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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Comparative Analysis of Deep Flow and Nutrient Film Technique in Vertical Farming

Dikey Tarımda Derin Akış ve Besleyici Film Tekniğinin Karşılaştırmalı Analizi

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Abstract

Unlike traditional agriculture, vertical farming systems utilize soilless cultivation methods. Various solid media cultures or hydroponic methods can be employed for soilless farming. The selection of methods and materials should be based on criteria such as economic feasibility, accessibility, sustainability, ease of use and management, as well as operating costs, efficiency, and quality. In these intensive production systems, it is crucial to design, establish, and operate them like a factory to maintain high profitability. Since plant growth and development in vertical farming are faster compared to other agricultural methods, all harvesting, planting, irrigation, and system maintenance operations need to be carried out promptly. Therefore, determining which method or methods are more efficient in these systems is highly important. For the widespread adoption and sustainability of vertical farming, analyses of different methods and systems are necessary. The aim of this study is to contribute to the literature on methods for vertical farming facilities. In this study, lettuce, rocket, cress, and dill were cultivated under controlled climatic conditions in a fully enclosed and computer-controlled laboratory using the Deep Flow Technique (DFT) and Nutrient Film Technique (NFT). The growth performance, yield characteristics, and quality parameters of the plants grown were compared between the two systems. For this comparison, total fresh weight, plant height and width, stem diameter, leaf count, discarded leaf count, and branching (in applicable species) were used. Additionally, the energy efficiency of the vertical farming systems established using the two techniques was evaluated. The energy use efficiency (EUE) of the NFT and DFT systems was calculated as 4.16 g kWh^{-1} and 5.89 g kWh^{-1}, respectively. The DFT system increased the total fresh weight and stem diameter in lettuce and dill plants by an average of 5%. Due to the higher biomass production in the DFT system, its EUE was calculated to be 5% higher.

Keywords: Nutrient film technique, Deep flow technique, Vertical farming, Energy use efficiency, Controlled environment agriculture

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Öz

Geleneksel tarımdan farklı olarak dikey tarım sistemlerinde topraksız kültür yöntemleri kullanılmaktadır. Topraksız tarım için çeşitli katı ortam kültürleri veya su kültürü yöntemleri kullanmak mümkün olmaktadır. Yöntemlerin ve materyallerin seçimi, ekonomik uygunluk, erişilebilirlik, sürdürülebilirlik, kullanım ve yönetim kolaylığı gibi kriterlerin yanı sıra işletme maliyetleri, verimlilik ve kalite açısından değerlendirilerek yapılmalıdır. Bu tür yoğun üretim sistemlerinde, karlılığı yüksek tutmak için bir fabrika gibi planlamak, kurmak ve işletmek önemlidir. Dikey tarımda bitkilerin büyüme ve gelişmesi diğer tarım yöntemlerine göre daha hızlı olduğu için tüm hasat, ekim, sulama ve sistem bakım işlemlerinin hızlı bir şekilde yapılmasını gerektirir. Dolayısıyla bu sistemlerde hangi yöntem veya yöntemlerin daha verimli olduğu oldukça önemlidir. Dikey tarımın yaygınlaşması ve sürdürülebilir olması için farklı yöntemlere ve sistem analizlerine ihtiyaç duyulmaktadır. Bu çalışmanın amacı, dikey tarım tesisleri için bir yöntem literatürü oluşturulmasına katkı sağlamaktır. Bu çalışmada, tamamen kapalı ve bilgisayar kontrollü bir laboratuvarda, iklim parametrelerinin kontrol edildiği koşullarda, Derin Akış Tekniği (DFT) ve Besleyici Film Tekniği (NFT) kullanılarak marul, roka, tere ve dereotu bitki türleri yetiştirilmiştir. Yetiştirilen bitkilerin gelişim durumları, verim özellikleri ve kalite parametreleri her iki sistem arasında karşılaştırılmıştır. Bu karşılaştırma yapılırken toplam taze ağırlık, bitki boyu ve eni, gövde çapı, yaprak sayısı, ıskarta sayısı ve uygun bitki türlerinde dallanma sayısı kullanılmıştır. Ayrıca, iki farklı teknik kullanılarak kurulan dikey tarım sistemlerinin enerji verimliliği değerlendirilmiştir. NFT ve DFT sistemlerin enerji kullanım etkinliği sırasıyla 4.16 g kWh^{-1} ve 5.89 g kWh^{-1} olarak hesaplanmıştır. DFT sistemi marul ve dereotu bitkilerinde toplam taze ağırlığı ve gövde çapını ortalama %5 oranında artırmıştır. DFT sisteminde daha fazla biyokütle üretildiği için Enerji Kullanım Etkinliği (EUE) %5 daha yüksek olarak hesaplanmaktadır.

Anahtar Kelimeler: Besleyici film tekniği, Derin akış tekniği, Dikey tarım, Enerji kullanım etkinliği, Kontrollü ortam tarımı

1. Introduction

Vertical farming is a relatively new approach to agriculture that involves growing crops in vertically stacked layers in controlled environments such as greenhouses or indoor facilities (Anpo et al., 2019). Unlike traditional agriculture, which relies on fertile soil and favorable weather conditions, vertical farming uses advanced technologies such as hydroponics, aeroponics, and aquaponics to grow crops in a soilless medium, using artificial light sources and climate control systems to optimize plant growth (Şahin and Kendirli, 2016).

1.1. Hydroponic vertical farming

Hydroponic farming system components usually include growing containers, nutrient solutions, water and air pumps, lighting systems, pH sensors, EC sensors and a controller. These components work together to create an optimal growing environment for plants, allowing for efficient and productive agriculture (Niu and Masabni, 2022).

The primary objective of vertical farming is to maximize crop yields while minimizing the environmental impact of farming (Lubna et al., 2022). By using efficient space and resource management techniques, vertical farming can produce more food per unit area than traditional agriculture, consume less water and fertilizer, and generate less plant waste and carbon emissions.

Vertical farming has the potential to revolutionize the food industry, enabling year-round production of fresh, locally grown produce in urban areas, reducing the need for long-distance transportation of food, and creating new opportunities for small-scale farmers and entrepreneurs. However, there are also challenges associated with the high upfront costs of building and operating vertical farms, as well as the technical expertise required to maintain the complex systems involved (Seyhan, 2023).

In the forthcoming years, urban agriculture should focus on elements conducive to the sustainability of agricultural progress. Such elements encompass the allocation of space, the selection and diversity of crops cultivated and the integration of innovative technologies (Fitri et al., 2024).

1.1.1. Nutrient film technique

NFT stands for “Nutrient Film Technique”, which is a hydroponic method used to cultivate plants. In an NFT system, plants are grown in a shallow stream of nutrient solution. The solution is pumped through a closed loop of plastic channels, and the roots of the plants are suspended in the solution stream. The nutrient film is extremely thin, usually around 5 millimeters deep (Resh, 2022).

One of the key advantages of NFT systems is that they use less water than other hydroponics methods, and because the roots are suspended in the solution, there is less risk of waterlogging, allowing for optimal oxygen levels for the roots. In addition, NFT systems can be used to cultivate a wide range of plants, including leafy vegetables, herbs, and some small fruiting plants, such as strawberries. Due to the nature of the system, it is generally not suitable for larger plants like fruit trees, but it can be effectively applied for ornamental plants or small-scale crops. This versatility makes NFT systems ideal for home gardens or small-scale commercial operations. (Alfredo, 2023).

NFT also has some limitations, one of the main ones being that the systems are often more fragile due to their reliance on continuous water flow and a thin nutrient film. Any interruptions, such as pump failures or power outages, can quickly deprive the water and nutrients, potentially causing stress or damage to the crops. Additionally, the channels can become clogged with debris or root growth, which may disrupt the flow of nutrients. As a result, water levels must be closely monitored to ensure plants receive the correct amount of water and nutrients. Inadequate water flow can lead to dehydration or nutrient deficiencies, especially in sensitive crops.

1.1.2. Deep flow technique

DFT stands for “Deep Flow Technique”, which is another hydroponic method used to cultivate plants (Vimolmangkang et al., 2010). In a DFT system, plants are grown in a deep (usually 1-2 cm) water culture where the roots are suspended in a nutrient-rich solution. The solution is circulated using a pump, providing the plants with a constant supply of oxygen and nutrients. One of the key advantages of DFT systems is that they are more stable and fail-safe. DFT systems are relatively simple to set up and maintain and can be used to cultivate a wide range of plants, including leafy vegetables, herbs, and certain small fruiting plants like strawberries. DFT has shown potential for sustainable food production in regions facing resource constraints. Efficient nutrient management in hydroponic systems, especially in DFT setups, plays a crucial role in optimizing crop yield and input use, including under resource-limited conditions (Majid et al., 2021).

However, due to the size and structural needs of larger plants, such as fruit trees, DFT systems are generally not suitable for them. They can also be effectively used for ornamental plants. It is important to ensure that the nutrient solution is properly balanced and that the pH levels are appropriate for the plants being grown.

2. Materials and Methods

The study was conducted in an indoor farming laboratory (2.80 m W × 4.20 m L × 2.60 m H) located at the Agricultural Machinery and Technologies Engineering Department, Ankara University, Turkey. The laboratory had automated controls for air conditioning, nutrient dosing, and lighting.

The air conditioning was programmed to cool the cultivation room to 16°C at night (1900h to 1000h) to simulate night chill. During the day, the temperature was maintained at 22°C. Plants were grown under a photosynthetic photon flux density (PPFD) of 265 µmol m^{-2} s^{-1} provided by LED lights, which resulted in a daily light integral (DLI) of 15.3 mol m^{-2} over a 16-hour photoperiod. Relative humidity in the cultivation room was controlled and maintained at 65–70% throughout the experiment.

Figure 1. Hydroponic unit

The hydroponic unit consisted of an opaque gray HDPE (High-Density Polyethylene) reservoir (60 liters), automated peristaltic dosing pumps for A and B nutrients and nitric acid (C), a main pump, PVC tubing, PVC NFT hydroponic channels and stainless steel DFT trays. The main pump (200 L h^{-1} at 3.5 m head) delivered water continuously via 20 mm PVC pipes.

Tap water was filtered through a 5 µm particle filter, an activated carbon filter, a 1 µm particle filter and an R/O filter, respectively. The electrical conductivity (EC) of R/O output was measured as 0.012 dS m^{-1}.

The hydroponic unit (0.60m W × 1.20m L × 2.0m H) had 4 layers with 3 plastic NFT channels (0.10m W × 1.20m L × 0.05m H) on each of the upper 2 layers and 1 stainless steel DFT tray (0.60m W × 1.20m L × 0.05m H) on each of the lower 2 layers. The upper NFT channels were interconnected for the nutrient solution transfer to the lower layers. Nutrient solution from the reservoir was supplied via a single pump (200 L h^{-1} at 3.5 m head) and was transferred sequentially through the upper NFT channels, the lower NFT channels, and finally to the DFT trays, before returning to the reservoir, creating a recirculating system (*Figure 1*).

The depth of the nutrient film in the NFT channels was maintained at approximately 3–5 mm to ensure optimal aeration for the roots. In the DFT trays, the nutrient solution depth was maintained at 10–15 mm to provide sufficient root submersion while preventing waterlogging. The depth levels in DFT trays were controlled using raised overflow drains installed at each DFT layer, which ensured the nutrient solution did not exceed the set levels.

To ensure that both systems received a uniform nutrient composition, the recirculating system was closely monitored. The nutrient solution was continuously mixed within the reservoir using the circulation of the main pump. Regular measurements of electrical conductivity (EC) and pH were taken to confirm consistent nutrient delivery across all layers. Although the NFT system received the solution first, the design of the interconnected system ensured that nutrient depletion was minimal before the solution reached the DFT trays. This was further validated by consistent growth and morphological data across both systems.

Plant spacing was 20 cm in both directions. This resulted in a total of 72 plant growth holes (36 NFT and 36 DFT) (*Figure 2*). The vertical distance between plant growth holes and LEDs was 40 cm for both NFT and DFT.

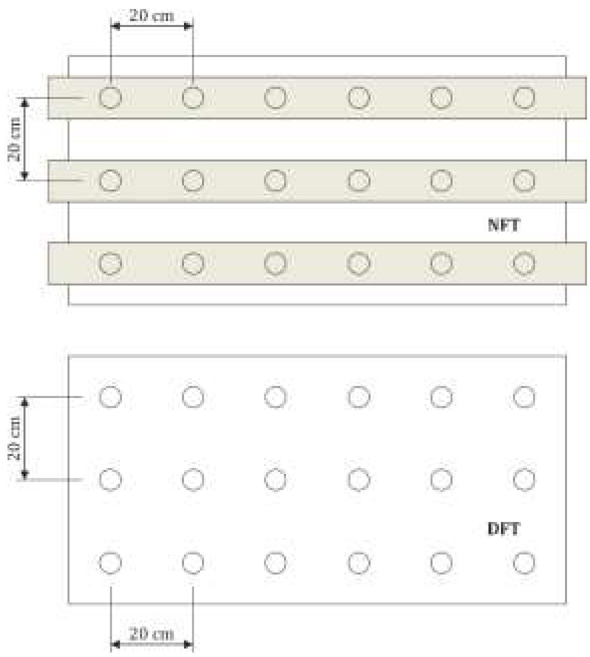

Figure 2. NFT and DFT layers

2.1. Plant material

The experiments were conducted with lettuce (*Lactuca sativa* L.)*,* rocket (*Eruca vesicaria*), dill (*Anethum graveolens* L.) and cress (*Lepidium sativum*).

Plants were grown in a growth chamber from seed to transplant. Seeds were sown in Oasis® Horticubes© growing media, pre-soaked with 1.2 dS m^{-1} nutrient solution. 1 seed per cube for lettuce and 10 seeds per cube for rocket, dill and cress were sown. Sowing multiple seeds in a single cube ensures that a sufficient number of plants germinate and grow together, creating a fuller, more marketable appearance suitable for culinary use. This method also helps mitigate the risk of uneven germination or growth issues in any single seed, ensuring that each cube produces a viable and marketable plant cluster. After germination, plantlets were moved under 150 µmol m^{-2} s^{-1} LED lights until transplantation. Plantlets were transplanted 15 days after sowing and harvested after 32 days in the main hydroponic unit. All plants experienced the same environmental conditions within the same growing room. At the end of each cultivation period, 3 plants out of 9 from NFT and DFT layers were selected randomly for morphological analysis.

2.2. Experimental design

This experiment was designed to compare NFT and DFT hydroponics methods in terms of plant yield, morphological attributes and energy use efficiency (EUE).

Plants were grown for 32 days under a PPFD of 265 µmol m^{-2} s^{-1} and 16 h photoperiod, reaching 15.3 mol m^{-2}

Daily Light Integral (DLI).

65 W LED modules were used to illuminate the growth area. LED lights were manufactured on demand by SpectBee (Ankara, Türkiye). The spectrum of LED lights is shown in *Figure 3*. Each day, plants were replaced randomly to ensure equal light reception.

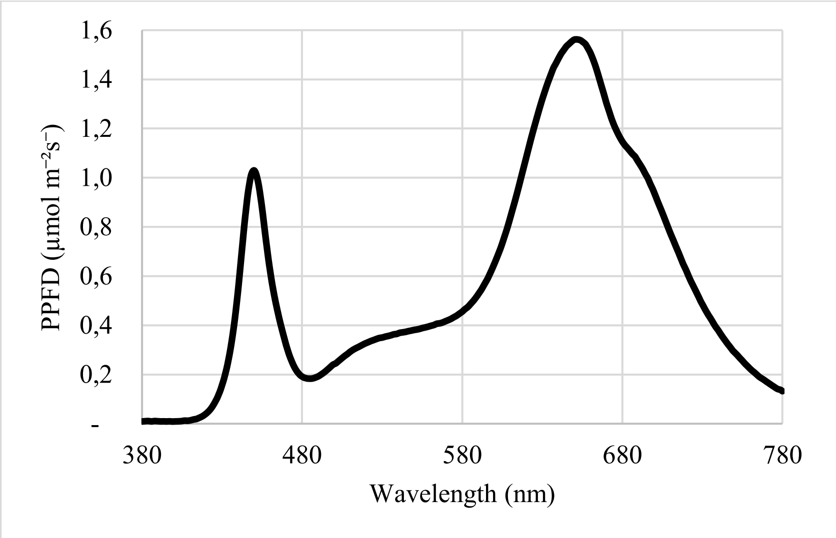

Figure 3. Spectrum of LED lights

Plants were fertigated with a nutrient solution (2.7 mM $NO3^-$, 5.5 mM K^+, 1.6 mM P, 1.9 mM Mg^{2+}, 4.7 mM Ca^{2+}, 2.5 mM S, 71.6 µM Fe, 1.5 µM Zn, 46.3 µM B, 1.6 µM Cu, 1.6 µM Mo, 9.1 µM Mn and 0.6 mM NH_4^+), with a target electrical conductivity of 1.9 dS m^{-1} and pH of 6.5. Experiments were conducted in the laboratory in two consecutive cycles (*Table 1*).

All crops (lettuce, rocket, cress, and dill) were harvested on the same day, 32 days after transplantation, to ensure consistency in comparing growth and morphological parameters across both NFT and DFT systems. The decision to harvest on the same day was based on the experimental design, which aimed to evaluate the performance of the two hydroponic techniques under uniform conditions. While these crops might require different harvesting periods in a commercial setting, the fixed harvest day was chosen for experimental comparability under controlled conditions.

Table 1. Experimental design

Stage	Date
First cycle sown	01.07.2022
First cycle transplanted	15.07.2022
Second cycle sown	22.07.2022
First cycle harvested	05.08.2022
Second cycle transplanted	05.08.2022
Second cycle harvested	19.08.2022

In the cultivation room, environmental conditions were carefully monitored and controlled to ensure uniformity across the experiment. The air temperature was maintained at 16 °C during the night (1900h to 1000h) and 22 °C during the day. Relative humidity was kept between 65% and 70%. A 3-day detailed chart of air and water temperature is given in *Figure 4*. The nutrient solution temperature was monitored to stay within the optimal range of 20–22 °C. The light was provided using LED modules at a PPFD of 265 µmol m^{-2} s^{-1}, resulting in a daily light integral (DLI) of 15.3 mol m^{-2} with a 16-hour photoperiod. The electrical conductivity (EC) of the nutrient solution was maintained at 1.9 dS m^{-1}, and pH levels were kept at 6.5 throughout the experiment.

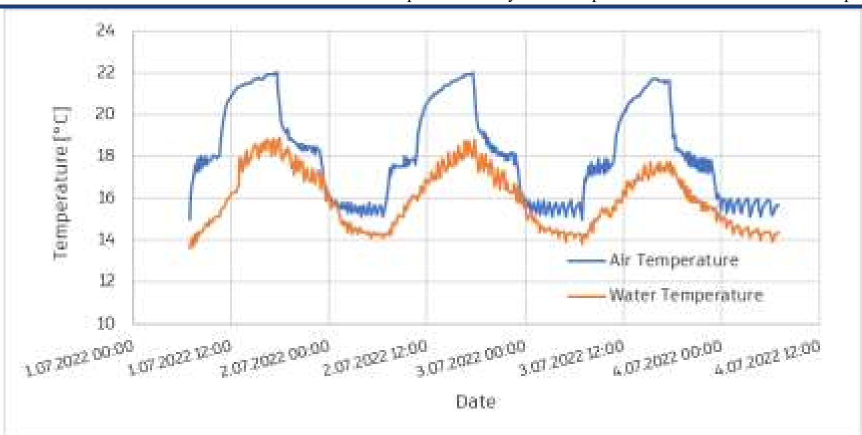

Figure 4. 3-day air and water temperature of cultivation room

Electrical conductivity (EC) was kept between 1.85 and 1.96 dS m^{-2} for the experiment period (***Hata! Başvuru kaynağı bulunamadı.***).

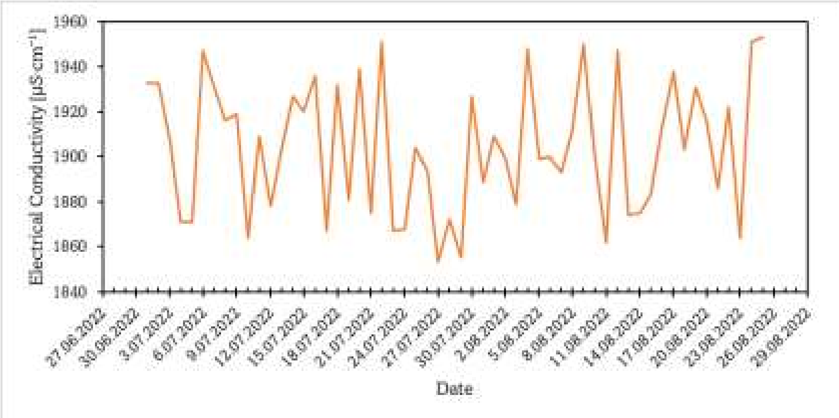

Figure 5. Electrical conductivity of the nutrient solution

2.3. Plant analysis

In this study, the development status, yield, and selected morphological attributes of lettuce, rocket, cress, and dill plants grown using the DFT and the NFT were compared. The selected morphological attributes were parameters such as total fresh weight, plant height, stem diameter, number of marketable leaves, and branching for herbs. However, chemical quality parameters such as nutrient content or antioxidant levels were not included in this study and could be the focus of future research.

The following analyses were done to collect plant morphological data:

Total fresh weight (g): Plants harvested with their roots from both hydroponics production systems were weighed together with their roots.

Plant height (cm): The distance between the root collar of the plants harvested from the systems and the highest point of the plant was determined.

Plant width (cm): The width of the harvested plants was measured. This analysis was only done for lettuce.

Stem diameter (mm): The stem diameter just above the root collar after harvest was measured.

Number of marketable leaves (pieces/plant): The marketable leaves of the plants were determined by counting the leaves in the marketable portion.

Number of discarded leaves (pieces/plant): The non-marketable leaves when the plants were harvested were determined.

Branch per plant (pieces/plant): Branches of the plant were counted. This analysis was only done for herbs.

2.4. Energy use efficiency

In this study, EUE was calculated based on the total biomass produced relative to the energy consumption of the system components, including LED lights, water pump, air pump, air conditioning, and automation systems. While this method provides a straightforward measure of energy efficiency specific to the hydroponic systems, we acknowledge that it does not account for additional input parameters such as human labor, nutrient costs, pest control, and other operational expenses. During the experiments, the total energy consumption of the LED lights, water pump, automation system and air conditioning was measured using a commercial electricity meter (Makel M550.2251, Makel, İstanbul, Türkiye). EUE was calculated by dividing total produced biomass by total energy consumption in cultivation duration (1) (Baran and Gökdoğan, 2017; Mohammadi et al., 2008; Pal et al., 2021).

$$EUE\ (\frac{g}{kWh}) = \sum Produced\ Biomass\ (g) / \sum Energy\ Consumption\ (kWh) \qquad \text{(Eq.1)}$$

2.5. Data analysis

To determine significant differences between the parameters measured in the two hydroponic systems (NFT and DFT), an analysis of variance (ANOVA) was applied. The significance level was chosen to be 0.05. Tukey's Honestly Significant Difference (HSD) test was applied to compare the two systems. Statistical analysis was conducted using JMP Pro 16 software.

3. Results and Discussion

3.1. Comparison of Systems Within a Shared Setup

The decision to compare the two systems within a single experimental setup was driven by the need to minimize the influence of environmental variability and focus solely on the performance differences between the systems. This approach ensured that both systems operated under identical, controlled conditions, including light intensity, temperature, relative humidity, and nutrient solution composition, thereby enabling a fair and direct comparison.

Advantages of This Approach:

- Environmental Consistency: By eliminating variations caused by differing environmental conditions, the results reflect only the differences inherent to the systems themselves.
- Direct Comparison: The shared setup allowed for direct performance comparisons between the systems under the same experimental conditions.

Limitations of This Approach:

- Nutrient Solution Interaction: Using a shared nutrient solution introduced the possibility of nutrient depletion in the first system (NFT) before reaching the second system (DFT). However, this was mitigated by continuous mixing of the solution and regular monitoring to maintain nutrient consistency.
- Mixed Cropping Design: The mixed-cropping approach may have limited each plant species' ability to reach its optimal growth potential, as different crops have varying nutrient and pH requirements.

Impact on Results:

This design successfully minimized environmental variability, providing a clearer assessment of system performance under shared conditions. However, it does not allow for independent evaluation of each system's performance when used alone. Therefore, the findings are specific to scenarios where the systems are integrated. Future studies should focus on evaluating the systems independently to provide a more comprehensive understanding of their individual performance under tailored conditions.

3.2. Yield and morphological comparison

Lettuce and herb production values for the NFT and DFT are represented in *Table 2*. The comparisons presented in the table are primarily focused on the performance of the same crop grown in two different hydroponic systems (NFT and DFT). For each crop (lettuce, rocket, dill, and cress), key parameters such as total fresh weight, plant height, stem diameter, and others were compared between the two systems. The statistical significance ($P < 0.05$) applies to the comparison of the same crop between the two systems, as indicated by superscript letters (e.g., a, b). Total fresh weight of lettuce and dill was significantly ($P < 0.05$) higher (67.85% and 72.4%, respectively) in DFT. Stem diameter of lettuce and dill were significantly higher (39.4% and 22.6%) in DFT. The number of marketable leaves of lettuce was significantly higher (34.5%) in DFT.

Table 2. Yield and morphological comparison of Lettuce, Rocket, Dill, and Cress grown in NFT and DFT systems

	Lettuce		Rocket		Dill		Cress	
	NFT	DFT	NFT	DFT	NFT	DFT	NFT	DFT
Total fresh weight (g)	$74.57^{b} \pm 2.49$	$124.73^{a} \pm 4.15$	$36.58^{a} \pm 0.41$	$31.67^{a} \pm 0.72$	$8.60^{b} \pm 0.36$	$14.83^{a} \pm 0.50$	$7.96^{a} \pm 0.16$	$9.60^{a} \pm 0.15$
Plant height (cm)	$18.40^{a} \pm 0.71$	$17.83^{a} \pm 0.89$	$29.33^{a} \pm 0.98$	$32.00^{a} \pm 1.25$	$31.33^{a} \pm 1.09$	$34.00^{a} \pm 0.82$	$20.67^{a} \pm 0.27$	$23.00^{a} \pm 1.70$
Plant width (cm)	$23.70^{a} \pm 1.19$	$26.00^{a} \pm 0.82$	-	-	-	-	-	-
Stem diameter (mm)	$10.97^{b} \pm 0.22$	$15.29^{a} \pm 0.73$	$10.86^{a} \pm 0.59$	$12.70^{a} \pm 0.49$	$7.00^{b} \pm 0.06$	$8.58^{a} \pm 0.22$	$6.22^{a} \pm 0.28$	$7.04^{a} \pm 0.60$
Marketable leaves (pieces/plant)	$19.33^{b} \pm 0.27$	$26.00^{a} \pm 1.70$	-	-	-	-	-	-
Discarded leaves (pieces/plant)	$2.33^{a} \pm 0.54$	$2.67^{a} \pm 0.72$	-	-	-	-	-	-
Branch per plant	-	-	$7.33^{a} \pm 0.54$	$8.33^{a} \pm 0.27$	$6.00^{a} \pm 0.00$	$6.33^{a} \pm 0.27$	$7.33^{a} \pm 0.27$	$7.33^{a} \pm 0.54$

[a], [b]: Values showing the same letter are not significant ($P > 0.05$)
*The data in the table are presented as mean ± standard deviation (SD)

The results of current trials demonstrated that the DFT system supported the plant growth in terms of total fresh weight and stem diameter for lettuce and dill.

Our findings are consistent with those of Nurza (2022), who observed that DFT systems significantly enhanced the growth of water spinach compared to NFT systems. This is attributed to the slower water flow in DFT, which allows for better nutrient absorption.

3.3. Energy use efficiency

Daily energy usages of various consumers are given in *Table 3*.

Table 3. Distributed energy usage of consumers

Consumer	Energy consumption (kWh day^{-1})	Percentage
LED lights	6.24	72.22%
Air pump	0.11	1.27%
Water pump	0.32	3.70%
Air conditioning	1.42	16.44%
Automation	0.55	6.37%
TOTAL	**8.64**	**100.00%**

Power consumption of air pump, water pump, air conditioning, and automation was divided between the two subsystems (NFT and DFT). Total biomass production of the NFT system (lettuce and herbs together) was 1.149.39 g at the end of 32-days production cycle. The total biomass production of the DFT system was 1,627.47 g. EUE of both systems in this study were calculated as 4.16 g kWh^{-1} for NFT and 5.89 g kWh^{-1} for DFT, which are relatively lower compared to the literature. For instance, Gillani et al. (2023) reported an EUE of 31.3 g kWh^{-1} for the NFT system and 24.53 g kWh^{-1} for the Deep-Water Culture (DWC) system, with the NFT system outperforming DWC. The lower EUE values in our study can be attributed to the type of crops grown. Unlike Gillani et al. (2023), where lettuce was the sole crop, this study included lightweight herbs such as rocket, dill, and cress alongside lettuce, resulting in lower overall biomass production and consequently, reduced EUE.

4. Conclusions

This study demonstrated that the Deep Flow Technique (DFT) generally outperformed the Nutrient Film Technique (NFT) in terms of total fresh weight and stem diameter for lettuce and dill, while similar performance was observed for rocket and cress. The higher biomass production in DFT also resulted in a 5% improvement in energy use efficiency (EUE) compared to NFT. These findings suggest that DFT systems may offer advantages for crops with greater water and nutrient uptake requirements.

The two systems were compared within the same experimental setup to minimize the effects of environmental variability and focus solely on system performance. This approach ensured that both systems were tested under identical conditions, including light intensity, temperature, relative humidity, and nutrient solution composition, enabling a fair and direct comparison. However, a limitation of this approach is the shared use of the nutrient solution, which may have introduced interactions between the systems. Specifically, the NFT system received the solution first, potentially affecting the nutrient homogeneity of the DFT system. Nonetheless, continuous mixing and regular monitoring of the nutrient solution helped mitigate this issue.

Additionally, the mixed-cropping design and the unified nutrient solution may have limited the potential of each crop to reach its optimal growth performance. Future studies should explore crop-specific nutrient management and mono-cropping systems to provide a more detailed understanding of the advantages and limitations of each hydroponic method. Lennard and Ward (2019) compared the NFT hydroponic system with the NFT aquaponic system in terms of plant growth rates. Researchers used lettuce, dill, rocket, coriander, and parsley as plant materials. They used commercial nutrient solutions for hydroponics and fish waste for aquaponics. Researchers found that both systems produce plants with equal quality. Lennard and Leonard (2006) found that DFT systems produced 0.34 kg m^{-2} more lettuce (Lactuca sativa L.) than NFT systems did, parallel to our research.

These results align with prior research highlighting the economic feasibility and productivity advantages of DFT systems. For instance, Afriyanti et al. (2024) demonstrated that DFT systems achieved a 16.9% ROI and a payback period of 5.89 years, compared to NFT systems with a 10.9% Return on Investment (ROI) and a payback period of 9.13 years. This emphasizes the potential of DFT systems not only in terms of biomass production but also in economic efficiency for hydroponic lettuce farming.

This study reinforces the potential of hydroponic systems like DFT and NFT to address challenges in urban agriculture. As noted by Indriani et al. (2022), these systems offer an effective means of producing high-quality crops in limited spaces while ensuring resource sustainability. This study highlights the trade-offs between DFT and NFT systems. As noted by Fukuyama (1990), while DFT is advantageous for maximizing fruit size, NFT systems excel in producing crops with higher sweetness and texture, emphasizing the importance of system selection based on target quality attributes.

Our findings suggest that the performance of hydroponic systems like NFT and DFT is highly crop-specific and influenced by experimental conditions. While Manggala et al. (2023) reported superior results for NFT systems in Caisim production, our study demonstrates that DFT systems may offer advantages for mixed cropping and crops with higher nutrient demands. This highlights the importance of tailoring hydroponic system design to the specific needs of the crop and growing environment.

These results provide valuable insights for optimizing vertical farming systems, particularly for environments where energy efficiency and resource conservation are critical. Future research could focus on independent evaluations of each system under tailored conditions to enhance our understanding of their standalone performance.

Ethical Statement

There is no need to obtain permission from the ethics committee for this study.

Conflicts of Interest

We declare that there is no conflict of interest between us as the article authors.

Authorship Contribution Statement

Concept: Seyhan, T. G.., Seyhan, S.; Design: Seyhan, S.; Data Collection or Processing: Seyhan, S.; Statistical Analyses: Seyhan, T. G.; Literature Search: Seyhan, T. G., Seyhan, S.; Writing, Review and Editing: Seyhan, T. G., Seyhan, S.

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