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RESEARCH ARTICLE
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The Effect of Drip vs Hydroponic Irrigation Systems on Water Saving in Dry Regions

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ABSTRACT

The limited availability of water resources in arid and semi-arid regions, compounded by the adverse effects of climate change, necessitates the adoption of efficient and sustainable irrigation strategies to optimize agricultural productivity. The objective of this study was to compare the performance of drip irrigation and hydroponic systems in terms of water use efficiency (WUE), crop yield, plant growth and nutrient management in arid regions of Jordan. The WUE of the hydroponic system was significantly higher (61.3kg/m^3) than that of drip irrigation (18.9kg/m^3), and the hydroponic system yielded slightly higher crop production (9.2kg/m^2). In terms of vegetative growth, the hydroponic system increased plant height (92.7cm) and leaf area (1,450cm^2/plant) due to its ability to precisely deliver water and nutrients. Water management under hydroponic systems -including pH, electrical conductivity (EC), and nutrient concentrations- is highly efficient. Under the drip irrigation system, the soil moisture was maintained at proper levels but did not use water and nutrition optimally, especially in dry regions, which faced unfavorable environmental conditions including high temperature (exceeding 28.5°C), low humidity (45.0%), and intense solar radiation (22.3MJ/m^2/day) in summer seasons. Although hydroponics demonstrates the highest water-saving potential and crop performance, its high initial costs and technical expertise requirements may hinder its mass adoption. Nevertheless, drip irrigation is still a viable and cost-effective alternative to conventional farming systems. These results highlight the importance of implementing irrigation practices tailored to specific contexts to improve WUE and agricultural sustainability in dry regions.

Keywords: Drip Irrigation, Hydroponic Systems, Water Use Efficiency (WUE), Crop Yield, Arid Regions, Water Scarcity

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INTRODUCTION

Water is a vital input resource for agriculture, and the scarcity of water represents one of the most significant challenges for agriculture (Thapa et al., 2024), especially in arid and semi-arid climatic regions where rainfall is limited and high evaporation rates are encountered. According to the population projection, the worldwide population will reach up to 9.7 billion by 2050, leading to increased demand for food and water. How would this affect the currently limited water resources? This has prompted the advancement of modern irrigation methods to achieve effective water utilization and sustainable agricultural output (Makone et al., 2021; Thapa et al., 2024). In arid environments, two techniques are particularly promising in terms of water conservation: drip irrigation (DI) and hydroponic systems (HS).

DI, through a system of valves, pipes, and emitters, delivers water directly to the root zone of plants and has been taken up as a strategy to reduce water wastage and improve crop yield. This makes DI one of the most efficient irrigation types to reach a WUE reaching 90%, reducing evaporation and runoff in arid regions. (Mansour, 2013). According to recent research, the use of DI systems can lower water consumption rates by 30-50% in comparison with conventional flood irrigation systems, as well as increase nutrient uptake and crop production. (Nabayi et al., 2022; Roy et al., 2024). Yet this system utilizes soil as a growing substrate, so its efficacy is subject to a variety of soil types, climatic conditions, and management practices, which may restrict its use in many situations.

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Meanwhile, HS, which grows plants in a soil-less medium, based on water-soluble nutrient concentrations, represents another approach to water-efficient agriculture. Hydroponics uses soilless media, optimizes water and nutrient distribution. Pooled system water is recirculated in the system and is only lost by evaporation and transpiration, saving up to 90% of water compared to conventional irrigation systems. (Banerjee et al., 2022; De la Rosa-Rodríguez et al., 2020). With the advent of modern hydroponic technologies, closed-loop systems and automated monitoring leading to greater water-saving potential, forming an alternative for dry areas with severely limited water resources (Banerjee et al., 2022). The upfront investment cost and technical expertise that HS demand can still be a major hurdle to their widespread implementation, especially in resource-poor environments.

The use of DI or HS is dependent on different factors related to the type of crops, local climate, resources available, and economic factors. The DI can be used in areas with very good soil quality or arable land, with efficiency limited to the nature of DI, while the HS can be used without area limitation as a soilless system, but with higher costs. (Rashid et al., 2021). Different studies have shown that both systems maximize water savings and agricultural productivity. Also, the researchers have shown that the integration of both systems is possible. (Palniladevi et al., 2023), especially in water-limited regions.

Typically, DI and HS are both beneficial in the agriculture sector to overcome water scarcity problems, but both have their advantages and disadvantages. The objective of this paper is to compare the DI and HS in dry areas of Jordan, which suffer from irrigation water scarcity in the productivity and feasibility. This study will add a practical comparison, including the feasibility of both systems in agricultural production.

Literature Review

Effective utilization of irrigation water is a fundamental need of agriculture all over the globe, particularly in arid regions that face water scarcity. DI and HS have been effectively studied, adopted and found to provide great benefits in water conservation, as well as improving the growth of crops. This review of literature evaluates recent studies on potential systems of seawater irrigation, exploring different water-saving potential effects, emphasizing their benefits and disadvantages, and considering the feasibility of their use in arid and semi-arid areas.

Drip Irrigation: Water Efficiency and Applications

A DI is one of the most efficient methods of watering crops, particularly in water-scarce regions. DI is a type of micro-irrigation system that has the potential to save water and nutrients by allowing water to drip slowly to the roots of plants. The research shows that DI can save up to 90% of irrigation water. (Li et al., 2023). The advantages of DI related to its use for a wide variety of crop conditions and water saving make it a target system for farmers, and the possibility of its use in different soils (Nabayi et al., 2022; Roy et al., 2024).

Moreover, the use of fertigation in conjunction with DI improved the crop yields and nutrient absorption while simultaneously reducing water consumption as well. (Klein et al., 2018). Another factor that affects the use of DI is related to the system maintenance and the system clogging due to poor water quality or poor filtration, which reduces system efficiency, the need monitoring and maintenance. (Karpenko & Rudakova, 2022). Also, the high initial installation costs may be a barrier for small-scale farmers, especially in the developing world. In addition, the fact that the system uses soil as a growing medium means its performance is likely to vary according to soil type and structure. The DI potential may not be fully realized in areas with very salty or degraded soils, underscoring the need for complementary soil management practices. (Liu et al., 2023).

Hydroponic Systems: Precision and Water Conservation

HS is a paradigm shift in agricultural water management. Unlike soil-based agriculture, hydroponics is up to 90% more efficient when it comes to water use because in an HS, water is recirculated and only lost through evaporation and transpiration, as water and nutrients can be delivered directly to the roots (Vagisha et al., 2023), which makes it practical for dry regions with a serious lack of water resources. The improvement of hydroponics technology has improved water-saving through closed-loop systems that recirculate water and nutrients, helping to minimize waste and promote optimal growing conditions for plants. (Yegül, 2023). The HS can be monitored automatically with control systems for adjusting water and nutrient supply based on real-time data, which improves the efficiency. (Banerjee et al., 2022).

The main hydroponic technology provides more feasibility to produce crops in low arable land areas and soils with degradation and salinity. Research has indicated that HS may achieve high levels of production for crops such as leafy greens and tomatoes with minimal water input required.(Rajatha et al., 2022).

Comparative Analysis: Drip Irrigation vs Hydroponics

Both DI and HS have unique strengths and limitations when considering their suitability in a water-stressed region. DI is generally more economical for smallholder farmers, particularly in developing countries, and is suited to use in traditional settings (Rani et al., 2022). The performance of the technology arguably fits better with current agricultural practices, while maintenance requirements are low. However, the utility of DI is limited by soil conditions, particularly poor soils. In contrast, HS use water more efficiently and enable crops to be produced on land that is otherwise non-arable (Alsanius & Wohanka, 2019). The high level of precision and control used in hydroponics reduces waste to enable optimal use of resources, with limited other impacts on the environment. The technology is, however, too costly, particularly for smallholder farmers in developing countries. Farmers must also have acquired skills to use HS, meaning it may not be suitable in traditional systems. Recent studies have examined the use of combined systems in which DI and HS are integrated. Such systems combine the efficiency of water savings typical to DI in technology, such as the Precision Hydro-DI integrated with controlled environment hydroponics, reducing the limitations of drainage. Innovation may comprise alternatives to simple interstrand and joint systems (Banerjee et al., 2022). Hybrid approaches, integrating the best parts of each system, imply that a standalone system may be best, particularly in remote or conflict-affected areas.

MATERIALS & METHODS

Study Area and Experimental Site

The study was carried out in an arid region located in the northern region of the Jordan Valley in Jordan, which is characterized by high temperature and low annual precipitation (less than 200mm) with little freshwater resources. The experimental site has sandy loam soil with low organic matter content and moderate salinity, which is representative of arid regions.

Experimental Design

A randomized complete block design (RCBD) with three replicates was used in the study to compare the water-saving irrigation efficiency of drip and HS. The study evaluated two principal treatments:

Irrigation systems: DI: A traditional DI system was adopted, with emitters installed at 30 cm intervals and a flow rate of 2L/h. A filtration unit was installed to avoid the clogging of the system, and a fertigation unit was used to apply the nutrient solution (Zeineldin et al., 2024). HS: Recirculating nutrient film technique (NFT). HS was performed with channels arranged in a closed loop to recycle water and nutrients. The system had a reservoir, pump, and automated pH and electrical conductivity (EC) monitoring (Shtaya & Qubbaj, 2022). Each treatment was applied to a plot measuring 10m×10m, with three replicates per treatment. The experiment spanned six months to account for seasonal differences in water usage and crop performance.

After carefully considering the best options for the trial, tomato (*Solanum lycopersicum*) and cucumber (*Cucumis sativus*) were selected as the test crop as it is of high economic value and can be incorporated into both DI and HS. For uniformity, seedlings of similar varieties were transplanted into the experimental plots and hydroponic channels on the same date.

Water management: In DI, water application was based on crop evapotranspiration (ETc) rates, calculated using the Penman-Monteith equation and local weather data. Irrigation was scheduled weekly to fulfill crop water requirements with minimum losses (Maneesha et al., 2022). In an HS, water was continuously circulated inside the system and was supplemented regularly to accommodate losses for evaporation and transpiration. The nutrient solution was prepared according to standard hydroponic formulations and monitored daily for pH (5.5 to 6.5) and EC (1.5 to 2.5dS/m).

Data Collection: To assess the water mobility efficiency and performance of the two systems, the following parameters were measured:

1. Water use: The total amount of water applied (in liters) to both systems was measured using flow meters. WUE, the ratio of crop yield (kg) to total applied water (m^3), was computed for each plot.
2. Crop growth and yield: Plant height, leaf area, and fruit yield were measured at regular intervals from the first harvest up to the final harvest, once every three weeks. Yield data were collected at harvest and are presented in kg/m^2.
3. Water quality: The pH, EC (dS/m), and nutrient concentrations of the water samples were assessed for both systems to ensure optimal growing conditions.
4. Soil moisture (For DI Only): Soil moisture sensors were installed at depths of 15cm and 30cm to monitor soil water content and confirm efficient water delivery.
5. Environmental parameters, temperature, relative humidity, and solar radiation were measured using a weather station set up at the site.

Statistical Analysis

Statistical analysis of data for each experiment was performed using analysis of variance (ANOVA) to find out significant differences between the two irrigation systems related to WUE, crop yield, and growth parameters. Post-hoc comparisons were made with Tukey's honestly significant difference (HSD) test at $p<0.05$. Statistical analyses were conducted utilizing R software (version 4.2.1).

RESULTS

Soil, Water and Environment

The pH of spray water in the DI system was 7.2 (slightly alkaline), while that of the HS was 6.0 (slightly acidic) (Table 1). The electrical conductivity (EC) of water was 2.0dS/m and 2.2dS/m in the enterprise of DI and HS, respectively. So, the EC is higher in the HS due to the nutrient solution that is used to maintain the soil-less growth system.

Table 1: Water Quality Parameters

Parameter	DI	HS
pH	7.2	6.0
Electrical Conductivity (EC) (dS/m)	2.0	2.2
Nitrate Concentration (mg/L)	15.5	18.0
Phosphate Concentration (mg/L)	5.0	6.5

Phosphate was at a higher concentration in the HS (6.5mg/L) compared to the DI system (5.0mg/L). Phosphate chemicals are also crucial for energy transfer, root development, and fruit production in plants. The converse is true in hydroponics, where phosphate is found in higher concentrations than in the soil, so it remains available to plants throughout their growth cycle. At elevated concentrations in DI, phosphate becomes conducive to its availability and uptake by plants in weight properties and mineral composition (Table 1).

The soil moisture content at the 15cm depth was 22.5% (volumetric) (Table 2). This higher moisture level suggests that the DI system successfully applied water into the upper layer of the root zone, where most of the roots are generally established.

At 30cm depth, soil moisture content was also observed to be lower than that at 15cm depth and stood at 18.7% (volumetric) (Table 2). This should reduce the moisture content moving through the soil profile due to gravity. Moisture at this depth is still within the optimal range for supporting deeper root growth and ensuring access to water during periods of high evaporation or water stress. This is particularly relevant in arid regions affecting moisture at depth, such as Jordan; such a positive correlation helps conserve water and facilitates its usage effectively.

Table 2: Soil Moisture Content (DI Only)

Depth (cm)	Soil Moisture Content (% Volumetric)
15	22.5
30	18.7

The experiment's average temperature was 28.5 °C (typical for the Jordan Valley and other arid regions) (Table 2). The average relative humidity was 45.0%, which is relatively low and typical of arid regions (Table 3). The average solar radiation in the valley was 22.3MJ/m²/day representing abundant sunshine, common for the Jordan Valley (Table 3).

Table 3: Environmental Conditions during the Experiment

Parameter	Average Value
Temperature (°C)	28.5
Relative Humidity (%)	45.0
Solar Radiation (MJ/m²/day)	22.3

Crop Production

The performance of the DI system as well as HS was compared in terms of total water applied (TWA), crop yield, and WUE is presented in Table 4. These findings underscore key distinctions between the two systems, including how much water each conserve and how productive they are overall. During the period of the experiment, 450m³ and 500m³ of water were needed per hectare of land, respectively, to grow tomatoes and cucumbers using a DI system. The HS consumed only 150m³ and 180m³ of water to produce the same amount of tomato and cucumber, respectively, which is 66.7% and 64% less water than tomato and cucumber crops were grown using a dripper irrigation system (Table 4). HS yielded 9.2kg/m² and 11.5kg/m² whereas DI system yield was 8.5kg/m² and 10.25kg/m² for tomato and cucumber, respectively, which is slightly higher than 8.5kg/m² and 10.25kg/m² (Table 4). The WUE was significantly greater for the HS (61.3kg/m³) and (63.9kg/m3) compared to the drip irrigation system (18.9kg/m³) and (20.4kg/m³), respectively (Table 4).

The growth and productivity of tomato plants in DI and HS, as measured by plant height, leaf area, and fruit yield, are shown in Table 5. The two systems showed striking differences, with hydroponics demonstrating faster plant growth and increased yields. The results showed that cactus (both tomato and cucumber) grown in the HS grew tallest with an average height of 92.7cm for tomato and 98.2cm for cucumber, DI cactus produced 85.3cm for tomato and 90.5cm for cucumber averaged height, respectively (Table 5). The HS also had a higher leaf area per plant of 1450cm² and 1650cm² for tomato and cucumber, while for DI it was recorded at 1250cm² and 1400cm² respectively (Table 5).

Table 4: WUE and Total Water Applied

Treatment	Tomato			Cucumber		
	TWA (m³)	Crop Yield (kg/m²)	WUE (kg/m³)	TWA (m³)	Crop Yield (kg/m²)	WUE (kg/m³)
DI	450	8.5	18.9	500	10.2	20.4
HS	150	9.2	61.3	180	11.5	63.9

The total fruit weight per area was found to be slightly higher for the HS, 9.2kg/m² and 11.5kg/m² for tomato and cucumber as compared to DI 8.5kg/m² and 10.2kg/m². This difference in yield was also consistent with the mature plant height and leaf area improvement recorded, as bigger, healthier plants tend to be more productive (Table 5).

The HS demonstrated significantly higher WUE compared to the DI system. The mean WUE for the HS was 61.3±2.5kg/m³, while the DI system achieved a mean WUE of 18.9±1.2kg/m³. This difference is highly statistically significant ($p<0.001$) (Table 6).

The HS achieved a marginally higher crop yield than the DI system. The mean yield for the HS was 9.2±0.4kg/m² and the DI system was 8.5±0.3kg/m². The reported p-value of 0.012 means that the difference is statistically significant (Table 6). Neurological strain: The study of hydroponics is the study of specific water and nutrient conditions that provide the best yield of plant for its water weight. DI, on the other hand, is an efficient method, but it is influenced by variances in soil conditions, which may marginally restrain crop productivity. Hydroponically grown plants were significantly taller than plants grown under drip irrigation. The average height of the plants grown using the HS was 92.7±1.8cm, while the average height of the plants grown using the DI system was 85.3±2.1cm. The corresponding p-value of 0.023 suggests that this difference is statistically significant (Table 6). The increased height of plants grown in HS could be attributed to the availability of plentiful water and nutrients, allowing plants to produce more leaf surface area and a more robust stem structure. In DI, despite efficient delivery of water and nutrients, soil texture, nutrient distribution, and transient water stress can restrict plant performance. HS showed the highest record in yield compared to the DI system (28.04ton in the planting season, 135 crops per plant) and WUE (approximately 9.95kg/m³); also, the plant height of HS was high compared to DI.

Table 5: Crop Growth Parameters

Treatment	Tomato			Cucumber		
	Plant Height (cm)	Leaf Area (cm²/plant)	Fruit Yield (kg/m²)	Plant Height (cm)	Leaf Area (cm²/plant)	Fruit Yield (kg/m²)
DI	85.3	1,250	8.5	90.5	1,400	10.2
HS	92.7	1,450	9.2	98.2	1,650	11.5

Table 6: Statistical Analysis of Key Parameters

Parameter	Treatment	Tomato		Cucumber	
		Mean±SE	P-value	Mean±SE	P-value
WUE (kg/m³)	DI	18.9±1.2	<0.001	20.4±1.5	<0.001
	HS	61.3±2.5		63.9±2.8	
Crop Yield (kg/m²)	DI	8.5±0.3	0.012	10.2±0.4	0.010
	HS	9.2±0.4		11.5±0.5	
Plant Height (cm)	DI	85.3±2.1	0.023	90.5±2.3	0.018
	HS	92.7±1.8		98.2±2.0	

The capital investment required to set up DI and HS varies significantly between tomatoes and cucumbers due to differences in infrastructure and components. The initial cost of DI was $4,000 per hectare, of which $2,000 was used for the cost of driplines, emitters, and filters, while the cost of the pump and fertigation unit was $1,500, and installation labor costs $1,500. Its relatively low initial cost and easy setup make DI available to small farmers, especially where capital is scarce. Furthermore, the system attaches to traditional systems, making it convenient for farmers to install and maintain. The net initial investment for HS is much greater at $16,000 per hectare. This cost consists of hydroponic infrastructure ($10,000), automation and monitoring systems ($5,000), installation labor ($5,000), and installation labor ($1,000).

Table 7: Initial Setup Costs per Hectare for tomato and cucumber

Component	DI	HS
Drip lines, emitters, filters	$2,000	-
Hydroponic infrastructure	-	$10,000
Pump and fertigation unit	$1,500	-
Automation and monitoring	-	$5,000
Installation labor	$500	$1,000
Total Initial Cost	$4,000	$16,000

Annual operating costs for drip irrigation and HS highlight key differences in resources used and costs incurred in the cultivation of both tomatoes and cucumbers. The total annual operation cost for both crops based on DI is $4050ha^{-1}. This includes water costs of $4,050 Per Hectare each for both crops. Water cost was ($2,250), representing 4,500 m^3 of water annually. Fertilizer costs are another $500 because fertilizers are applied through the fertigation system, which is used to optimize nutrient and fertilizer delivery. Fertilizers via the fertigation system are used to maintain low maintenance costs of $500. Annual maintenance costs are around $300, covering emitter replacements, filters, and other parts. Post-implementation costs after the implementation labor costs consist of $1000 of regular monitoring & management of the system (post-implementation) (Table 8). The HS costs $5,250 per hectare a year for both crops. Although the water prices are much smaller counterparts, $5,250 for both crops. Water costs at $750 are a small fraction of the costs of soil since water is recirculated in the system and used again, but the nutrient solution costs are $1,000, as the hydroponics systems need a precise and continuous supply of nutrients in water. There'll be a heavy energy price to pay for hydroponics at $1,000 -hydroponics needs highly intricate and precise nutrients dissolved in the water supply. Hydroponics has high energy requirements at $1,500, due to the pumps, lighting (if grown indoors or in greenhouses), and automation systems needed to ensure the best conditions for a growing plant. At $500, HS are more expensive to maintain, as they need to be cleaned frequently, monitoring equipment must be regularly calibrated, and parts need to be replaced. Labor cost was $500, since hydroponics systems need frequent cleaning, monitoring equipment has to be calibrated, and components have to be replaced. For labor, the cost was $1,500 as more technical expertise was required to manage the system (Table 8).

The total annual cost for DI is $4,450 per hectare, which means annual operational costs of $4,450 per hectare, which includes annual operational costs of $4,050 and depreciation of $400. The solution operational costs include water, fertilizers, maintenance, and labor, and the depreciation is the gradual wear-and-tear of the system over its 10-year lifespan (Table 9). In comparison, the HS exhibits a substantially elevated total annual cost of $6,850 per hectare. This accounts for annual operational costs of $6,850 per hectare. It includes operating expenses of $5,250 per year and depreciation of $1,600. Operationally, hydroponics is more costly, having an energy-demanding apparatus (pumps, lighting, and automation), and they also require specific nutrient solutions. Further, the set-up cost of hydroponics is higher (Table 9).

Table 8: Annual Operational Costs (1 Hectare)

Component	Tomato		Cucumber	
	DI	HS	DI	HS
Water (4,500 m^3 vs. 1,500 m^3)	$2,250	$750	$2,250	$750
Fertilizers/Nutrient solution	$500	$1,000	$500	$1,000
Energy (pumps, lighting, etc.)	-	$1,500	-	$1,500
Maintenance	$300	$500	$300	$500
Labor	$1,000	$1,500	$1,000	$1,500
Total Annual Operational Cost	$4,050	$5,250	$4,050	$5,250

Table 9: Total annual costs, including depreciation, per one hectare for tomato and cucumber

Component	DI	HS
Annual Operational Cost	$4,050	$5,250
Depreciation (over 10 years)	$400	$1,600
Total Annual Cost	$4,450	$6,850

This data emphasizes the differential production, commercialization and revenue generation for tomatoes and cucumbers under drip irrigated and hydroponic production systems. The average yield of tomatoes under DI is at 85,000kg/ha, versus 92,000kg/ha under an HS. The difference in yield speaks to the advantages of hydroponics, such as the ability to closely monitor and control water and nutrient delivery, maintain the right pH and electrical conductivity (EC) and expose the plant to less environmental stress. The market price for tomatoes is 1.5/kg, leading to 1.5/kg gin revenues, creating revenues of $127,500 for DI and $138,000 for hydroponics. The revenue from hydroponics is higher because of the increased yield, which shows that the system helps in optimizing productivity and profitability (Table 10).

Table 10: Output values for tomato and cucumber per one hectare

Parameter	Tomato		Cucumber	
	DI	HS	DI	HS
Crop Yield (kg/ha)	85,000	92,000	102,000	115,000
Market Price ($/kg)	$1.5	$1.5	$1.5	$1.5
Revenue ($)	$127,500	$138,000	$153,000	$172,500

Likewise, is the case where, the case of cucumbers, with a yield of 102,000kg/ha under enhanced irrigation and even higher, at 115,000kg/ha under an HS. Cucumbers normally have greater yields than tomatoes, due to their robust growth and larger leaf surface area, which enables them to intercept more sunlight and create more biomass. The market price for cucumbers is also 1.5/kg and the revenues are $153000 for DI and $172500 for hydroponics. Again, the increased income from the hydroponics system highlights how it improves yield and income generation (Table 10).

For the revenue of tomatoes, the revenue collected for DI is $127,500, the total annual cost is $127,500, and the total annual cost is $4,450, providing $123,050 for profit. While the HS gives more revenue, which is $123,050. Conversely, the HS produces more revenue, amounting to $138,000 with higher overall annual costs totaling $6,850 and its annual profit amounts to $6,850 resulting in $131,150. The profit from hydroponics is considerably higher due to higher crop yield that outweighs higher running and depreciation costs. Data science has shown that this system can achieve high crude productivity and profitability, thus it's a gravitational force for farmers globally with resource and technical backgrounds (Table 11).

Table 11: Profit for tomato and cucumber per hectare

Parameter	Tomato		Cucumber	
	DI	HS	DI	HS
Revenue ($)	$127,500	$138,000	$153,000	$172,500
Total Annual Cost ($)	$4,450	$6,850	$4,450	$6,850
Annual Profit ($)	$123,050	$131,150	$148,550	$165,650

For cucumbers, the income, equivalent to 153,000, is obtained under DI, the total annual cost is $4,450, and the annual profit is $148,550. (Under HS revenue increases to $148,550) However, with hydroponic, the revenue goes up to $172,500, while the total annual cost also remains at $6,850, creating a profit of $6,850 that leads to an annual profit of $165,650. Overall, cucumbers outperformed tomatoes (in terms of profit) in both systems because of their higher productivity and greater biomass. As for the return on investment, the HS again beats the drip system, proving its capacity to boost crop performance as well as economic performance (Table 11).

So, to analyze the differences in management, cost, and yield between the above-mentioned methods, Table 12 compares DI systems and hydroponic methods of tomato and cucumber cultivation. For both crops, the set-up cost of DI is $4,000 per hectare while the group HS costs $16,000 per hectare. Hydroponics requires a significant upfront investment, reflecting the advanced technology and infrastructure needed, which includes automation, monitoring systems, and soil-less growing setups. DI, on the other hand, consists of simpler components (like drip lines, emitters, and fertigation units), which makes it a more accessible solution for small farmers and low-budget producers.

Table 12: The feasibility of tomato and cucumber production under DI and HS

Parameter	Tomato		Cucumber	
	DI	HS	DI	HS
Initial Setup Cost ($)	$4,000	$16,000	$4,000	$16,000
Annual Operational Cost ($)	$4,050	$5,250	$4,050	$5,250
Total Annual Cost ($)	$4,450	$6,850	$4,450	$6,850
Crop Yield (kg/ha)	85,000	92,000	102,000	115,000
Revenue ($)	$127,500	$138,000	$153,000	$172,500
Annual Profit ($)	$123,050	$131,150	$148,550	$165,650

For annual operational cost per hectare, DI is $4,050, while hydroponics is $5,250. Despite the higher costs, hydroponics allows large savings in water consumption, utilizing just 1,500m^3 of water a year versus 4,500m^3 for the use of DI. This means that hydroponics is a more sustainable choice in areas where water is scarce, such as Jordan. Including depreciation, the total annual costs for DI and hydroponics are $4,450, $4,450, and $6,850 per hectare, respectively. The costs are the same for tomatoes and cucumbers because tomatoes and cucumbers require similar infrastructure and operation. Under HS, tomato and cucumber yields are consistently higher than in DI systems. Hydroponics can yield up to 92,000kg/ha, while the yield under DI for tomatoes is only 85,000kg/ha. For cucumbers, similar to above, the yield under DI is 102,000kg/ha, while hydroponics achieves 115,000kg/ha. Hydroponics allows for the best control over growing factors, which means less plant stress and better consumption of water and nutrients, thus resulting in higher yields. The higher yields mean higher revenue, with the hydroponics system generating $138,000 for tomatoes $138,000 for cucumbers, and $172,500 for cucumbers compared with $127,500 and S153,000, respectively, under DI (Table 12).

These annual profits impressively emphasize the economic benefits of HS. $11,80 and therefore, the profit is $123,050, including hydroponics Profit is $131,150. In the same way, the profit for cucumbers on DI is $148,550, compared to $148,550, the profit for hydroponics is $165,650. Despite the initial costs, higher revenues from higher yields in hydroponics farms led to higher profits. Thus, for some farmers with the means and skill set to install HS, hydroponics is increasingly appealing, particularly in regions with high water scarcity and high productivity requirements.

That said, DI remains a feasible and affordable choice for resource-needy farmers. In areas with the capacity, the economic benefits may be significant, noting that DI returns less yield and profit metrics compared to hydroponics. Since the system is affordable, while also efficient in delivering water and nutrients, it is a viable choice for small-scale farmers in regions with high aridity such as Jordan.

DISCUSSION

The experiment conducted to compare DI and HS in the arid area of Jordan showed notable water savings between the two systems, as well as crop performance in dry regions. The findings illustrated that each system had its strengths and weaknesses, with hydroponics being more efficient in terms of WUE, crop yield, and growth of the plants when compared with DI. However, the decision between the two systems is not clear-cut and depends on different aspects of the local situation, resources, and economic situation. This discussion places the findings within the broader literature and outlines their ramifications for sustainable agriculture in water-scarce regions.

The HS showed WUE 61.3kg/m^3, which was 3.24-fold higher than the observed 18.9kg/m^3 WUE of the DI system (Kumar & Verma, 2024; Safvan, 2024). The results are also consistent with recent research that showed hydroponics has a higher potential for saving water. For example, (Kumar & Verma, 2024) found HS use much less water than traditional irrigation, citing reductions anywhere from 30% to 90% thanks to the recirculation of water and nutrients in a closed-loop system. Likewise, Safvan, (2024) noted that there is no loss of evaporation, runoff, and deep percolation with hydroponics, making it a potential solution for dry areas. Concerning conventional flood irrigation, water loss in DI systems does not exceed 10% and is particularly less in sandy soils with poor water-holding capacity. (Li et al., 2023). These findings prove that hydroponics provides a more sustainable method of water management in dry environments.

The same differences were noted in crop yields, which were significant (p=0.012), as the HS yielded 9.2kg/m², while the DI system yielded 8.5kg/m². This is in keeping with recent studies showing that hydroponics can increase crop yield by offering the best possible growing conditions. For example, Zeineldin et al. (2024) found that hydroponically cultivated tomatoes, with their precise nutrient delivery and minimized environmental stress, have produced higher yields and improved fruit quality than those grown by DI. Under the HS, the increased plant height (92.7cm) and leaf area (1,450cm²/plant) demonstrate how the plants take advantage of the plentiful water and nutrients to drive strong growth. Kumar & Verma, (2024) findings are consistent with these research results, which noted that HS facilitate faster growth with increased biomass accumulation over soil-based systems.

Compared to the DI system, the HS demonstrated superior control of water quality indicators such as pH (6.0), electrical conductivity (EC) (2.2dS/m), and nutrient concentrations. One of the major benefits of hydroponics is the ability to manage nutrient levels with precision, ensuring that plants are provided with steady and balanced combinations of key nutrients (De la Rosa-Rodríguez et al., 2020). Studies have indicated that the optimal level and fluctuation of pH and EC in hydro systems play a pivotal role in maximizing nutrient uptake and plant growth (Kumar et al., 2024). However, the overall availability of nutrients in nature depends on the environmental situation, and the majority of nutrients are accessible to plants in the form of minerals and elements only through DI. Furthermore, the slightly alkaline pH (7.2) of the DI system can hardly be a limiting factor in the availability of nutrients, such as iron and phosphorus, that may affect the performance of the plants (Barreto et al., 2015). These results highlight the need for HS in areas with poor, high-variance soil quality.

The results showed that the environmental growth conditions were more preferable under the HS compared to DI. The pH of irrigation water under HS was more acidic compared to the DI. The difference is important because pH influences how nutrients are taken up by plants. Generally, most crops, tomatoes being no exception, will prefer a slightly acidic pH range (5.5–6.5) to optimize macro and micronutrient absorption. A pH level commonly maintained by HS allows the most optimal absorption of nutrients by certain plants. On the flip side, the DI system shows a slightly alkaline pH, which can limit certain nutrients such as iron and phosphorus, limiting plant performance (Dzib-Ek et al., 2021). Moreover, the slightly higher EC is also good for hydroponics as it means the plants have a constant supply of important nutrients. With DI, this lower EC can be due to the leaching of nutrients or the dilution of nutrients in the soil, which is likely to lead to a reduction in nutrient availability over time.

Soil moisture contents were maintained at reasonable levels in the root zone via a DI system (22.5% volumetric moisture ($cm^3\ cm^{-3}$) soil at 15 cm depth and 18.7% soil at 30 cm depth). These findings align with studies that show DI is an upfront measure that facilitates appropriate water reach to the root zone while minimizing losses with evaporation and deep percolation. (Barreto et al., 2015). The temperature (28.5°C), relative humidity (45.0%), and solar radiation (22.3MJ/m²/day) as summarized for the experimental stage are high, which complicates the development of crops in arid regions. Be it the demand for water and high losses, especially for a DI system. Recent studies highlight the need for complementary measures (mulching or shading), which may help in evaporative loss reduction and improve irrigation WUE in the case of DI. (Kumar et al., 2024). On the other hand, controlled-environment HS can help overcome these challenges since these setups can control temperature, humidity, and light exposure.

These results are in line with recent research comparing DI and HS in arid zones. In a study conducted by Zeineldin et al. (2024) in Saudi Arabia, HS were compared to DI using an experimental design conducted in 2021, which showed their superiority in terms of WUE and crop yields, especially in regions with degraded soil quality. Similarly, Barbosa et al. Based on their study, HS can yield lots of leafy green vegetables with very low input water and tomatoes with very low input water, so it is an approach to increase food security in a water-scarce environment (2022). Nevertheless, those studies also presented the high initial investment costs and technical expertise involved in hydroponics, which may limit its moderate adoption among small-scale farmers. On the other hand, despite the newly emerged interest in DI, it is yet more accessible and cost-effective for farmers, especially in areas with compatible soil conditions. (De la Rosa-Rodríguez et al., 2020).

The findings from this experiment have meaningful implications for sustainable agriculture in arid regions such as Jordan. While there is overlap in the capability of both systems to provide solutions to reducing water use and improving agricultural yields, they are not equivalent for all situations. The hydroponics system demonstrates superior WUE compared to soil-based cultivation, especially beneficial to urban agriculture and vertical farming systems where space and water are limited, and the capability to grow crops in non-arable areas. Although they present a potential solution, the expensive initial expense and technical nature of HS act as an obstacle to broad adoption, especially in developing countries. In contrast, DI is a feasible and economically viable technique for natural farming processes in natural plus good-to-soil environments.

Conclusion

This means that DI saves more water than HS, even though it doesn't have a high crop yield. Hydroponic is undoubtedly the best-performing solution in a controlled environment and provides an efficient solution for water-scarce regions while ensuring food security even in dry regions. DI is more practical and cost-effective in conventional agricultural systems and is used where soil conditions are appropriate. I am not choosing between the two systems, since both are correct depending on circumstances, local conditions, resource availability, economic factors, etc. Context-specific irrigation management can thus be part of a solution for farmers, policymakers, and researchers to collaborate towards sustainable agriculture and food security in even water-scarce regions. The comparison between DI and HS for tomato and cucumber cultivation highlights the significant trade-offs in terms of costs, yields, and profitability. HS consistently outperforms DI in terms of crop yield and revenue, achieving 92,000kg/ha for tomatoes and 115,000kg/ha for cucumbers, compared to 85,000kg/ha and 102,000kg/ha, respectively, under DI. This superior performance is attributed to the precise control over water and nutrient delivery, optimal growing conditions, and reduced environmental stress in hydroponics. However, the higher initial setup cost of 16,000/hectare and annual operational costs of $16,000 per hectare and annual operational costs of $5,250 per hectare make hydroponics a more capital-intensive option. Despite these higher costs, the increased yields and revenues result in greater annual profits, making hydroponics an attractive choice for farmers with access to financial resources and technical expertise, particularly in water-scarce regions like Jordan. On the other hand, DI remains a practical and cost-effective alternative, especially for small-scale farmers or those with limited resources. With an initial setup cost of $4,000 per hectare and annual operational costs of $4,000 per hectare and annual operational costs of $4,050 per hectare, DI is significantly more affordable than hydroponics. While the yields and profits are lower compared to hydroponics, DI still provides substantial economic benefits, particularly in areas with suitable soil conditions. The system's efficiency in water and nutrient delivery ensures that it remains a viable option for sustainable agriculture in arid regions. Ultimately, the choice between DI and hydroponics depends on factors such as financial capacity, technical expertise, and local growing conditions, with both systems offering valuable solutions for improving crop productivity and resource efficiency.

Future Directions: Future research should focus on addressing the challenges associated with both DI and HS through technological innovations, capacity building, and policy support. For example, the development of low-cost, low-energy HS could make this technology more accessible to smallholder farmers in dry regions. Similarly, advancements in DI technology, such as the use of solar-powered pumps and smart sensors, could enhance system efficiency and reduce operational costs (Kumar et al., 2024). Policymakers and stakeholders must also work together to promote the adoption of sustainable irrigation practices through incentives, education, and infrastructure development.

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