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Comparison of Energy-use Efficiency for Lettuce Plantation under Nutrient Film Technique and Deep-Water Culture Hydroponic Systems

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Abstract

Energy conservation opportunities in closed plant production systems have been widely discussed, however, a comparison of energy-use efficiency (EUE) for different types of hydroponic systems is lacking. This paper compares the EUE of two different hydroponic systems, namely nutrient film technique (NFT) and deep-water culture (DWC), within an aquaponics facility. The energy is monitored in a controlled environment using artificial lighting and its impact on the growth dynamics of the crops is measured, in this case, on a leafy green crop (Lactuca Sativa L. 'Little Gem'). Offering better efficiency and reliability, light-emitting diode (LED) irradiation is used with a photosynthetic photon flux (PPF) of 140 $\mu mol \cdot s^{-1}$ and a photoperiod of 12-hours. The seeds are then placed in growth chambers, kept at an ambient temperature of 18°C for 21 days. These seedlings are then transplanted in rockwool cubes, followed by placement in NFT or DWC systems in equal numbers. Both systems are illuminated with LED irradiation having a PPF of 200 $\mu mol \cdot s^{-1}$. Continuous irradiation with a photoperiod of 16-hours is provided to both systems for 5 weeks. Crop growth parameters, such as leaf count and plant height, are measured in both systems resulting in similar numbers obtained, however, shoot fresh weight, leaf area, and root length are significantly different. Furthermore, the NFT system exhibited an EUE of 31.3 g. kWh^{-1} and outperformed the DWC system with an EUE of 24.53 g. kWh^{-1}; indicating higher growth and better energy savings associated with NFT systems. These results suggest that NFT systems has a higher potential to offer better energy-use efficiency for producing crops in plant factories and aquaponics facilities.

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1. Introduction

Traditional soil-based agriculture practices are facing threats in the form of unpredictable weather patterns owing to rising temperatures, depleted soil productivity due to continuous cultivation, reduced per capita land availability on account of rising population, and more importantly, poor water management leading to wastage of the most precious resource, water [1]. Modern techniques that rely on soil-less production, such as hydroponics and aquaponics, can complement conventional approaches to ensure productive and ecologically sustainable food supply chain [2]. Such systems allow increased quality of produce gained by avoiding soil-borne diseases, reduced exposure to fertilizers and pesticides, and enabling better control of environmental parameters, such as temperature, relative humidity, light intensity, among several other variables [3]. At the same time, the energy demand of advanced agricultural systems that can be operated in harsh weather conditions and indoor facilities using artificial illuminance instead of the traditional solar radiation needs to be investigated to examine the applicability of these emerging technologies [4]. The environmental footprint of such systems depends mostly on the energy-use efficiency for lighting and supplemental conditioned air flow and is usually assessed on a per-project basis [5].

1.1. Hydroponics – Soilless Alternative

Hydroponics is a class of horticulture that involves cultivation of plants by exposing its roots to a liquid nutrient solution. Instead of the traditional approach of using soil, crop roots can be physically supported by inert media such as gravel, pearlite, rockwool, or other substrates. Distinguished as an engineered way of vegetation, hydroponics technique utilizes soilless growing medium along with enriched nutritive solution tailored to meet plant specific needs and ensure growth and development [6]. Such systems minimize resource wastage as the nutrient rich solution can be reused for maximum efficiency, achieving highest yields by utilizing much less water per gram of produce [7]. Hydroponic systems have also been designed in coherence with aquaculture, labelled as Aquaponics – a merger of hydroponics and aquaculture, that work in a symbiotic environment promoting resource efficiency and sustainability [8], [9].

Removing the barrier between crop and its nutrients, hydroponics provides roots with direct access to water, oxygen, and other supplements to enhance growth and vegetation. This access can be achieved through different arrangements and is what differentiates the various types of hydroponic systems. Based on the mode of nutrient delivery and water distribution, hydroponic systems can be mainly classified as:

- Nutrient Film Technique (NFT)
- Deep Water Culture (DWC)
- Aeroponic Systems

1.1.1 Nutrient Film Technique (NFT)

A recirculating type of hydroponic system, NFT comprise of grow channels through which a layer of nutrient solution, typically 1-2 cm high, circulates with the help of mechanical pumps [10]. Such systems have great potential for automation and optimizing plant density, however, limited water availability and premature root system ageing pose major constraints in production of crops with over 4 – 5 months growth cycle [3]. One of the main advantages of NFT system is the way it handles the supplement solution. The recirculating nutrient rich water can maintain healthy oxygen levels for plant growth and development and is one of the main reasons for its popularity amongst hydroponic enthusiasts. Furthermore, this setup requires minimal to no growing media and thus decreases the potential pH fluctuations that may occur otherwise.

1.1.2 Deep Water Culture (DWC)

DWC hydroponic systems are of stationary type and comprise of floating rafts that support plants placed over containers filled with nutrient rich water. Such systems require minimum cost and supervision but possess limited scope for automation [11]. The inexpensive nature and relatively easier maintenance requirement of DWC hydroponic system attracts many growers. However, there are certain drawbacks with this type of a setup. DWC systems are not recommended for larger plants or ones with longer grow periods. Furthermore, plant roots require oxygen for growth and development, without which they may drown. Thus, oxygen monitoring and control becomes vital for DWC hydroponic growers. The oxygen levels necessary for plant growth and development are maintained using air bubblers or venturi systems.

1.1.3 Aeroponic System

A less popular type of hydroponic system, aeroponics, works by exposing plant roots to a fine spray of nutrient rich solution. Plants are supported by horizontal or vertical panels thereby allowing the suspend roots to encounter the nutrient rich solution sprayed directly on them using static sprinklers [12]. Aimed at smaller horticulture species, aeroponic systems require high investment and running cost leading to less popularity of such hydroponic systems. Furthermore, the nozzles run a risk of getting clogged which can have dire effects on the plants. On the bright side, this system allows the roots greater exposure to oxygen thus resulting in enhanced growth and development.

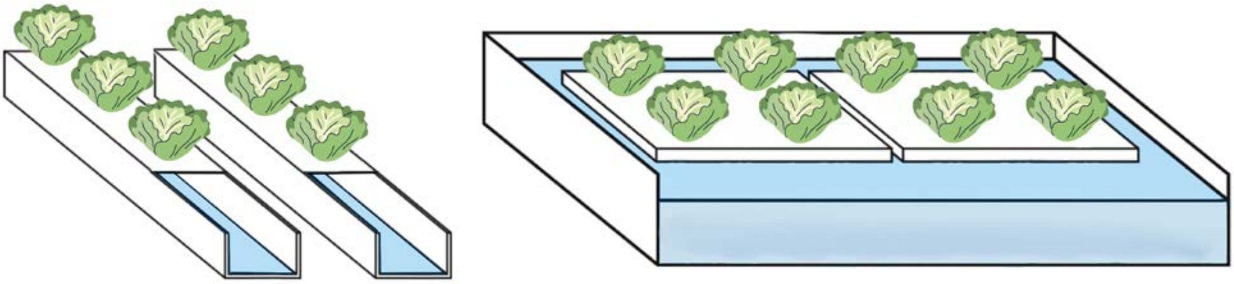

Figure 1. Schematic view of (a) NFT and (b) DWC hydroponic system

1.2. Energy-use Efficiency in Closed Plant Production Systems

One of the main advantages of hydroponic systems is its tolerance against seasonal changes and harsh weather conditions, leading to higher annual productivity as compared to traditional agricultural practices [13]. Categorized into either greenhouses or closed plant production systems (CPPS), the benefit of each type of hydroponic system differs significantly. CPPS require artificial illuminance and heating, cooling, and ventilation apart from the water/air circulation leading to increased energy consumption when compared to greenhouse hydroponic facilities but offer the advantage of year-round production [5].

Energy consumption is considered as one of the main challenges for indoor hydroponic and aquaponic facilities in terms of sustainability and environmental footprint [14]–[16]. Implementation of energy efficient solutions such as light-emitting diodes (LEDs) for artificial illuminance and use of renewable energy sources for heating, ventilation and air conditioning has significantly reduced the ecological consequences of modern agriculture [17], [18]. The energy demand of a typical hydroponic facility is illustrated in Figure 2 [14].

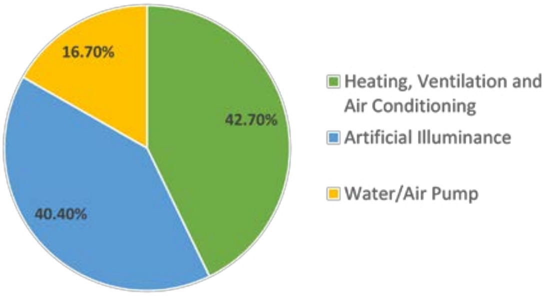

Figure 2. Energy demand of a typical hydroponic facility, after [14].

Though a lot of research has been published on enhancing the energy efficiency of modern agricultural technologies, there exists limited literature comparing the energy-use efficiency of NFT and DWC hydroponic systems in an aquaponic setup [19]–[22]. As the two hydroponic systems tested are mechanically and conceptually distinct, they consume different amount of energy and generate varying yield. This experiment is an attempt to understand the impact of choice of hydroponic system on the plant fresh biomass per unit of energy consumption.

2. Material and Methods

The experiment to compare the EUE performance of NFT and DWC hydroponic systems is performed in Allfactory, an aquaponics facility situated at the University of Alberta, Canada, which focuses on advanced digital manufacturing processes applied to vertical farming and closed plant production systems [9], [23]–[26].

2.1. Environmental Conditions

Little Gem lettuce (Lactuca Sativa L.) is chosen for this experiment, as it is ideal for small scale vertical farms due to its compact head size [27]. Having a germination rate of 93%, 50 seeds (Little Gem LT476, west coast seeds, British Columbia, Canada) are placed in growth chambers with ambient temperature of 18°C and 70% relative humidity. These seeds are irradiated with light-emitting diode (LED W-SF10, Wills, Texas, USA) for a 12-hour (12 hours light / 12 hours dark) photoperiod. Twenty-one days after sowing, 40 healthy lettuce seedlings are transplanted in rockwool cubes (Hydroponic mineral wool cubes, zxcv-de1-396, Holland Industry, Ontario, Canada). Twenty of these rockwool cubes are placed in the NFT system (3 x 2.8 ft^2) attached to a sump filled with 20 gallons of water mixed with nutrient solution (Liquid Plant Food 4-3-6, 9401-0QZ, AeroGarden, Colorado, USA) containing 4.0% total nitrogen (N), 3.0% available phosphate (P2O5), 6% soluble potash (K20), 1% Calcium (Ca) and 0.5% Magnesium (Mg) per liter. This supplement rich water is siphoned into the system using a submersible pump (Pomp800, Hydrofarm, California USA). The remaining twenty rockwool cubes are accommodated in the DWC system (2 x 4 ft^2) loaded with 20 gallons of the same nutrient rich solution. Two air bubblers (Air stone ASD-040, Pawfly) connected to two identical air pumps (HG-811, Hygger) are used to disperse dissolved oxygen throughout the system. The two systems are illuminated using light-emitting diodes (LED RAZRx RRR-X-P-1-06-N5-H, Fluence Bioengineering, Texas, USA) with maximum photosynthetic photon flux (PPF) of 200 $\mu mol \cdot s^{-1}$. Since the two systems differ in dimensions, the intensity of the light is optimized such that both the systems receive similar photosynthetic photon flux density (PPFD). Spectral scans are recorded at 25 cm from the lighting source at four corners and the center of each system using a spectroradiometer. PPFD for NFT system was approximately 258.33 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and that for DWC system was 269.10 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Light source spectrum has been illustrated in Figure 3 (Adapted from [28]).

Both the systems are set up in an indoor aquaponics facility. The heating, cooling, and air conditioning is provided by building facility services and controlled using thermostat. The smart sensor (WS1 Pro, UbiBot, Texas, USA) is

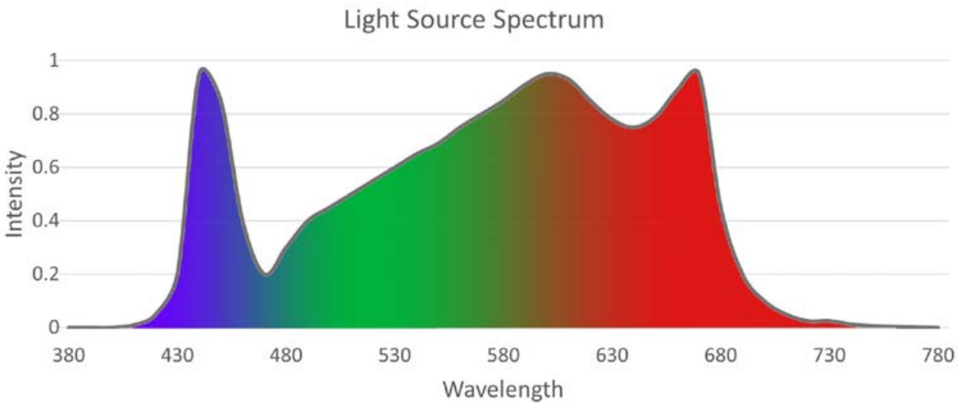

Figure 3. Artificial illuminance light source spectrum

employed to monitor room temperature, relative humidity, and illumination at constant intervals. Furthermore, electroconductivity (Pencon Conductivity Pen, Bluelab, New Zealand) and pH (pH Pen, Bluelab, New Zealand) values are also recorded and balanced for both systems. The obtained data is logged for the entire period from seeding to harvesting to ensure the study is commensurable. The daily average value for these parameters for the entire duration of lettuce growth has been displayed in Table 1.

Table 1. Parameter values maintained for NFT and DWC hydroponic systems during growth cycle

Hydroponic System	Relative Humidity (%)	Ambient Temperature (°C)	PPFD ($\mu mol\cdot m^{-2}\cdot s^{-1}$)	EC (dS/m)	pH
NFT System	70.2	18.8	258.33	1.26	5.9
DWC System	70.2	18.8	269.1	1.27	5.9

2.2. Growth Characteristics and Energy-use Efficiency

Lettuce seeds are placed in both hydroponic systems, NFT and DWC, for a period of 5 weeks. After plantation cycle, the lettuce is harvested and growth characteristics, such as plant fresh weight, shoot and root weight, leaf count, plant height, plant width, and root length are measured. An electronic scale (Digital scale EK9000, Etekcity, China) is used to determine the fresh biomass of lettuce.

Throughout the duration of plantation, the energy consumption of the LED lights and water and air pumps is measured using smart energy meters (Smart plug B08CVSSVWP, Emporia Energy, Colorado, USA) and the data is transmitted to a cloud platform. Energy-use efficiency (EUE) is calculated (1) by dividing the plant fresh weight to the total kilowatt hour energy consumption (g. kWh-1) after 5 weeks of treatment [22].

$$EUE = \sum Plant\, Fresh\, Weight \div \sum Energy\, Consumption \quad (1)$$

2.3. Statistical Analysis

Prior to transplantation, lettuce seedlings are randomized going into the two hydroponic systems. Data related to lettuce growth characteristics is captured after harvesting the produce and statistical analysis on this recorded data is performed using unpaired t-test. This test compares the growth characteristics for both NFT and DWC grown hydroponic lettuce, which are two independent and unrelated groups. It then determines if there exists any significant difference between the lettuce growth characteristics. These statistics along with the energy consumption results are eventually utilized to compute the energy-use efficiency (EUE) of lettuce plantation under nutrient film technique and deep-water culture hydroponic systems.

3. Results and Discussion

3.1. Energy Consumption

Energy demand for a typical indoor plantation facility is mainly in the form of environmental conditioning (heating, ventilation, and air conditioning), artificial illuminance and mechanical systems [14]. As both the systems are placed in the same facility, adjacent to each other, heating ventilation and air-conditioning (HVAC) load remain constant for both systems and are therefore not considered during this analysis. Energy consumption for the artificial illuminance and the water and air pumps for both hydroponic systems has been listed in Figure 4.

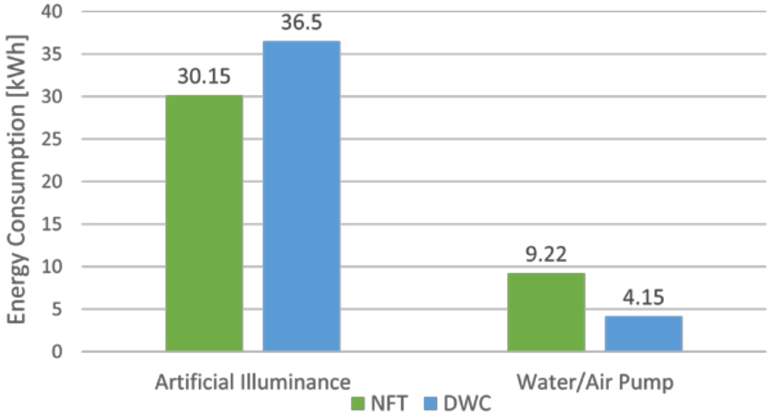

Figure 4. Energy consumption for NFT and DWC hydroponic system

The higher energy consumed by the DWC system for artificial illuminance can be attributed to the higher light intensity employed in this system to ensure that similar photosynthetic photon flux density (PPFD) is received by crops in both DWC and NFT systems and that the environmental conditions are identical. However, the NFT system did require more energy for water circulation and exceeded the mechanical energy demand of the DWC hydroponic system that employed a relatively small air pump to maintain water oxygen levels. In total, for this experiment, the DWC system consumed a 3.25% more energy than the NFT system with the same number of lettuce crops.

3.2. Growth Characteristics

Growth of lettuce cultivated under LED artificial illuminance for a period of 5 weeks is influenced by the type of hydroponic system as depicted in Table 2. A sample size of 20 lettuces is used for this statistical comparison, and an unpaired t-test is performed to validate the results. Important growth characteristics, such as plant fresh weight, shoot and root weight have shown to be significantly higher in the NFT hydroponic system. Other parameters such as plant height, plant width, and leaf count have been found unaffected by the type of hydroponic system employed. This conclusion is drawn after obtaining the two-tailed P test values for the recorded data, which tests the null-hypothesis that both NFT and DWC hydroponic lettuce growth characteristics have similar means. The values obtained by the test denote the probability of null hypothesis being correct.

Table 2. Lettuce growth characteristics under NFT and DWC hydroponic systems based on a sample size of 20 lettuce plants

	Plant Fresh Weight (g)		Shoot Weight (g)		Root Weight (g)		Plant Height (cm)		Plant Width (cm)		Root Length (cm)		Leaf Count	
	NFT	DWC	NFT	DWC	NFT	DWC	NFT	DWC	NFT	DWC	NFT	DWC	NFT	DWC
Total	1234.2	977.4	905.9	829.4	323.4	145.8	-	-	-	-	-	-	309	297
Max	90.7	87.8	72.4	73.6	24.0	15.6	14.0	12.0	23.0	21.3	44.0	54.1	25	20
Min	40.2	32.7	24.2	25.9	6.7	3.8	7.5	8	8.0	11.3	23.0	27.7	9	12
Mean	61.7	49.9	45.3	41.3	16.2	7.3	10.4	10.3	15.6	14.3	33.3	37.5	15.5	14.9
Median	58.0	47.2	43.5	38.5	17.6	6.4	11.0	10.6	14.0	14.4	32.0	37.6	14.0	15.0
Standard Deviation	13.9	14.2	13.3	11.8	4.6	3.0	2.0	1.0	4.0	2.5	6.6	6.9	3.8	2.0
Two-tailed P test	0.0115		0.2289		0.0001		0.4333		0.709		0.0132		0.6118	

The mean plant fresh weight for NFT grown lettuce was found to be 61.7 grams, 23.6% higher than DWC grown lettuce. Similar patterns were observed for NFT grown lettuce shoot and root weight, with mean values of 4.0 grams and 8.9 grams greater than DWC system, respectively. Though NFT system witnessed higher lettuce root weight, the average root length for DWC grown lettuce was found to be 12.6% greater. Both the systems resulted in similar leaf count of about 15 leaves per lettuce crop. Based on these results, NFT system performs better as compared to DWC system in producing hydroponic lettuce with higher biomass. A pictorial depiction of hydroponic lettuce grown in NFT and DWC has been shown in Figure 5.

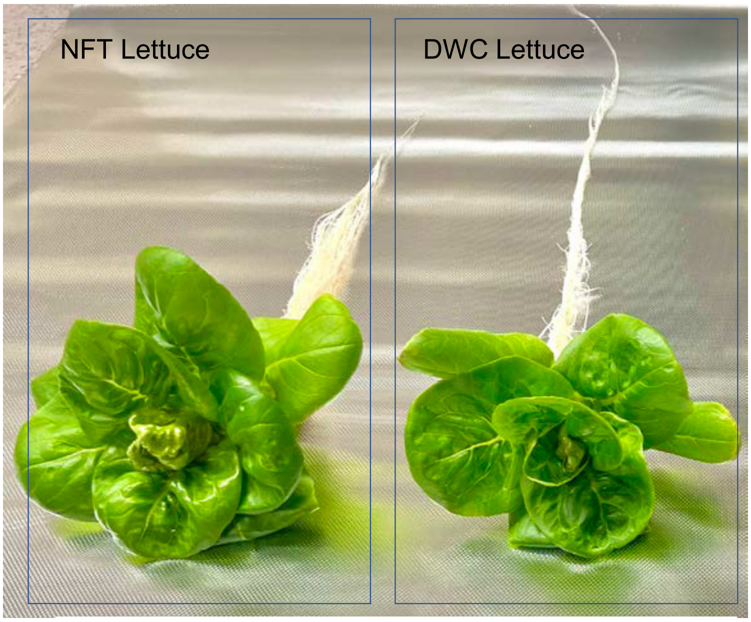

Figure 5. Pictorial representation of NFT and DWC grown hydroponic lettuce

3.3. Energy-use Efficiency

To evaluate energy consumption levels of hydroponic lettuce plantation more intuitively and provide qualitative results for commercial hydroponic lettuce production, data gathered from the growth characteristics and energy consumption is utilized to come up with the energy-use efficiency for the two hydroponic systems. An EUE of 31.34 g. kWh^{-1} is recorded for the NFT grown hydroponic lettuce, outperforming the DWC system with an EUE of 24.53 g. kWh^{-1}. These results have been plotted in Figure 6.

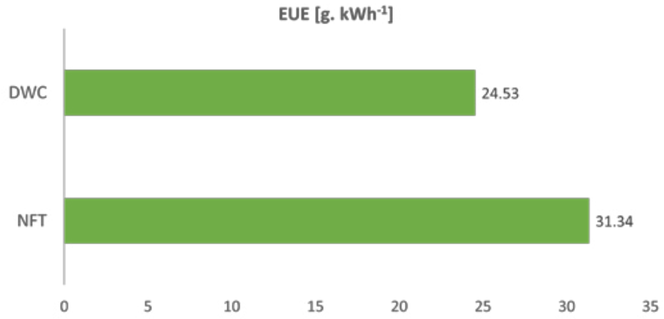

Figure 6. EUE comparison of NFT and DWC grown hydroponic lettuce

Industrialization of modern agricultural plant factories and aquaponics is hindered by excessive energy consumption, and thus calls for improving produce yield per unit of energy consumed [17]. In this experiment, the 27.7% higher EUE associated with NFT based hydroponic system can be attributed to two factors. The first being the enhanced growth of lettuce plants due to better nutrient flow and optimal plant density during crop cycles, and the second being a reduced energy consumption associated with the NFT hydroponic system in general [6]. As such, this study proposes the use of NFT hydroponic systems for lettuce plantation in indoor plant factories and aquaponics facilities.

4. Conclusion

Both nutrient film technique (NFT) and deep-water culture (DWC) based hydroponic systems offer several advantages over the traditional agricultural practices, but the environmental footprint of such modern agricultural operations needs to be optimized. This study was an attempt to compare the energy-use efficiency for Lactuca Sativa L. ‘Little Gem’ plantation in NFT and DWC based hydroponic systems for an aquaponics facility in a controlled environment. Forty healthy lettuce seedlings were divided into NFT and DWC hydroponic systems and irradiated with light-emitting diode (LED) having a photosynthetic photon flux (PPF) of 200 $\mu mol \cdot s^{-1}$ and a photoperiod of 16-hours for five weeks. Throughout the crop cycle, energy consumption for artificial illuminance and mechanical pumps was logged on a cloud platform. Upon harvesting, lettuce growth characteristics such as fresh plant weight, shoot and root weight, plant height, root length, and number of leaves were recorded and used to compute the energy-use efficiency of the two hydroponic systems. Based on the results, NFT grown hydroponic lettuce offers 27.7% better energy-use efficiency when compared to DWC system, which can be attributed to better nutrient flow and optimized plant density deployed in the NFT hydroponic system. These results suggest that NFT based hydroponic system has the capability to offer better energy-use efficiency for producing crops in indoor plant factories and aquaponics facilities.

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