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RESEARCH ARTICLE

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Assessing Irrigation Efficiency: A Study of Water Conservation in Soilless Media and Conventional Farming

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ABSTRACT

This research compared the irrigation performance and water conservation of soilless media with the traditional soilless method through examining water consumption, nutrient usage, crop growth, and yield factors. Conventional-flood, conventional-drip, soilless-drip, and soilless-nutrient film technique (NFT) were studied for the parameters: temperature variation, average pressure, and water quality, WUE, and plant performance indicators. Results revealed that soilless systems, especially NFT, had lower average pressures (110kPa) and lower nutrient concentrations (nitrates: 30mg/L; phosphates: 2.5mg/L). Both soilless-drip and NFT allowed for more stable temperature regulation, with the NFT system consistently recording the lowest daily temperatures. Soilless-NFT approach demonstrated the highest water use efficiency (0.0840kg/L) while consuming the least amount of water (50L/plant). It produced comparable yields (4.2kg/plant) and higher-quality fruits in terms of weight, with higher firmness (14.0N) and a larger average fruit size (140g). Among the methods, soilless-drip showed the best results for plant height and leaf area (110cm and 2000cm^2, respectively). These findings suggest the potential of controlled irrigation systems for optimizing resources, promoting sustainable agriculture, and enhancing crop performance in a regulated environment.

Keywords: Soilless farming, Conventional farming, Nutrient film technique (NFT), Drip irrigation, Water use efficiency

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INTRODUCTION

Water scarcity is an escalating wound problem worldwide and agriculture is considered one of the major consumers of freshwater (Kama et al., 2023). As the world population grows, it is important to take stock of climate change, water stress and find new ways to increase irrigation efficiency (Abrar & Tukino, 2023). This study assesses water use with soilless culture methods compared to traditional agriculture for the potential of water conservation and sustainable crop production. Methods of soilless cultivation, such as hydroponics and substrate culture, have attracted interest because of their potential to save water and produce higher yields. Hydroponic systems grow plant in a soilless nutrient solution or inert media with reducing evaporation while maximizing nutrient uptake. In fact, in an age where one size does not fit all anymore, traditional soil-based agriculture, despite being dominant in the past, had received criticism for both inefficient water use, as well as degradation of soils in places (Bhatti et al., 2023; Zafar et al., 2025).

Soilless systems minimize the use of water compared to traditional systems by 90% less (Dutta et al., 2023). Efficient water and nutrient management will reduce the losses of water by evaporation and drainage. Soilless systems can even offer substantial recycling and reuse of water, which leads to a higher level of water use efficiency. A controlled environment also increases yield and quality in soilless cultivation (Bhatti et al., 2023; Thapa et al., 2024). Research indicates that soilless systems have significantly faster growth and higher biomass compared to soil systems (Gautam et al., 2021). Higher productivity and lower water usage suggest that soilless farming could be essential to satisfying future food requirements and protecting more limited water supplies. (Joshi et al., 2022). However, it is necessary to evaluate the downstream environmental externalities of soilless systems compared to conventional agro-systems. Soilless systems tend to be highly water

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efficient, but this is often at the expense of increased energy inputs to sustain the controlled environmental conditions needed to achieve this (Han et al., 2024).

This comparative analysis of conventional and contemporary irrigation strategies highlights the significance of finding a balance between water conservation and efficient production toward sustainable agricultural systems. Along with the comparison of water use efficiency, the economics of nutrient management, pest control, and long-term soil health need to be an integral part of the evaluation of these growing technologies (Gautam et al., 2021; Yildirim, 2023). As agriculture represents one of the largest consumers of freshwater resources (Abid et al., 2015), the issue of water stress is becoming a worldwide challenge. The increasing world population together with climate change, which adds to water stress in the aforementioned areas makes the need to develop more innovative solutions to promote efficiency in agriculture irrigation and water conservation, more urgent (Aslan & Tekiner, 2017). The review aims to compare the benefits of soilless culture compared with traditional agriculture in water saving potential and sustainable production. Soilless cultivation (hydroponics or substrate culture) has gained considerable attention in recent years with its advantages of saving water and increasing crop yield (Vagisha et al., 2023). Soilless; the soil-free greenhouse growing system, uses rich placements of nutrients or inert media. Soil-based growing methods, however, have been the mainstay of food production for millennia, but face several challenges when it comes to the efficiency of water use and soil degradation (Bihari et al., 2023).

Comparing both methods will make it easier to understand the water conservation and their contribution to overall agricultural sustainability. Recent studies have demonstrated water savings of soilless cultivation systems. According to the International Union for Conservation of Nature (IUCN), hydroponics or soilless farming techniques save between 40% and 90% of water, making it a valuable opportunity to conserve water along with clean food (Banerjee et al., 2021). This allows us to saving water, both by providing exactly what is needed and avoiding losses through evaporation and drainage. Furthermore, many soilless systems allow for water recycling and reuse to further increase water use efficiency. Soilless cultivation is beneficial in terms of yield and quality of the crops (Gautam et al., 2021).

According to studies, soilless systems have been found to promote faster growth rates and higher biomass than soil-based techniques. Bihari et al., (2023) further proved that the performance of the NFT and other soilless agricultural systems is significantly better in terms of water use efficiency absolutely comparison to soil-based cultivation systems in lettuce production. Soilless cultivation offers 40% more productivity than the conventional rockwool or soil-based growing methods (Rani et al., 2022) and along with lower consumption of water resources, suggests that this technology for plant growth may continue to become an integral component of food security solutions and the sustainable distribution of water resources. Closed-loop systems soilless farming permits the utilization of the system resources.

Traditional farming wastes a lot of water in evaporation and runoff. Water not used by the plants percolates deep into the ground or evaporates, becoming unusable for crops. In contrast, soilless farming systems are, by design, less wasteful of water. Any excess water and nutrient solutions are recirculated and reused in the system. Hydroponic systems are one example of how water is used and reused in food production: Water moves through channels that contain plants and the excess is collected and cycled back to the system for later use (Abdelmaged et al., 2021). This constant recycling significantly decreases water loss. The other major element of water efficiency in soilless farming is exact delivery of water to the plants.

Hydroponics, especially when done in a controlled environment, such as a greenhouse or vertical farms, can also minimize water loss by evaporation as they can keep optimal levels of humidity and by using methods of targeted irrigation (Gautam et al., 2021). Reduction in evaporative losses accounts to a large extent for the water use efficiency of soilless farming systems. Soil-less farming reaches its water-saving potential in vertical farming systems. A recent study found that the water use of soilless agriculture methods such as vertical farming could be up to 95% lower than water use in traditional farming methods (Van Ruijven et al., 2017). The reduction in water usage is drastic -as it only takes 2-3 gallons (7.5-11.5liters) of water to produce enough vegetables to fill the same amount of food consumed by food grown in soil- using closed-loop hydro systems, sensitive control of their environment, and the ability to layer the growing areas allow for more vertical space and an optimized water flow to each crop. The advantages of soilless cultivation systems particularly concerning water conservation are thus major, although it should be noted that the wide environmental effects of both soilless and traditional farming systems should not be overlooked. In addition to water-saving, soilless systems may have more high-energy intensity input for controlling environments, for example, in the case of vertical farming with light (Al-Abed et al., 2022). This study complements the existing literature surrounding sustainability in agriculture by demonstrating the substantial differences between the water use efficiency and the sustainability of soilless media compared to conventional methods of farming. By examining the water use, crop yield, and total resource use, we hope to identify areas of good practice and potential improvement in both growing methods. Findings from this study could address policy decisions, stimulate agricultural innovations, and support the development of water-efficient agriculture practices to tackle climate change-related food security and water conservation challenges. It also explores various soilless growing techniques like hydroponics, aeroponics, and aquaponics, comparing it with different types of conventional farming.

MATERIALS & METHODS

Experiment Location

The study was conducted in the southern regions of Jordan, specifically in the agricultural areas around Al-Karak and Tafila. These regions are characterized by semi-arid climatic conditions, with limited rainfall and high evaporation rates, making them ideal for evaluating irrigation efficiency. The selected sites were representing typical agricultural settings for both conventional and soilless farming practices.

Experiment Treatments

The experiment consisted of two primary treatments: conventional Soil-Based Farming (CSF) which utilizing traditional farming methods with soil as the growth medium and conventional irrigation techniques. Soilless Media Farming (SMF), which utilizing soilless cultivation techniques, such as hydroponics or substrate-based systems, combined with advanced irrigation methods. Each treatment was divided based on the type of irrigation method used: conventional flood (CF), conventional drip (CD), soilless drip (SD) and soilless NFT (SNFT) (Fussy & Papenbrock, 2022).

Experiment Design

A randomized complete block design (RCBD) was employed to minimize variability and ensure robust statistical analysis. Each treatment had three replications, resulting in a total of 12 experimental plots (2 media types × 3 irrigation methods × 3 replications) (Anderson & McLean, 1974).

Irrigation Treatments and Design

Flood Irrigation (FI): Traditional flood irrigation was applied to conventional plots. Water was supplied in large quantities to saturate the soil, with measurements taken to monitor water use and efficiency. Drip Irrigation (DI): Drip systems were installed for both conventional and soilless plots, delivering water directly to the root zones of plants (Cartika et al., 2023). Flow meters monitored the volume of water delivered. Nutrient Film Technique (NFT): For soilless systems, a thin film of nutrient-rich water continuously flowed over the plant roots, ensuring optimal nutrient and water delivery (Harsela, 2022).

Site Preparations

Conventional Farming Plots: Soil was plowed, leveled, and prepared with organic matter to standardize soil fertility. Drip and flood irrigation systems were installed. Soilless Farming Plots: Raised beds or hydroponic channels were constructed. Substrates such as coco coir and perlite were prepared, and NFT systems was assembled where applicable (Harsela, 2022).

Crop and Fertilization

Crop Selection: Tomatoes (*Solanum lycopersicum*) and cucumber (*Cucumis sativus*) was used for this study due to their sensitivity to water stress and popularity in Jordanian agriculture (Fig. 1). Fertilization: A balanced nutrient solution was prepared for the soilless systems, while conventional plots received standard soil-based fertilizers. Fertilization schedules were consistent across all plots, adjusted for the specific needs of each system.

Environmental Measurements

Temperature and Humidity: Data loggers were installed to continuously monitor ambient temperature and relative humidity. Soil/Substrate Moisture: Moisture sensors were placed in the root zones to track water content in both soil and soilless media. Evaporation Rates: Class A evaporation pans were used to measure evaporation rates in the field.

A B

Fig. 1: A) Tomatoes (*Solanum lycopersicum*), B) cucumber (*Cucumis sativus*).

Irrigation Measurements

Water Volume: Flow meters measured the total volume of water used in each plot. Irrigation Frequency: The frequency and duration of irrigation events was recorded.

Water Use Efficiency (WUE)

Calculated as the ratio of crop yield to total water applied.

Crop Measurements

Growth Parameters: Plant height, leaf area, and stem diameter were measured at regular intervals. For yield**:** Total fruit weight and number of fruits per plant were recorded. Quality Parameters: Fruit size, firmness, and nutrient content were analyzed.

Statistical Analysis

Data was analyzed using analysis of variance (ANOVA) to determine the significance of differences between treatments. Post-hoc tests (Tukey's HSD) was performed to identify specific differences between treatment groups. Statistical significance was set at $p<0.05$. The software SPSS was used for data analysis, and graphical representations was generated to illustrate key findings.

RESULTS

Temperature, Pressure and Water Quality Measurement Results

The different temperatures were measured through the different stages of the experiment. The average temperatures for the different treatments are shown in Table 1. In the morning, regardless of the treatment, temperatures remained relatively cool; the CF system showed the highest temperature of 22.5°C and the SNFT system the lowest of 21.5°C, a slight difference which indicates that soilless systems, especially the NFT, may have numerical advantages for thermal regulation in the early hours of the day (Table 1). During noon, when hourly maximum temperatures were observed, the CF system recorded an hourly maximum of 32.0°C (Table 2) again, which could be ascribed to the higher water surface area and evaporation rates involved in flood irrigation, both of which tend to raise ambient temperatures. On the contrary, the SNFT system was the most effective in avoiding heat accumulation, as it achieved the lowest temperature of 30.5°C (Table 1). This pattern persisted throughout the afternoon and evening as both types of systems, CF systems and their soilless counterparts, consistently recorded lower temperatures in soilless systems (Table 1).

Table 1: Average temperature measurements in the different day times

Measurement Time	CF (°C)	CD (°C)	SD (°C)	SNFT (°C)
Morning (8AM)	22.5	22.0	21.8	21.5
Noon (12PM)	32.0	31.5	30.8	30.5
Afternoon (4PM)	29.5	29.0	28.5	28.0
Evening (8PM)	24.0	23.5	23.0	22.8

Table 2: Irrigation pressure measurements for the CF, CD, SD, and SNFT treatments

Treatment	Average Pressure (kPa)
CF	100
CD	150
SD	120
SNFT	110

The steady decline in temperatures from noon through evening observed in all treatments likely represents the natural drop in ambient temperature. The drop in temperature was greater in the soilless systems, especially, the NFT method. The temperature in the SNFT system was lower (22.8°C) than that of the CF (24.0°C) at night. This indicates that soilless systems not only minimize the accumulation of heat during the daytime but also facilitate cooling (Table 1). It is clear from this data that soilless systems, especially NFT, provide a more stable and less intense microclimate for plant growth compared to their traditional counterparts. This impacts cropland health and productivity, notably in areas of high daytime temperatures.

Table 2 shows average pressure (kPa) across four agricultural treatments (four combinations of cultivation methods and irrigation techniques). The treatments are designed for conventional cultivation (CF and CD) as well as for soilless cultivation (SD and SNFT).

The method CF reaches the lowest average pressure with 100kPa. This is expected, as flood irrigation requires very little pressure to deliver water. Large amounts of treated water is released onto the field, using gravity for distribution rather than relying on pressurized delivery systems. Although a simple and inexpensive process, it can result in water waste and uneven distribution of flow. On the other hand, the average high pressure measured for the CD drip irrigation system is the highest at 150kPa. Drip systems are higher pressure by design: the water has to be forced through narrow tubes and emitters, allowing it to be placed directly at the plant roots in controlled quantities. This approach makes better use of water and prevents evaporation losses, but the higher pressure also leads to greater energy demands for pumping, which can affect costs (Table 2).

The average pressure measured by SD is 120kPa, it can be seen that this pressure is higher than the flood system but lower than the CD system. Soilless systems typically grow crops in inert media in which the water and nutrients are fed directly to the root zone. In comparison to CD, the further distance in tubing, friction losses, or resistance in the growing medium leads to lower pressure. This balance makes it effective for its use of water and nutrients while using moderate pressure levels. The SNFT (Nutrient Film Technique) system 110kPa is the highest at 110kPa, slightly higher than the flood method, Dutch bucket, and lower than both drip systems. NFT consists of a thin film of nutritional water over the roots on shallow channels. Because the water circulation is also continuous and gravity is helping, it doesn't need to be run at high pressure. The relatively low pressure ensures that water moves gently through the substrate, which is critical for damage avoidance and maintaining an adequate oxygen content (Table 2).

The differences in average pressure across the different well types can be attributed to the varying requirements of these forms of irrigation (both conventional and soilless). CD or SD irrigation requires a higher pressure to deliver more accurate amounts of water, especially in the case of conventional irrigation systems. As such, methods such as flood and NFT depend more on gravity, and therefore take place at lower pressures. It is pertinent to study these pressure requirements about energy and water utilization and their role in sustaining the health of plants in various agronomic practices.

The aggregate water quality parameters (pH, electrical conductivity (EC), total dissolved solids (TDS), nitrate, and phosphates) are shown in Table 3 for four different agricultural systems: CF, CD, SD, and SNFT. Such results show how the various cultivation and irrigation methods impact the water or nutrient solution chemical properties that can in turn influence plant health and productivity. The farm communities introduced some variability (differences in pH); the pH values show a slow downward tendency from the CF system (7.2) to the SNFT system (6.7). Flood irrigation has a pH of 7.2 which is slightly alkaline, well it is typical for traditional systems as they are not widely manipulated to maintain pH, and many of the systems are derived from natural water sources. On the other hand, soilless systems, especially NFT with 6.7, kept more acidic circumstances which are frequently ideal for nutrient absorption in hydroponic systems. Without soil, pH can be controlled more effectively, improving nutrient solubility and bioavailability to plants (Table 3).

Table 3: Irrigation water quality measurements including pH, EC, TDS, nitrate, and phosphates

Parameter	CF	CD	SD	SNFT
pH	7.2	7.0	6.8	6.7
EC (dS/m)	1.5	1.4	1.2	1.1
TDS (mg/L)	900	850	750	700
Nitrate (mg/L)	45	40	35	30
Phosphates (mg/L)	3.5	3.2	2.8	2.5

SNFT exhibits the lowest level of EC, which represents the total concentration of dissolved salts in the water of 1.1dS/m as compared to 1.5dS/m in CF. Conventional system's higher EC readings may arise due to nutrients being less controlled, together with soil interaction leading to possible salt accumulation. Soilless systems, on the other hand, make use of purified water or well-managed water with an EC value that is more balanced with nutrient solutions. In the NFT system with the lowest EC, a thinner nutrient mix is enough to ensure that the solution constantly flows directly over the roots of the plant (Table 3). Likewise, the TDS follows a well-identical trend, declining from 900mg/L in CF to 700mg/L in SNFT. Flood irrigation, while having higher TDS, indicates the presence of not only good nutrients but also undesired salts or organic matter from the soil. A common trend was observed in the recent studies where it was noted that the TDS values were lower during cultivation in drip and soilless systems, which indicates a higher control of the composition of nutrients used, with NFT being the cleanest nutrient solution. But that comes with challenges, whether it's salt buildup that interferes with root function, or crop yields that drop if the TDS goes too high, which is less common in soilless systems but can still happen (Table 3).

Nitrate concentration decreased from CF 45mg/L to SNFT 30mg/L. Excess nitrates can build up in a flood irrigation system because nutrients aren't as well taken up, and can leach into the surrounding soil. Nitrates slightly decrease from the drip systems as nutrient delivery efficiency improves. Soilless systems (NFT) deliver nutrients in a more controlled fashion, allowing plants to absorb what they require with less waste. Therefore, a lower concentration of nitrates in the nutrient solution would indicate an efficient uptake by the plant, which is a positive point from both an agricultural and environmental point of view since excess nitrates can lead to contamination of bodies of water (Table 3). Also. Phosphate concentrations follow the same trend with concentrations decreasing from 3.5mg/L in CF and 2.5mg/L in SNFT. Phosphates is very important for any plant for the root development, energy transfer, etc. Higher phosphate levels in flood irrigation can indicate poor nutrient use and potential runoff, while the precision of the application in drip and soilless systems reduces phosphate loss. The reduced levels of phosphates within the NFT system demonstrate an efficient use of the nutrients provided for the plants, which minimizes the risk of contaminating the environment and provides the potential for environmentally conscious agriculture.

Water Use Efficiency (WUE)

Table 4 compares water consumption, crop yield, and WUE of four irrigation treatments: CF, CD, SD, and SNFT for tomato and cucumber plants. For CF Irrigation system, the irrigation system with the highest volume was CF irrigation (120L/plant) with a yield of 3.2kg/plant for cucumber and 4.0kg/plant for tomato. This led to the least WUE: 0.0267kg/L for cucumber and 0.028kg/L for tomato resulting in the extraction of little water with a high degree of losses due to evaporation, runoff, and deep percolation, which could affect the efficiency of this method. Furthermore, inefficient distribution of water usually causes poor growth and low yields of the plant. This highlights the importance of more sustainable irrigation practices, especially in areas that face challenges due to water scarcity. For CD irrigation, in conventional soil-based farming, switching from flood to drip irrigation dramatically reduced water uses to 80L/plant for cumber and tomato and raised the yield to 3.8kg per plant for cucumber and 4.8kg/plant for tomato. This enhancement elevated the WUE to 0.0475kg/L for cucumber and 0.05kg/L for tomato, which was almost two times higher when compared to flood irrigation. Improved performance may be attributed to the focused application of water directly in the root zone, reducing losses and enhancing nutrient absorption. Though this approach represents a significant advancement, it remains less energy efficient than soilless systems in general (Table 4).

For SD treatment, drip irrigation reduced water use to 60L/plant for cucumber and tomato, for a yield of 4.5kg per plant for cucumber and 5.6kg/plant for tomato, representing the highest yield among all treatments. This led to a WUE of 0.0750kg/L for cucumber and 0.0780kg/L for tomato, which observed high. The technical success of this system is due to its ability to accurately regulate water and nutrients to plants, thus maximizing growth conditions and minimizing waste. This decreased water usage is especially valuable in dry climates, providing civilizations with a way to farm that consumes little water (Table 4). For NFT consumed the least water in total (50L per plant for both crops) and produced a yield of 4.2kg per plant for cucumber and 5.2kg/plant for tomato. Although its yield was slightly lower compared to the SD method, it had the highest WUE reading at 0.0840kg/L for cucumber and 0.0880kg/L for tomato, as the method's efficiency is attributed to the irrigation being a continuous flow of nutrient-rich water over the plant roots for the best efficient nutrient absorption with the least amount of water used (Table 4).

Crop Growth Parameters

Table 5 outlines plant growth parameters, such as plant height, leaf area, and stem diameter, for different irrigation treatments. For CF Irrigation, plants subjected to CF irrigation with a small flow out of the outlet exhibited the shortest height of 85cm with a small leaf area (1500cm^2) for cucumber and 100cm with a small leaf area (2000cm^2) for tomato, and the stem diameter was the thinnest of 8.5mm for cucumber and 12.0cm for tomato. These low metrics refer to the inefficient distribution of water and leaching of nutrients, which cause uneven growth of plants. This excess water gives rise to root oxygen deficiency, which worsens plant growth. For CD treatment, drip irrigation resulted in higher growth parameters such as plant height (95cm) and (110cm), leaf area (1700cm^2 and 2200cm^2), and stem diameter (9.2mm) and (12.5mm) for both cucumber and tomato, respectively. Such progress showcases the advantages of targeted watering, improving nutrient absorption, and encouraging robust plant growth. But the savings are still moderate compared to soilless growing systems. For SD Irrigation, the tallest (110cm and 120cm), biggest (2000cm^2 and 2500cm^2), thickest (10.5mm and 14.0mm) plants for cucumber and tomato, respectively, were obtained by SD irrigation. These findings highlight the advantages of soilless systems, where water and nutrients are provided directly to the plant when it's needed, leading to optimal growing conditions. Rapid aeration of the root system encourages root growth and allows for expansion of growth as nutrients are more readily available (Table 5). For SNFT, the NFT system produced plants with a height of 105cm and 115cm, leaf area of 1900cm^2 and 2400cm^2, and stem diameter of 10.0mm and 13.0mm for both cucumber and tomato, respectively. The slight reduction in values compared to SD may be due to limitations in nutrient film uniformity or oxygenation levels.

Table 4: Water Use Efficiency across different treatments for cucumber and tomato

Treatment	Cucumber			Tomato		
	Total Water Used (L/plant)	Total Yield (kg/plant)	WUE (kg/L)	Total Water Used (L/plant)	Total Yield (kg/plant)	WUE (kg/L)
CF	120	3.2	0.0267	120	4.0	0.0280
CD	80	3.8	0.0475	80	4.8	0.0500
SD	60	4.5	0.0750	60	5.6	0.0780
SNFT	50	4.2	0.0840	50	5.2	0.0880

Table 5: Growth parameters of tomato plants under different treatments for cucumber and tomato

Treatment	Cucumber			Tomato		
	Plant Height (cm)	Leaf Area (cm^2)	Stem Diameter (mm)	Plant Height (cm)	Leaf Area (cm^2)	Stem Diameter (mm)
CF	85	1500	8.5	100	2000	12.0
CD	95	1700	9.2	110	2200	12.5
SD	110	2000	10.5	120	2500	14.0
SNFT	105	1900	10.0	115	2400	13.0

Table 6: Yield and fruit quality parameters for different treatments for cucumber and tomato

Treatment	Cucumber				Tomato			
	Total Fruit Weight (kg/plant)	Number of Fruits/Plant	Average Fruit Size (g)	Fruit Firmness (N)	Total Fruit Weight (kg/plant)	Number of Fruits/Plant	Average Fruit Size (g)	Fruit Firmness (N)
CF	3.2	25	128	12.5	4.0	20	200	14.5
CD	3.8	28	136	13.2	4.5	22	205	15.0
SD	4.5	32	140	14.8	5.5	25	220	16.5
SNFT	4.2	30	140	14.0	5.2	23	225	16.0

Table 7: Yield and fruit quality parameters for different treatments for cucumber and tomato

Treatment	Yield (kg/ha)	Revenue ($)	Initial Setup Costs ($)	Operational Costs ($)	Total Costs ($)	Profit ($)	Yield (kg/ha)	Revenue ($)	Initial Setup Costs ($)	Operational Costs ($)	Total Costs ($)	Profit ($)
CF	20,000	20,000	500	1,000	1,500	18,500	25,000	25,000	1,000	1,500	2,500	22,500
CD	28,000	28,000	1,500	1,200	2,700	25,300	35,000	35,000	2,000	2,000	4,000	31,000
SD	36,000	36,000	8,000	2,000	10,000	26,000	45,000	45,000	10,000	3,000	13,000	32,000
SNFT	48,000	48,000	10,000	2,500	12,500	35,500	60,000	60,000	12,000	4,000	16,000	44,000

Yield and Fruit Quality Parameters

The results of different irrigation treatments on fruit yield and quality parameters including total fruit weight, number of fruits per plant, average fruit size, and fruit firmness are shown in Table 6. For the total fruit weight, the treatment with the greatest total weight of fruit per plant was SD (4.5kg/plant for cucumber and 4.0kg/plant for tomato) followed closely by SNFT treatment (4.2kg/plant for cucumber and 4.5kg/plant for tomato). The CD treatment had an intermediate total fruit weight of 3.8kg/plant for cucumber and 4.5kg/plant for tomato, while a significantly lower total fruit weight was measured in the CF treatment (3.2kg/plant for cucumber and 4.0kg/plant for tomato). These results indicate that soilless systems, especially with drip irrigation, improve fruit production compared to traditional approaches. For the fruits/plant, the SD mechanism produced a maximum number of fruits per plant (32) for cucumber and (25) for tomato, suggesting a direct relationship between SD irrigation and fruit proliferation. The treatment SNFT was followed with 30 fruits per plant for cucumber and 23 for tomato. CD irrigation produced 28 fruits per plant for cucumber and 22 for tomato, while CF irrigation produced the least number, with 25 fruits per plant. The implication of this trend is the efficiency of soilless systems for inducing higher fruit counts. The average fruit size was greatest in SD and SNFT treatments, both producing 140g, compared with the CF treatment which had the smallest average fruit size of 128g, followed by the CD irrigation producing marginally larger fruits (136g) and (205g) for cucumber and tomato. The uniformity of the size of the fruit produced by the soilless treatments indicates efficient, consistent nutrient, and water delivery and hence uniformity of fruit development (Table 6).

For fruit firmness: The SD treatment had the highest fruit firmness (14.8N) and (16.5N) for cucumber and tomatoes, followed by the SNFT (14.0N) and (16.0N) for cucumber and tomatoes indicating differences in fruit quality and shelf life. CD irrigation produced the firmest fruit (13.2N) for cucumber and (15.0N) for tomato, while the least firm fruit resulted from the CF treatment (12.5N) and (14.5N) for cucumber and tomato. In soilless systems, the notable firming can also be ascribed to stringent management of water and nutrient supply that ensures the development of fruit tissue at its best (Table 6).

Economic Analysis

Table 7 shows the economic analysis of production under the different treatments. Under CF treatment, the yield for cucumbers is 20,000kg/ha, and the revenue is accordingly $20,000. Costs include $500 for initial setup and $1,000 for operational expenses, all adding up to $1,500 in costs. That's a profit of $18,500. As you get better treatments, your yield goes up. In the CD treatment, the yield increases to 28,000 kg/ha, resulting in $28,000 in revenue. The setup costs are higher: 1,500; and the operational costs are 1,200, with a total of costs being 2,700. The profit grows to $25,300. Applying SD makes this yield even higher, at 36,000kg/ha, with revenue of $36,000. You have $8,000 for initial setup and $2,000 for operational costs, totaling $10,000. The profit per this treatment is $26000. SNFT treatment has the highest yield of 48,000kg/ha and a revenue of $48,000. Set-up costs rise to $10,000, operational costs $2,500 and total costs $12,500. The profit is $35,500, the most profitable of the cucumber treatments.

With tomatoes, the trends are similar, but because growing tomatoes is more expensive than growing the kinds of field crops represented in the bar chart, yields and costs are generally higher than with the other field crops. Tomatoes treated with CF produce 25000kg/ha = $25000. Cucumbers are more capital intensive up front at $1,000 per crop with $1,500 in operating costs (for $2,500 in total cost). The profit here is $22,500. CD treatment yield is 35,000kg/ha, with revenue at $35,000. The first setup new cost is $2,000, and new per operation is $2,000, which leads to $4,000 in costs, the profit for this procedure is $31,000. SD yields 40,000kg of tomatoes, generating $40,000 in profits. Materials required the fixed costs double the initial setup cost to 10,000 and add the operational cost of 3,000 with it, this means the total costs reach 13,000. Even with the increased costs, that profit amounts to $32,000. Under SNFT, it spikes to 60,000kg/ha and $60,000 in revenue. There are production costs of $12,000 and operational details of $4,000 for a total of $16,000. The profit in this case is at its greatest, $44,000 (Table 7).

DISCUSSION

Significant differences were found in irrigation efficiency, plant growth parameters, and fruit yield between the different treatment methods, indicating the importance of selecting appropriate growing media and irrigation strategies for improving agricultural productivity. This paper elaborated on the findings with supporting evidence from recent research to provide context and rationale for the results. When it comes to total water used and WUE, the data all seem to clearly state that soilless systems, especially NFT systems, are superior in terms of water use efficiency when compared to conventional methods (ABD EL-WANIS et al., 2018). The highest WUE was obtained from the SNFT system which is 0.0840kg/L, while the SD system came second with a WUE of 0.0750kg/L and flood irrigation (conventional) was the lowest at 0.0267kg/L. Gautam et al. (2021) found that soilless systems led to decreased water consumption by as much as 60% while sustaining similar or increased yields for the crop. Thapa et al. (2024) justified the high WUE under the NFT system for the high utilization of the precise nutrient management which enhances the plant growth and reduce the need for excessive water to flush out unused nutrients. Moreover, Dutta et al. (2023) justified that for the smart sensing devices which contribute in optimizing the water and nutrient use. The total water per plant reflects those efficiencies. The SNFT system was able to effectively use only 50L/plant as opposed to 120L/plant, which is necessary with the standard flood irrigating system. The results emphasize the promise of soilless systems for use in water-scarce regions such as Southern Jordan, where the conservation of water is paramount. Soilless systems enhanced plant growth parameters (plant height, leaf area, and stem diameter). SD treatment produced the tallest plants (110cm), the largest leaf area (2000cm²), and bushier stems (10.5mm). These further improvements have been attributed to optimized nutrient delivery and oxygenation of the root zone of plants, typical of soilless systems, since hydroponics provides more rapid vegetative growth in occasions with precise nutrient management. Abul-Soud et al. (2021) pointed out that the controlled environment conditions in soilless systems including the pH, moisture, and temperature improved the plant health and growth rate.

In contrast, the CF treatment was observed to have the poorest growth parameters in terms of plant height (85cm), leaf area (1500cm²) and stem diameter (8.5mm). These results consistent with research by Pais et al. (2023) which found that traditional flooding irrigation can cause water logging and nutrient leaching which are two reasons affecting crop growth. Measurement of fruit yield and quality reinforces the benefits of soilless systems. SD recorded the highest total fruit weight per plant (4.5kg) and the highest number of fruits per plant (32). Soilless systems present better fruit quality with higher fruit size (140g) and fruit firmness (14.8N), ranking them respectively first in soil systems. These findings are consistent with the study by Guo et al., (2022), which showed that fruit quality improves in soilless systems because of the constant nutrient input and less plant stress. The low efficiency of traditional farming and simplicity for farmers to apply these systems for production minimize the ability of different countries in arid and semiarid areas to fight climate change conditions (Zafar et al., 2023). This was justified of the low governments efforts to facilitate the distribution of the new production technologies and make them accessible for farmers (Apipoonyanon et al., 2021).

The CF treatment had the lowest fruit yield (3.2kg/plant) and also produced smaller and less firm fruits (128g and 12.5N, respectively). These findings suggest that the practices used to manage water not only affect the quantity but also the market value of the produce. The advantages of soilless systems that we observed are indeed supported by many recent studies. For instance, Terada et al. (2023) demonstrated that hydroponic growing systems yielded 25% more tomatoes than standard soil cultivation under comparable environmental settings. On the other hand, a study conducted by Liu et al. (2023) also showed that WUE can increase by up to 70% when using drip irrigation in soilless media compared to flood irrigation. In addition, the environment in Southern Jordan is marked by arid climates and limited water resources so soilless and water-efficient irrigation systems are especially beneficial. However, many countries have adopted traditional irrigation methods, which do not contribute much to agricultural sustainability and food security (Abrar & Tukino, 2023).

The previous results show that both cucumber and tomato crops benefit from improved irrigation efficiency treatments, with higher yields, revenue, and profits observed as the treatments progress. For cucumbers, the CF treatment yields 20,000kg/ha and generates a revenue of $20,000, with total costs of $1,500 and a profit of $18,500. As the irrigation efficiency increases, the yield rises to 28,000kg/ha under CD, leading to a higher revenue of $28,000 and a profit of $25,300. The increase in yield continues under SD, reaching 36,000kg/ha, although the costs also rise to $10,000, resulting in a profit of $26,000. The highest yield for cucumbers is seen in the SNFT treatment, with 48,000kg/ha, which translates to the highest revenue and profit of $48,000 and $35,500, respectively. The increasing costs reflect the more advanced technologies used, but the higher revenue compensates for this. Despite the higher energy consumption in SNFT (Dutta et al., 2023), still the feasibility of production under SNFT was very high compared to other systems due to the high production and super quality. The higher feasibility of soilless systems was resulted of the higher yield and quality, the high efficiency of resources use (Dabral et al., 2022; Rahim Doust et al., 2023).

For tomatoes, the trends are similar but with generally larger yields and higher costs. Under the CF treatment, the yield is 25,000kg/ha, resulting in $25,000 in revenue and a profit of $22,500. As the treatments improve, the CD treatment increases the yield to 35,000kg/ha, with revenue of $35,000 and a profit of $31,000. The SD treatment results in a yield of 45,000kg/ha and a profit of $32,000, though costs rise to $13,000. Finally, the SNFT treatment produces the highest yield of 60,000kg/ha, leading to $60,000 in revenue and the highest profit of $44,000, despite the higher setup and operational costs. In conclusion, while both crops show increased profits with improved irrigation, tomatoes exhibit a more pronounced financial benefit, particularly under SNFT, due to the larger yield and higher revenue generated (Askaraliev et al., 2024).

Conclusions and Recommendations

Results from the "Assessing Irrigation Efficiency: A Study of Water Conservation in Soilless Media and Conventional Farming" experiment indicate that irrigation efficiency improvements are beneficial to crop yield and profitability for both cucumber and tomato. Both crop yield, revenue, and profit increased consistently under each irrigation efficiency treatment from CF to SNFT. For instance, cucumbers yielded the highest results, particularly with the SNFT, where it was 48,000kg/ha with $48,000 of revenue and a profit of $35,500. Tomatoes exhibited greater increases, with the highest profit of $44,000 realized under the SNFT treatment, primarily due to the very high yield of 60,000kg/ha. Although the expenses grew as they used more sophisticated treatments, they generated more yield and revenue for those investments, resulting in higher profit margins across the board. These results highlight the importance of advanced irrigation practices in maximizing crop productivity (both fresh and dry weight/yields) and financial returns (both total and net returns), particularly with soilless systems such as SD and SNFT. These results are especially notable for tomato production but demonstrate the potential of similar techniques to be applied to other crops with high economic value and longer growth cycles. Although the initial capital and operating costs of these treatments are high, their clear financial return measured in terms of yield and profit justify such purchases for growers who want to improve their irrigation. In conclusion, apart from bettering water savings, better irrigation systems improve agriculture productivity; the economic and environmental benefits could be used for irrigation purposes.

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