to achieve the expected harvest weight at full bloom. **Table 1** summarizes environmental conditions such as PPFD ($\mu mol/m^2 \cdot s$), DLI ($mol/m^2 \cdot d$), temperature (˚C), VPD (kPa), and relative humidity (%) inside the grow tent throughout the growth cycle.

The mean PPFD in the NFT setup varied between 131.7 and 178.7 $\mu mol/m^2 \cdot s$. The mean DLI in the NFT setup varied between 7.58 and 10.29 $mol/m^2 \cdot d$. The mean PPFD in the DWC setup varied between 117.67 and 194.00 $\mu mol/m^2 \cdot s$. The mean DLI in the DWC setup varied between 6.78 and 11.17 $mol/m^2 \cdot d$. We believe the light intensity in the DWC system fluctuated more due to the dark color of the reservoir, resulting in higher absorption of light near the sides of the reservoir than in the middle. Both systems were within the recommended minimum DLI of 6.5 - 9.7 $mol/m^2 \cdot d$ [27].

The mean temperature (˚C) in the NFT setup ranged between 22.17˚C - 28.11˚C and 22.90˚C - 27.30˚C in the DWC setup. The temperature regime was within the optimal range of 17˚C - 28˚C [24]. There was minimal temperature variation due to the indoor grow tent and thermal insulation inside both GREENBOX units. The mean relative humidity in the NFT setup varied between 37% - 72% and 36% - 66% in the DWC setup. The relative humidity stayed

Table 1. Light intensity PPFD ($\mu mol/m^2 \cdot s$), DLI ($mol/m^2 \cdot d$), temperature (˚C), relative humidity (%), and VPD (kPa) in NFT and DWC systems using GREENBOX technology over the growth cycle.

Environmental Conditions	PPFD ($\mu mol/m^2 \cdot s$)	DLI ($mol/m^2 \cdot d$)	Temperature (˚C)	Relative Humidity (%)	VPD (kPa)
NFT	153.15 ± 10.52	8.87 ± 0.62	24.79 ± 1.09	54.98 ± 6.30	1.38 ± 0.24
DWC	148.24 ± 17.19	8.65 ± 0.98	25.45 ± 1.22	50.99 ± 4.61	1.55 ± 0.21

within the recommended 40% - 60% for most of the study but sometimes exceeded the recommended range for short time periods. The mean VPD in the NFT setup ranged from 0.86 to 2.10 kPa and 0.96 to 2.04 kPa in the DWC setup. The environmental conditions presented throughout this growth cycle are suitable for the year-round production of "Rex Butterhead" lettuce. The inability of the crop to be affected by external environmental hazards such as storms, droughts, tornadoes, and hurricanes increases the reliability and resilience of the food supply system which may be a strength of GREENBOX technology as it is unaffected by external environmental influences [28].

The biomass and productivity data in the NFT and DWC systems were comparable to the average harvest weight of 181 g per lettuce head [29] and data collected from previous GREENBOX growth cycles [14] [15]. The wet weight at harvest was 23.22 g higher in DWC than in NFT systems. The dry weight was 0.6 g higher in DWC than in NFT systems. Wet and dry weights represent the aggregate gas exchange in photosynthesis and evapotranspiration throughout the growth cycle [30]. The paired t-tests revealed no statistically significant differences between the wet weight ($t = 2.43$, $df = 5$, $p = 0.0594$) or dry weight ($t = 2.35$, $df = 5$, $p = 0.0655$) for lettuce grown using NFT versus DWC. SLA in DWC was 166 cm^2/g higher than NFT system. The leaf count was significantly higher per head of DWC than NFT lettuce on the day of harvest by 13 leaves. We observed a slightly higher chlorophyll concentration in NFT grown lettuce than DWC grown lettuce that will require further investigation to determine the cause. The productivity of DWC-grown lettuce was slightly higher than that of NFT-grown lettuce. Both NFT and DWC systems were compatible with GREENBOX technology and could carry out crop production to full harvest. **Table 2** presents the collected biomass data from crop harvest.

Figure 2 presents the growth trend following the wet and dry weights over the growing cycle. The growth curve demonstrates similar growth rates for both systems, but DWC is slightly higher. As a result, we observe a slightly higher wet and dry weight for DWC than NFT on the day of harvest.

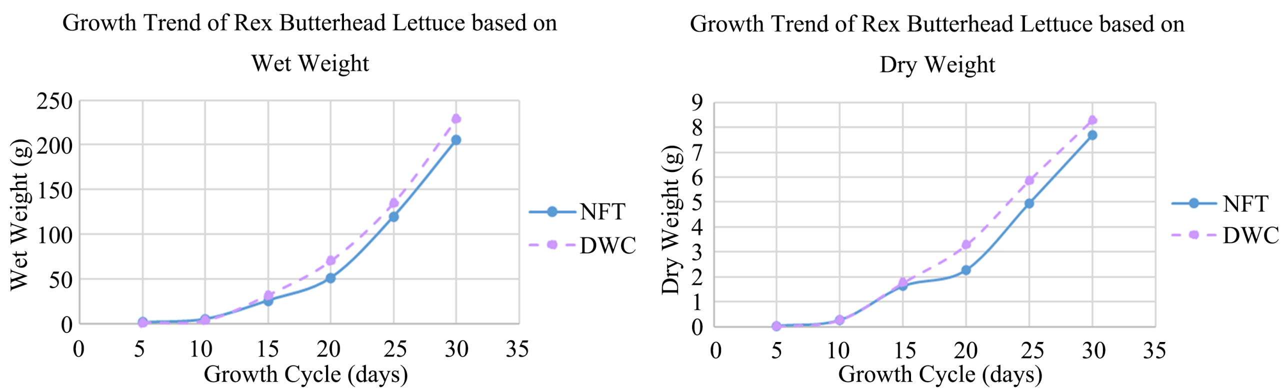

Figure 2. A graphical representation of wet weight (g) and dry weight (g) over time (days) demonstrating similar growth trends in both the DWC and NFT systems.

Table 2. Wet weight (g/head), dry weight (g/head), SLA (cm^2/g), leaf count (n), chlorophyll ($\mu mol/m^2$), SPAD, and productivity (kg/m^2) in NFT and DWC systems at harvest on day 30 of the growth cycle.

Biomass Data	Wet Weight	Dry Weight	SLA	Leaf Count	Chlorophyll	SPAD	Productivity
	(g/head)	(g/head)	(cm^2/g)	(EA)	($\mu mol/m^2$)		(kg/m^2)
NFT	205.68	7.68	256.74	37	35.68	25.20	4.94
DWC	228.90	8.28	423.65	50	34.40	24.0	5.49

4. Conclusion

The main aim of this study was to compare the environmental conditions and biomass parameters using NFT and DWC soilless methods of hydroponic systems using GREENBOX technology for lettuce *Lactuca sativa* "Rex Butterhead" crop production. We found the environmental conditions in both systems were similar and that both hydroponics methods could produce "Rex Butterhead" lettuce for consumption at the expected harvest weight by the end of the growth cycle, comparable to previous growing cycles using GREENBOX technology and other peer-reviewed literature. Statistical analysis of the wet and dry weights using the NFT and DWC hydroponic methods suggests no statistically significant difference between the biomass of the crops using GREENBOX technology. The results from this work would inform future design iterations of GREENBOX technology which demonstrates DWC and NFT systems may be suitable for use in this technology.

Acknowledgements

We would like to thank Christal Niemeyer for her assistance in coordinating and acquiring the supplies necessary to complete this project, and Dr. Greg Tolley of The Water School at FGCU for providing a space to perform this project and financial assistance. We also thank Dr. Minh Nguyen and the Honors College, Dr. Heather Skaza-Acosta and the Whitaker Center.

Conflicts of Interest

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

References

[1] Pison, G. (2017) Tous les pays du monde. *Population et sociétés*, **547**, 1-4. https://hal.science/hal-02082693/file/Pop-et-soc_547-2017.tous.les.pays.du.monde.fr.pdf
https://doi.org/10.3917/popsoc.547.0001

[2] Kloas, W., *et al.* (2015) A New Concept for Aquaponic Systems to Improve Sustainability, Increase Productivity, and Reduce Environmental Impacts. *Aquaculture Environment Interactions*, **7**, 179-192. https://doi.org/10.3354/aei00146

[3] Kozai, T. (2018) Current Status of Plant Factories with Artificial Lighting (PFALs) and Smart PFALs. In: Kozai, T., Ed., *Smart Plant Factory*: *The Next Generation Indoor Vertical Farms*, Singapore, Springer, 3-13. https://doi.org/10.1007/978-981-13-1065-2_1

[4] Pörtner, L.M., Lambrecht, N., Springmann, M., Bodirsky, B.L., Gaupp, F., Freund, F., Lotze-Campen, H. and Gabrysch, S. (2022) We Need a Food System Transformation—In the Face of the Russia-Ukraine War, Now More than Ever. *One Earth*, **5**, 470-472. https://doi.org/10.1016/j.oneear.2022.04.004

[5] Wahome, P.K., Oseni, T.O., Masarirambi, M.T. and Shongwe, V.D. (2011) Effects of Different Hydroponics Systems and Growing Media on the Vegetative Growth, Yield and Cut Flower Quality of Gypsophila (*Gypsophila paniculata* L.). *World Journal of Agricultural Sciences*, **7**, 692-698.

[6] Khan, S., Purohit, A. and Vadsaria, N. (2021) Hydroponics: Current and Future State of the Art in Farming. *Journal of Plant Nutrition*, **44**, 1515-1538. https://doi.org/10.1080/01904167.2020.1860217

[7] Hamza, A., Abdelraouf, R.E., Helmy, Y.I. and El-Sawy, S.M.M. (2022) Using Deep Water Culture as One of the Important Hydroponic Systems for Saving Water, Mineral Fertilizers and Improving the Productivity of Lettuce Crop. *International Journal of Health Sciences*, **6**, 2311-2331. https://doi.org/10.53730/ijhs.v6nS9.12932

[8] Kikuchi, Y., Kanematsu, Y., Yoshikawa, N., Okubo, T. and Takagaki, M. (2018) Environmental and Resource Use Analysis of Plant Factories with Energy Technology Options: A Case Study in Japan. *Journal of Cleaner Production*, **186**, 703-717. https://doi.org/10.1016/j.jclepro.2018.03.110

[9] Xydis, G.A., Liaros, S. and Avgoustaki, D.D. (2020) Small Scale Plant Factories with Artificial Lighting and Wind Energy Microgeneration: A Multiple Revenue Stream Approach. *Journal of Cleaner Production*, **255**, Article ID: 120227. https://doi.org/10.1016/j.jclepro.2020.120227

[10] Hayden, A.L. (2006) Aeroponic and Hydroponic Systems for Medicinal Herb, Rhizome, and Root Crops. *HortScience*, **41**, 536-538. https://doi.org/10.21273/HORTSCI.41.3.536

[11] Grigas, A., Kemzūraitė, A., Steponavičius, D., Steponavičienė, A. and Domeika, R. (2020) Impact of Slope of Growing Trays on Productivity of Wheat Green Fodder by a Nutrient Film Technique System. *Water*, **12**, Article 3009. https://doi.org/10.3390/w12113009

[12] D'Imperio, M., Renna, M., Cardinali, A., Buttaro, D., Santamaria, P. and Serio, F. (2016) Silicon Biofortification of Leafy Vegetables and Its Bioaccessibility in the Edible Parts. *Journal of the Science of Food and Agriculture*, **96**, 751-756. https://doi.org/10.1002/jsfa.7142

[13] Liu, C., Wu, J., Raudales, R., McAvoy, R., Theobald, D. and Yang, X. (2018) An Experimental Study on Energy and Water Uses of A Newly Developed Greenbox Farming System. 2018 *ASABE Annual International Meeting*, Detroit, 29 July-1 August 2018, 2-9. https://doi.org/10.13031/aim.201800891

[14] Singh, A.K., McAvoy, R.J., Bravo-Ureta, B. and Yang, X. (2021) An Experimental Study on GREENBOX Technology: Feasibility and Performance. 2021 *ASABE Annual International Virtual Meeting*, 12-16 July 2021, 145-166. https://doi.org/10.13031/aim.202100453

[15] Singh, A.K., McAvoy, R.J., Bravo-Ureta, B. and Yang, X. (2021) Comparison of Environmental Condition, Productivity, and Resources Use between GREENBOX and Greenhouse for Growing Lettuce. 2021 *ASABE Annual International Virtual Meeting*, 12-16 July 2021, 2-10. https://doi.org/10.13031/aim.202100455

[16] Singh, A.K., McAvoy, R.J., Bravo-Ureta, B. and Yang, X. (2022) Financial Feasibility Study of GREENBOX Technology for Crop Production in an Urban Setting. 2022 *ASABE Annual International Meeting*, Houston, 17-20 July 2022, 1-16. https://doi.org/10.13031/aim.202201068

[17] Yang, X., Theobald, D., McAvoy, R., Wu, J. and Liu C. (2017) Greenbox Farming: A New System for Urban Agriculture. 2017 *ASABE Annual International Meeting*, Spokane, 16-19 July 2017, 1 p.

[18] Singh, A.K. and Yang, X. (2021) GREENBOX Horticulture, an Alternative Avenue of Urban Food Production. *Agricultural Sciences*, **12**, 1473-1489. https://doi.org/10.4236/as.2021.1212094

[19] Singh, A.K., Bravo-Ureta, B., McAvoy, R. and Yang, X. (2023) GREENBOX Technology II—Comparison of Environmental Conditions, Productivity, and Water Consumption with Greenhouse Operation. *Journal of the ASABE*.

[20] Singh, A.K., McAvoy, R., Bravo-Ureta, B. and Yang, X. (2023) GREENBOX Technology I—Technical Feasibility and Performance in Warehouse Environment. *Journal of the ASABE*.

[21] National Oceanic and Atmospheric Administration (2022) Climate—Southwest Florida. https://www.weather.gov/wrh/Climate?wfo=tbw

[22] Zheng, C., Mohammad, S.J., Pengpeng, M., Mengmeng, W., Xiaoying, L. and Shirong, G. (2020) Functional Growth, Photosynthesis and Nutritional Property Analyses of Lettuce Grown under Different Temperature and Light Intensity. *The Journal of Horticultural Science and Biotechnology*, **96**, 53-61. https://www.tandfonline.com/doi/epdf/10.1080/14620316.2020.1807416?needAccess=true&role=button

[23] Holmes, S.C., Wells, D.E., Pickens, J.M. and Kemble, J.M. (2019) Selection of Heat Tolerant Lettuce (*Lactuca sativa* L.) Cultivars Grown in Deep Water Culture and Their Marketability. *Horticulturae*, **5**, Article 50. https://doi.org/10.3390/horticulturae5030050

[24] Anderson, C.J.R. and Rosas-Anderson, P.J. (2017) Leafscan. Version 1.3.21. Mobile Application Software. https://apps.apple.com/app/id1254892230

[25] Zhu, J., Tremblay, N. and Liang, Y. (2012) Comparing SPAD and at LEAF Values for Chlorophyll Assessment in Crop Species. *Canadian Journal of Soil Science*, **92**, 645-648. https://doi.org/10.4141/cjss2011-100

[26] R Core Team (2022) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

[27] Paz, M., Fisher, P.R. and Gómez, C. (2019) Minimum Light Requirements for Indoor Gardening of Lettuce. *Urban Agriculture & Regional Food Systems*, **4**, 1-10. https://doi.org/10.2134/urbanag2019.03.0001

[28] Despommier, D. (2013) Farming up the City: The Rise of Urban Vertical Farms. *Trends in Biotechnology*, **31**, 388-389. https://doi.org/10.1016/j.tibtech.2013.03.008

[29] Tokunaga, K., Tamaru, C., Ako, H. and Leung, P. (2015) Economics of Small-Scale Commercial Aquaponics in Hawai'i. *Journal of the World Aquaculture Society*, **46**, 20-32. https://doi.org/10.1111/jwas.12173

[30] Kubota, C. (2016) Chapter 10—Growth, Development, Transpiration and Translocation as Affected by Abiotic Environmental Factors. In: Kozai, T., Niu, G. and Takagaki, M., Eds., *Plant Factory*, Academic Press, San Diego, 151-164. https://doi.org/10.1016/B978-0-12-801775-3.00010-X