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## Optimizing Water and Energy Productivity in Greenhouse Bell Pepper Cultivation Using Smart Irrigation Systems in North Sinai

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SMART irrigation systems (SIS) are valuable tools for scheduling irrigation and determining plant water requirements to optimize water use. In Egypt, SIS utilize cutting-edge technologies to enhance food security and improve water management. This study evaluates the impact of SIS on the energy productivity (EP) and water productivity (WP) of bell peppers grown under greenhouses in North Sinai. A split-plot design with three replicates was employed to compare SIS with traditional irrigation techniques (TIT) during the winter seasons of 2023–2024 and 2024–2025. The study examines water application, consumptive water use, irrigation efficiency, crop yield, WP, EP, and economic performance while testing surface drip irrigation at a depth of 0 cm (D0) and subsurface drip irrigation at depths of 10 cm (D10), 20 cm (D20), and 30 cm (D30). Compared to TIT, SIS with D10 reduced water application by 27.1% and 27.4% in the first and second seasons, respectively. Additionally, under SIS,total yield increased by 36.9% and 34.0% compared to D0 (control). WP improved by 32.4% and 31.8% in both seasons, while EP exceeded that of TIT by 34.8% and 34.5%. The highest net return (NR) was observed at D10 in SIS, reaching 28,623 L.E. in 2023–2024 and 43,472 L.E. in 2024–2025. Overall, in a recent study, Smart Irrigation Systems (SIS) **enhanced** crop yields, **conserved** water, and **improved** irrigation efficiency in greenhouse bell pepper cultivation. Their adaptability supports sustainable agriculture, making them suitable for various crops and climates. Future research integrating SIS with precision fertigation and renewable energy could further enhance both efficiency and sustainability.

**Keywords:** Irrigation efficiency (IE), Subsurface Drip Irrigation (SSDI), Surface Drip Irrigation (SDI).

### 1.Introduction

Water scarcity is one of the most pressing challenges globally, particularly in arid and semi-arid regions like Egypt (**Gohar and Ward, 2013**). With added pressures from population growth, urbanization, and climate change, managing water resources efficiently is critical to sustaining agricultural productivity. In such regions, improving irrigation practices is essential for enhancing water use efficiency (WUE) and ensuring long-term food security (**Abd El-Aty et al., 2023; Walters and Jha, 2016).** Bell pepper (*Capsicum annuum L.*) is a high-value crop known for its rich water content and nutritional benefits (**Kwon et al., 2023**). Globally, it is cultivated on approximately 2 million hectares, yielding 36 million tons annually (**FAO, 2023**). In Egypt, traditional farmland produces 411,116 tons from 18,354 hectares, while newly reclaimed regions, including North Sinai and Ismailia, contribute 459,027 tons from 20,422 hectares (**Ministry of Agriculture, 2023)**. However, bell pepper is highly sensitive to water stress particularly during flowering and fruiting stages making efficient irrigation crucial (**Steduto et al., 2012**).

Greenhouse cultivation of bell peppers demands significant water and energy inputs. Research shows that mild deficit irrigation can reduce water use without compromising yield or fruit quality (**Kabir, 2021**). Therefore, adopting effective water management strategies is key to improving productivity. Smart irrigation systems (SIS) offer a promising solution by integrating sensor-based monitoring, automated controls, and data-driven decision-making. These technologies optimize water delivery, minimize waste, and reduce operational costs, thereby enhancing both water and energy productivity (**Fernández et al., 2020**). Water productivity (WP) the yield obtained per unit of water used is particularly vital in water-scarce regions, as agriculture consumes over 80% of global freshwater supplies (**Tzanakakis et al., 2020**). Addressing water scarcity through efficient irrigation is also essential for mitigating climate change impacts and ensuring sustainable food production (**Mukherjee et al., 2023; Liao et al., 2021; Yang et al., 2024).** Enhancing WP supports the growth of controlled-environment agriculture, such as greenhouses, by optimizing irrigation schedules and minimizing losses (**Wu et al., 2022;**

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**Parkash et al., 2020**). Poor irrigation management can result in waterlogging, under-watering, and nutrient leaching, reducing both yield and efficiency (**Koech et al., 2018; Broner et al., 2024**). Advanced systems use real-time data on soil moisture, weather, and plant status to guide irrigation decisions (**Dong, 2024; Wang et al., 2015**). Although manual methods are still common, modern sensor-based techniques offer greater accuracy and efficiency (**Rasheed et al., 2022**). Among modern irrigation methods, subsurface drip irrigation (SSDI) has demonstrated superiority over surface drip irrigation (SDI) in improving crop yield, vegetative growth, and WUE (**Tolba et al., 2023**). SSDI reduces water losses from evaporation and runoff, enhances root-zone distribution, and lowers labor and operational costs (**Yao et al., 2021**). It can reduce water use by 25–50% compared to conventional surface systems, making it a viable option for sustainable agriculture in North Sinai.

Energy use is another critical aspect of greenhouse farming. Efficient irrigation systems help lower energy consumption associated with water pumping and environmental control systems, thus reducing costs and environmental impact (**Lopez et al., 2021**). Enhancing both WP and energy productivity (EP) through SIS aligns with the Sustainable Development Goals (SDGs), promoting resource conservation and agricultural resilience. This study evaluates the effectiveness of smart irrigation systems in enhancing water and energy productivity in greenhouse-grown sweet peppers in North Sinai. The specific objectives are to (1) determine optimal irrigation strategies that balance crop yield, energy use, and water efficiency under controlled conditions., (2) compare water productivity (WP) and energy productivity (EP) between subsurface drip irrigation (SSDI) and surface drip irrigation (SDI), and (3) assess differences in yield, irrigation performance, and water application efficiency between automated smart systems and traditional irrigation methods. By integrating advanced irrigation technologies, this research aims to contribute to sustainable agricultural development and resilient farming systems in North Sinai and similar arid regions.

## 2. Materials and Methods

### 2.1. Study Location and Experimental Design

The experiments were conducted at the Experimental Farm of El-Arish University, Faculty of Environmental Agricultural Sciences, located at 31°0'8" N latitude and 33°0'49" E longitude, with an elevation of 18.78 meters above mean sea level. North Sinai is characterized by an arid climate, sandy soils, and limited freshwater resources, making agriculture a challenging yet vital sector for local development. Despite these harsh conditions, the region has seen increasing efforts to expand agricultural activities, particularly through controlled-environment farming such as greenhouse cultivation. However, growing competition for water resources, coupled with climate change, threatens the sustainability of agricultural production (**El-Sawy et al., 2022; El-Sayed et al., 2022**). In such regions, improving irrigation management is crucial for enhancing water-use efficiency and sustaining agricultural productivity (**Abd El-Aty et al., 2023**). The study spanned the winter growing seasons of 2023-2024 and 2024-2025. Bell peppers Hybrid F1 Lamuyo type, was planted in a 9 × 60 m plastic greenhouse. In the greenhouse, 1,500 plants were planted in ten rows of five lines, 180 cm width for each, with 40 cm between plants. Each pair of rows represented one treatment, while the first two rows acting as borders. In particular, two rows were allocated for each irrigation treatments (D0, D10, D20, and D30). In order to accommodate the two irrigation systems, the greenhouse was divided into two areas, 30 x 9 meters for each. The first area was used for the smart irrigation system (SIS), while the second section was used for the traditional irrigation technique (TIT). Each area was separated to three pieces, representing three replications (Fig.1b&c). In a split-plot design with three replicates, the experiment evaluated two irrigation techniques as main plot treatments:

1. Smart Irrigation System (SIS): This system applied irrigation water automatically based on soil moisture sensors at the required depths and the data from an automatic weather station.

2. Traditional Irrigation Technique (TIT): In this system, irrigation water was applied manually, mimicking the conventional practices typically followed by the farmers.

Both techniques were tested under surface irrigation (D0) and sub-surface irrigation systems at depths of 10 cm (D10), 20 cm (D20), and 30 cm (D30), which served as sub-plot treatments.

### 2.2. System Installation

A 1 HP engine-powered pump with an 80 cm vertical head and a 3 $m^3$/h discharge capacity was one of the irrigation system's components. Additionally installed were a flow meter, control valves, pressure gauges, regulator, screen filter, and backflow protection device. PVC pipes with an outer diameter (OD) of 63 mm comprised the main line, which transported water from the source to the greenhouse's primary control stations. PE pipes with an OD of 40 mm were used to build the sub-main lines, which were connected to 60-meter-long lateral drip lines built of PE with an ID of 16 mm. With a discharge rate of 4 ℓ/h per 100 meters, the emitters on these lines were 40 cm apart. In surface irrigation, the GR drippers were 40 cm apart, and the pipes were 16 mm in diameter. The 16 mm diameter porous pipes for subsurface irrigation were buried 10 cm, 20 cm, and 30 cm below the surface.

### 2.3. Soil Analysis

Soil samples were collected before planting and analyzed for their physical and chemical properties according to the methods described by **Sparks (2020).** Soil texture is sandy (sand content ranging from 88.5% to 90.9%). Soil pH varied between 8.1 and 8.7, with an average of 8.3, while electrical conductivity (EC) ranged from 0.46 to 0.72 dS·m$^{-1}$. Selected physical and chemical characteristics of the study soil are presented in Table 1.

**Table 1. Some soil physical and chemical properties of the study soil.**

| Depth (cm) | Sand (%) | Silt (%) | Clay (%) | Texture | FC (%) | PWP (%) | AW (%) | Bd (kg/m³) | pH | EC (dS/m) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0-15 | 88.6 | 3.5 | 7.9 | Sandy | 17.21 | 7.37 | 9.85 | 1.53 | 8.1 | 0.68 |
| 15-30 | 88.5 | 3.8 | 7.7 | Sandy | 17.58 | 7.14 | 10.44 | 1.52 | 8.3 | 0.72 |
| 30-45 | 89.7 | 3.2 | 7.1 | Sandy | 17.13 | 7.35 | 9.78 | 1.56 | 8.5 | 0.61 |
| 45-60 | 90.9 | 1.8 | 7.3 | Sandy | 17.05 | 7.11 | 9.94 | 1.53 | 8.7 | 0.46 |

**FC** Field capacity**, PWP** permanent wilting point**, AW** available water**, Bd** Bulk density, **pH** potential of Hydrogen and **EC** Electrical conductivity

Figure 1a represents an experimental approach to assessing smart vs. traditional irrigation methods in greenhouse-grown bell peppers. It explores how different irrigation depths impact water use, productivity, and economic feasibility, with the goal of identifying the most efficient and sustainable irrigation strategy.

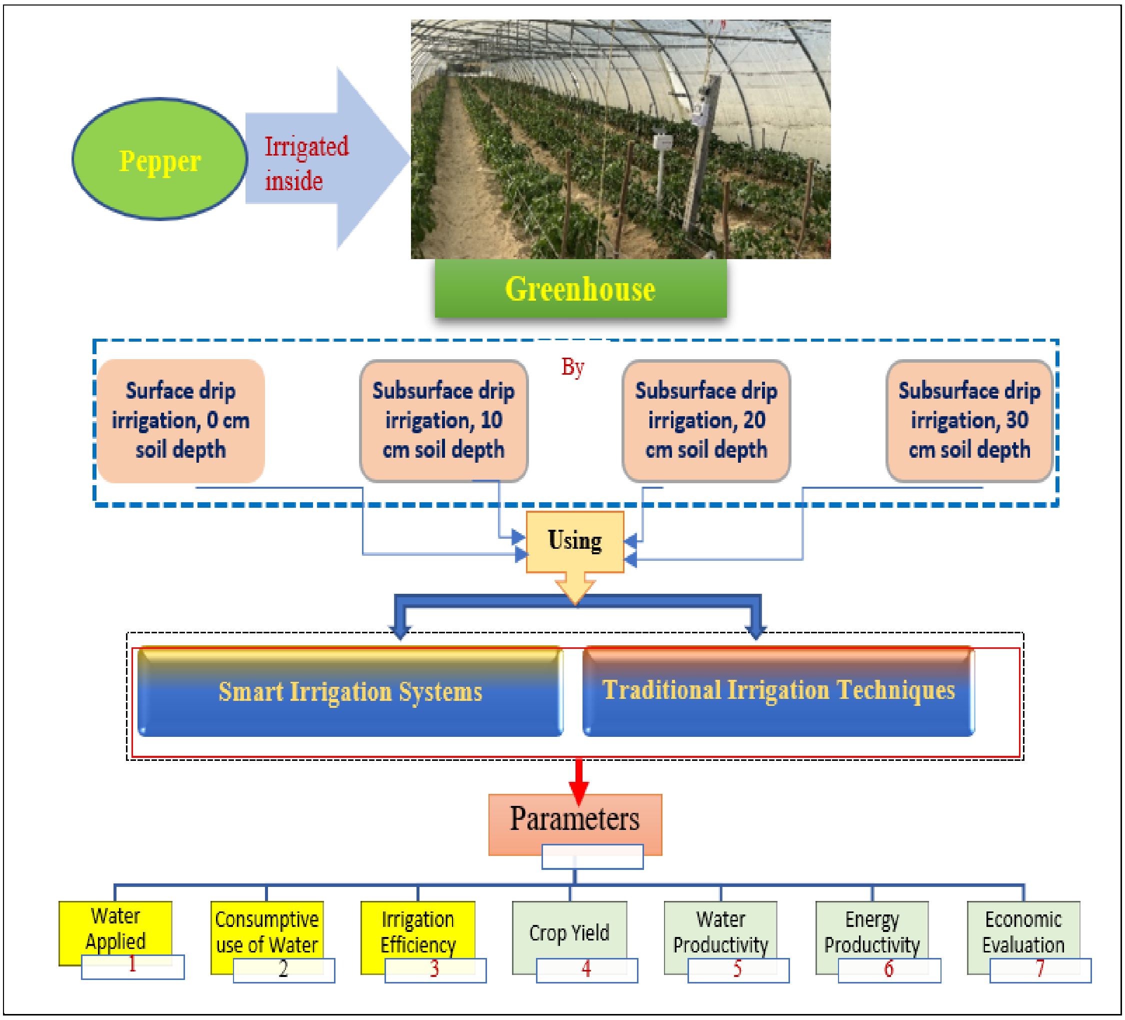
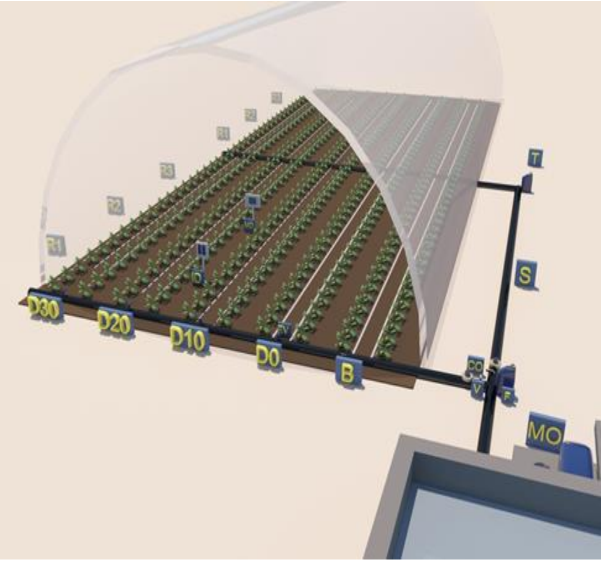



**Fig. 1a. General overview of the greenhouse experiment and studied parameters.**




B

C

S: Smart irrigation,
T: Traditional irrigation,
B: Border,
D0: Surface irrigation,
D10: Subsurface irrigation (10 cm),
D20: Subsurface irrigation (20 cm),
D30: Subsurface irrigation (30 cm),
ID: Irrigation device,
MD: Meteorological device,
V: Valve,
EV: Electric valve,
F: Fertilizer,
Co: Counter,
MO: Motor,
R1, R2, R3: Three replicates


D


E

**Fig. 1. Growing bell pepper in North Sinai.**

B. Schematic diagram showing the distribution of treatments as related to the layout of the experiment,
C. An experiment comparingSIS andTIT,
D. Automatic irrigation system controlling water application based on soil moisture data and environmental condition.
E. TDR sensor used for real-time soil moisture monitoring to optimize irrigation scheduling.

### 2.4. Irrigation Water Quality

Table 2 presents the chemical composition of the irrigation water, analyzed according to **APHA (2017).** The water exhibits a neutral to slightly alkaline pH (7.73) and low electrical conductivity (EC = 0.52 dS/m), indicating low salinity and making it suitable for irrigation use. The sodium adsorption ratio (SAR) is 3.60, reflecting a moderate sodicity risk; however, it remains within acceptable limits for most agricultural applications. The concentrations of major cations sodium ($Na^+$, 3.5 meq/L), calcium ($Ca^{2+}$, 0.8 meq/L), magnesium ($Mg^{2+}$, 1.1 meq/L), and potassium ($K^+$, 0.1 meq/L) are within safe thresholds for irrigation water. Similarly, the dominant anions include chloride ($Cl^-$, 2.5 meq/L), bicarbonate ($HCO_3^-$, 2.5 meq/L), and sulfate ($SO_4^{2-}$, 0.5 meq/L). Carbonate ($CO_3^{2-}$) was not detected, minimizing concerns related to alkalinity hazards.The analysis of soluble cations, anions, pH, and EC followed the procedures described by **Estefan et al. (2013).** The SAR was calculated using the equation proposed by **Richards (1954):**

$$SAR=\frac{[Na^+]}{\sqrt{([Ca^{2+}]+[Mg^{2+}])/2}}$$

where the amounts of Na, Ca, and Mg are given in milliequivalents per liter (mEq/L). When all concentrations are given in milliequivalents of charge per liter, the sodium adsorption ratio (SAR) is a number that indicates the proportion of sodium ions to the total quantity of calcium and magnesium ions in water.

**Table 2. Chemical Composition of Irrigation Water.**

| Parameter | pH | EC (dS $m^{-1}$) | SAR | $Na^+$ | $Ca^{++}$ | $Mg^{++}$ | $K^+$ | Cl- | $CO_3^-$ | HCO3- | $SO_4^=$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fresh water | 7.73 | 0.52 | 3.60 | 3.5 | 0.8 | 1.1 | 0.1 | 2.5 | 0.0 | 2.5 | 0.5 |

### 2.5. Water Applied ( $m^3/m^2$)

Water applied was measured using volumetric meters. The smart irrigation system (SIS) was activated when 50% of plant-available water (PAW) was depleted, following the recommendations of Johnson et al. (2018), using an automatic humidity control device (Fig. 1d). In contrast, the traditional irrigation technique (TIT) was implemented based on conventional farmer practices. Soil moisture was monitored using a Time Domain Reflectometry (TDR) probe (Fig. 1e), calibrated using the thermogravimetric method (Gardner, 1986).

### 2.6. Smart Irrigation System Components and Operation

Arduino is an open-source platform for electronics prototyping, built on adaptable and user-friendly hardware and software. By gathering data from various sensors, the Arduino Uno (Fig. 2) can detect environmental conditions and influence them by controlling actuators, motors, lights, and other devices. An Arduino board consists of an Atmel 8-bit AVR microcontroller and supporting components that facilitate programming and integration into other circuits.

Figure 2 also presents the ESP32-Devkit V1 microcontroller, which managed irrigation using Wi-Fi and Bluetooth for remote monitoring.

**System Components**

Valves: Four solenoid valves controlled water flow.

Relays: Allowed the ESP32 to regulate high-power valves.

Power Supply: 5V for the ESP32, 24V for the valves.

**System Operation:**

1. Component Integration: The ESP32, sensors, valves, relays, and power supply were connected.

2. ESP32 Programming: Irrigation started when soil moisture dropped below WP + 50% PAW (12.25%) and stopped at field capacity (17.25%).

3. Monitoring: Sensors were placed in the root zone, with remote tracking enabled via Wi-Fi.

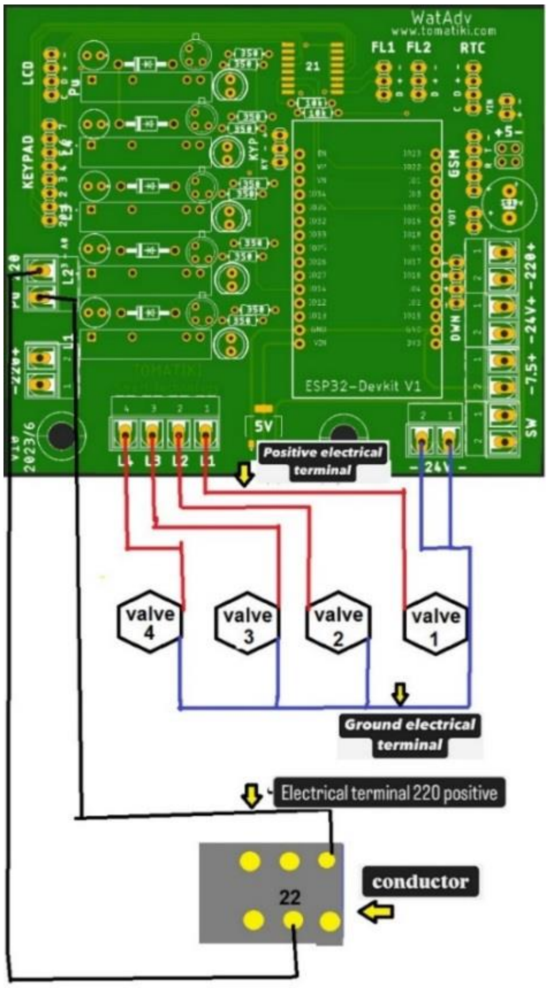



**Fig. 2. Smart Irrigation System Circuit Diagram with ESP32 Controller and Solenoid Valves.**

### 2.7. Consumptive Use of Water (CU)

Calculated following Chauhan and Sharma (2021):

$$\mathrm{CU} = D \times AD \frac{W_1 - W_2}{100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where: CU = Consumptive use (cm), D = Irrigated soil depth (cm), AD = Bulk density (g/cm³) and $W_1$, $W_2$ = Soil moisture before/after irrigation

### 2.8. Irrigation (Efficiency IE)

Following Pereira et al. (2012):

$$\text{Irrigation Efficiency} = \frac{Water\ Stored\ in\ the\ Root\ Zone\ (m^3)}{Water\ Applied\ (m^3)} \times 100 \ldots\ldots\ldots\ldots\ldots (2)$$

### 2.9. Yield and Water Productivity

**Yield Assessment:** 72 plants per replicate (n=3) were harvested at commercial maturity.

**Water Productivity (WP)** [(Naroua et al., 2014)]:

$$\mathrm{WP(kg/m^3)} = \frac{Total\ Fruit\ weight(kg)}{The\ amount\ of\ water\ used(m^3)} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

### 2.10. Energy Productivity (EP)

(EP) refers to the crop Energy Productivity yield produced per unit of energy consumed (kg/kWh). The formula for EP is:

$$EP = \frac{\text{Yield}}{Energy\ Consumption} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Total Energy = Power × Irrigation Time × Irrigation Frequency……………...  …... (5)

Smart Irrigation:

$= 0.746 \times (25/60)\ 80 = 24.864\ /270\ m^2 = 0.0921\ kWh.m^{-2}$

Traditional Irrigation:

$= 0.746 \times (35/60)\ 80 = 34.614\ /270\ m^2 = 0.128\ kWh.m^{-2}$

### 2.11. Economic Evaluation

The Benefit-Cost Ratio (BCR) associated with irrigation was calculated following the methodology proposed by Li et al. (2005) using the following formulas:

The Benefit-Cost Ratio (BCR) associated with irrigation was calculated following the methodology proposed by Li et al. (2005) using the following formulas:

Net Return (NR) = Gross Revenue – Total Costs …………………………..…………… (6)

BCR = NR / Total Costs ………………………………………………………………… (7)

### 2.12. Statistical Analyses

Duncan's Multiple Range Test was used to compare the means of the different treatments, with a significance level of P < 0.05. Based on Gomez and Gomez (2016), the CoStat computer software package (Version 6.303, CoHort, USA, 1998-2004) was used to conduct this analysis.

## 3. Results

### 3.1. Water Applied (Wa)

The total water applied (Wa) during two growing seasons (2023–2024and 2024-2025) utilizing Smart Irrigation Systems (SIS) and Traditional Irrigation Techniques (TIT) is contrasted in the fig3.According to the findings, SIS considerably decreased water use when compared to TIT, particularly when planted at a depth of 10 cm (D10), with D10 providing the most effective irrigation. In the first season, SIS and TIT used 0.35 and 0.48 $m^3/m^2$ of water, respectively, whilst in the second season, SIS and TIT used 0.36 and 0.48 $m^3/m^2$, respectively. With SIS, water usage was reduced by 27.1% in the first season and by 27.4% in the second. Despite a minor rise in water consumption during the second season, SIS's overall effectiveness stayed stable, proving its superiority over TIT in terms of water conservation.

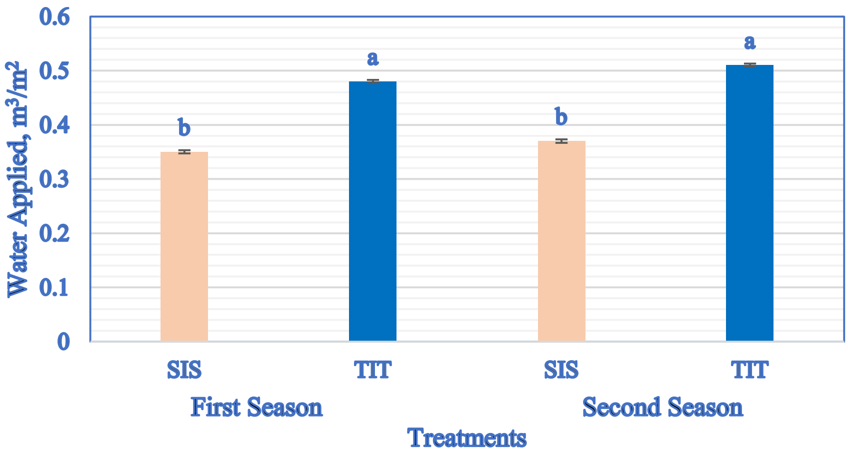



**Fig. 3. Water Applied, Wa ($m^3m^{-2}$) using smart irrigation system (SIS) and traditional irrigation technique (TIT) over two seasons.**

Bars represent ± S.E. Bars with the same letters are not significantly different (*P* < 0.05 level).

### 3.2. Water consumptive use

Figure 4 illustrates the consumptive water use (m³/m²) under the Smart Irrigation System (SIS) and the Traditional Irrigation Technique (TIT) over two consecutive growing seasons (2023–2024 and 2024–2025). Water consumption values for the SIS were significantly lower (0.35 and 0.37 m³/m²) than those for the TIT (0.45 and 0.46 m³/m²) in the first and second seasons, respectively.

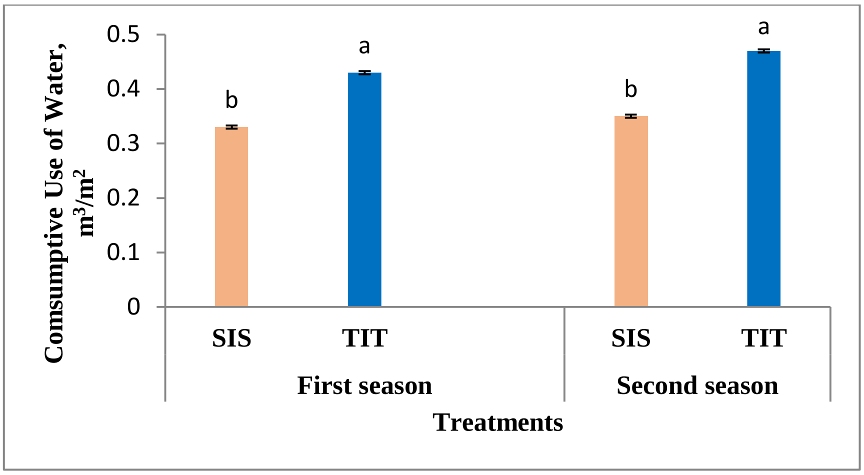



**Fig.4. Water Consumptive Use ($m^3$ $m^{-2}$) for Smart Irrigation System (SIS) and Traditional Irrigation Technique (TIT) Over Two Seasons.**

Bars represent ± S.E. Bars with the same letters are not significantly different ($P < 0.05$ level).

### 3.3. Irrigation Efficiency (IE)

As shown in Fig. 5, the irrigation efficiency of SIS generally exceeds that of TIT in both seasons, as indicated by the taller bars for SIS across all depth categories. For SIS maximum irrigation efficiency was observed at D10 (97.14% in 2023-2024, 92.74% in 2024-2025) suggesting that shallow subsurface irrigation is optimal. For TIT, irrigation efficiency gradually decreased as depth increased with the lowest efficiency recorded at D30.

The overall irrigation efficiency of both techniques declined slightly in 2024-2025 compared to 2023-2024:2023-2024 Season SIS Mean Irrigation Efficiency 93.57%, TIT Mean Irrigation Efficiency 88.02%.2024-2025 Season: SIS Mean Efficiency**:** 90.45%**,** TIT Mean Efficiency: 86.32%.

### 3.4. CropYield (kg/m²)

The SIS system generally produced higher crop yields than the TIT system across all depths in both seasons. The highest yield in both seasons was observed at D10 (subsurface drip irrigation at 10 cm depth), achieving 8.33 kg/m² in the first season and 7.92 kg/m² in the second under SIS, suggesting that this depth provides optimal irrigation for crop growth. In contrast, the D30 treatment under TIT produced the lowest yield, with 3.64 kg/m² in the first season and 3.46 kg/m² in the second. These findings highlight the importance of selecting the appropriate irrigation depth to optimize agricultural output (Table 3).

### 3.5. Water Productivity (kg/m³)

Data in Table 3 showed that SIS consistently outperforms TIT in terms of water productivity at all depths in both seasons. The highest water productivity in both seasons was observed at D10 under SIS, with values reaching 23.80 kg/m³ in the first season and 23.26 kg/m³ in the second season. The lowest water productivity occurred at D30, particularly under TIT, reflecting inefficiency at deeper irrigation depths. Among different depths, the water productivity values at D10 under SIS (23.80 and 23.26 kg/m³, in the 1st and 2nd season, respectively) was significantly higher than those at the other depths D0 (14.74 and 14.43 kg/m³), D20 (15.08 and 14.97 kg/m³) and D30 (11.34 and 11.27 kg/m³), fof the same seasons, respectively.

### 3.6. Energy Productivity (kg/kWh)

Energy Productivity values are presented in Table 3**.** SIS yields better energy productivity compared to TIT, particularly at D10. In the first season, SIS at D10 achieved 90.45 kg/kWh, while TIT at the same depth yielded only 60.31 kg/kWh. The corresponding values in the 2nd season were 86.03 and 57.27 kg/kWh, respectively. As with yield and water productivity, D30 consistently shows the lowest energy productivity across both systems and seasons. Similar to the previous parameters, energy productivity is significantly higher under SIS at D10 compared to other treatments. Overall, SIS consistently outperforms TIT in yield, water productivity, and energy productivity across all irrigation depths. Subsurface drip irrigation at a depth of 10 cm (D10) is the most efficient in terms of water productivity, energy productivity, and crop yield in both seasons. However, as irrigation depth increases (from D0 to D30), the performance of both SIS and TIT declines, with D30 showing the lowest productivity across all measures.

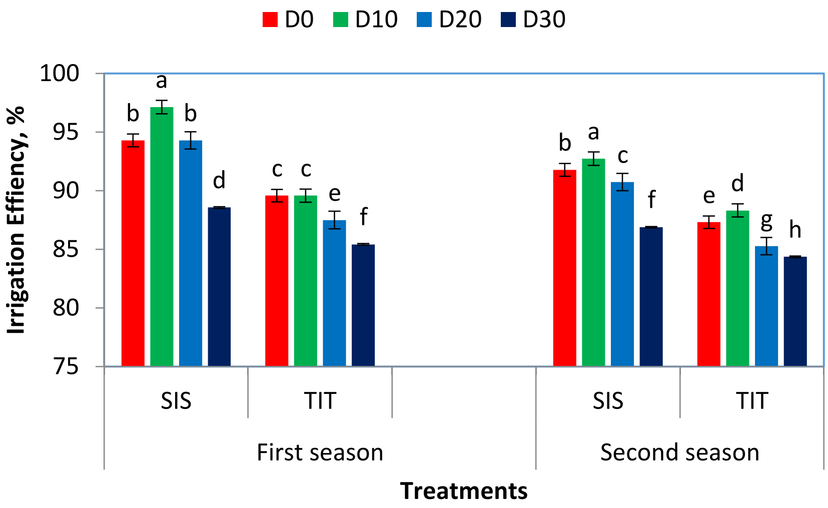



**Fig. 5. Irrigation efficiency for different irrigation techniques SIS and TIT under surface (D0) and subsurface D10, D20, and D30 in the 2023-2024 and 2024-2025 seasons.**

Bars represent ± S.E. Bars with the same letters are not significantly different (*P* < 0.05 level).

**Table 3. Effects of Irrigation Technique and Drip Irrigation Depth (Surface and Subsurface) on Yield, Water Productivity, and Energy Productivity of Greenhouse Bell Pepper During the First (2023–2024) and Second (2024–2025) Seasons.**

| | First season 2023-2024 | | | Second season 2024-2025 | | |
|---|---|---|---|---|---|---|
| | Yield (kg /$m^2$) | Water productivity (kg/$m^3$) | Energy productivity (kg/kWh) | Yield (kg /$m^2$) | Water productivity (kg/$m^3$) | Energy productivity (kg/kWh) |
| **Effect of irrigation technique** | | | | | | |
| SIS | **5.83 a** | 16.24 a | 63.32 a | 5.54 a | 15.99 a | 60.61 a |
| TIT | **5.32 b** | 10.83 b | 41.61 b | 5.06 b | 10.76 b | 39.65 b |
| **Effect of surface drip irrigation (D0) and subsurface drip irrigation at 10,20 and 30cm depth** | | | | | | |
| $D_0$ | 5.50 b | 12.42 b | **51.72 b** | 5.225 b | 12.32 b | 49.53 b |
| $D_{10}$ | 8.06 a | 19.94 a | **75.38 a** | 7.62 a | 19.61 a | 71.65 a |
| $D_{20}$ | 4.98 c | 12.32 b | **46.98 c** | 4.74 c | 12.17 b | 45.02 c |
| $D_{30}$ | 3.80 d | 9.46 c | **35.79 d** | 3.615 d | 9.40 c | 34.34 d |
| **Interaction between surface and subsurface drip irrigation × irrigation technique** | | | | | | |
| $D_0$ × SIS | 5.75 c | 14.74 c | 62.43 b | 5.48 c | 14.43 c | 59.54 b |
| $D_{10}$ × SIS | 8.33 a | 23.80 a | 90.45 a | 7.92 a | 23.26 a | 86.03 a |
| $D_{20}$ × SIS | 5.28 d | 15.08 c | 57.33 c | 5.09 d | 14.97 c | 55.27 c |
| $D_{30}$ × SIS | 3.97 f | 11.34 d | 43.11 d | 3.83 f | 11.27 d | 41.62 d |
| $D_0$ × TIT | 5.25 d | 9.90 e | 41.02 d | 5.06 d | 9.92 e | 39.53 d |
| $D_{10}$ × TIT | 7.72 b | 16.08 b | 60.31 b | 7.33 b | 15.93 b | 57.27 bc |
| $D_{20}$ × TIT | 4.69 e | 9.77 e | 36.64 e | 4.45 e | 9.67 e | 34.77 e |
| $D_{30}$ × TIT | 3.64 g | 7.59 f | 28.48 f | 3.46 g | 7.52 f | 27.06 f |

Means with different letters in the same column or row are statistically different at 0.05 level, SIS smart irrigation system and TIT traditional irrigation technique, $D_0$ Surface irrigation, $D_{10}$ sub surface 10cm depth. $D_{20}$ sub surface 20cm depth, $D_{30}$ sub surface 30cm.

### 3.7. Economic Evaluation

The data in Table 4&5 presents the requirements for planting a 9 × 60 m greenhouse cultivated with pepper in the El-Arish region during the winter seasons of 2023–24 and 2024–25. Fixed costs remain the same across both seasons, while variable costs increased in the second season due to rising input costs (seedlings, labor, fertilizers, and energy). Overall production costs increased from the first to the second season, mainly driven by variable costs. However, the cost of smart irrigation system equipment remains constant at 20,000 L.E, with an annual share of 2,000 L.E per season, based on an expected lifespan of 10 years. The total cultivation cost (TCC) for the traditional irrigation technique (TIT) was 36,850 L.E in the first season and 40,100 L.E in the second season, while for the smart irrigation system (SIS), it was 38,850 L.E and 42,100 L.E, respectively.

**Table 4. Fixed and Variable Costs of Sweet Pepper Production in Greenhouse during the First and Second Seasons.**

| Item | Cost (L.E) | Useful Life (Years) | First season L.E | Second season L.E |
|---|---|---|---|---|
| **Fixed Costs** | | | | |
| Greenhouse Structure | 40,000 | 5 | 8,000 | 8,000 |
| Plastic Cover | 20,000 | 2 | 10,000 | 10,000 |
| Irrigation Network | 5,000 | 5 | 1,000 | 1,000 |
| Irrigation Motor | 3,000 | 5 | 600 | 600 |
| Tools and Accessories | 2,000 | 2 | 1,000 | 1,000 |
| **Irrigation equipment consumption (SIS only)** | **20000** | **10** | **2000** | **2000** |
| **Total Annual Fixed Costs** | | | **22,600** | **22,600** |
| **Variable Costs** | | | | |
| Pepper Seedlings (2500 seedlings × 1.5 L.E) | 3,750 | | 3,750 | 4,500 |
| Fertilizers and Pesticides | 4,000 | | 4,000 | 4,800 |
| Labor Costs | 6,000 | | 6,000 | 7,200 |
| Energy for Irrigation Motor | 1,500 | | 1,500 | 1,800 |
| Maintenance | 1,000 | | 1,000 | 1,200 |
| **Total Variable Costs** | **16,250** | | **16,250** | 19,500 |
| **TCC** | | | **38850** | 42100 |

**Table 5. Yield (kg/540 m²) and Total Revenue (L.E) as affected by irrigation technique, irrigation depth, and their interaction during the 1st and 2nd seasons.**

| Treatment | 1st season 2023-2024 | | 2nd season 2024-2025 | |
|---|---|---|---|---|
| | Yield (kg /540m²) | Total Revenue (TR) (L.E)) | Yield (kg /540m²) | Total Revenue (TR) (L.E)) |
| **Effect of irrigation technique** | | | | |
| SIS | 3149.6 a | 47243a | 3014 a | 60291 a |
| TIT | 2876.2 b | 43142b | 2740 b | 54819 b |
| **Effect of irrigation depth (surface and subsurface at 0, 10, 20, and 30 cm)** | | | | |
| $D_0$ | 2970.6 b | 44550 b | 44550 b | 56934 b |
| $D_{10}$ | 4333.5 a | 65002 a | 65002 a | 82368 a |
| $D_{20}$ | 2691.9 c | 40378 c | 40378 c | 51516 c |
| $D_{30}$ | 2056.6 d | 30840 d | 30840 d | 39402 d |
| **Interaction between surface and subsurface drip irrigation × irrigation technique** | | | | |
| $D_0$ × SIS | 3105 c | 46575 c | 2961 c | 59220 c |
| $D_{10}$ × SIS | 4498.2 a | 67473 a | 4278 a | 85572 a |
| $D_{20}$ × SIS | 2851.2 d | 42768 d | 2748 d | 54972 d |
| $D_{30}$ × SIS | 2143.8 f | 32157 f | 2070 f | 41400 f |
| $D_0$ × TIT | 2835.0 d | 42525 d | 2732 d | 54648 d |
| $D_{10}$ × TIT | 4168.8 b | 62532 b | 3968 b | 79164 b |
| $D_{20}$ × TIT | 2532.6 e | 37989 e | 2403 e | 48060 e |
| $D_{30}$ × TIT | 1968.3 g | 29524 g | 1870 g | 37404 g |

Note:
- SIS: Surface Irrigation System; TIT: Traditional Irrigation Technique.
- D0: Surface drip irrigation; D10, D20, D30: Subsurface drip irrigation at 10, 20, and 30 cm, respectively.
- Means within each column followed by different letters are significantly different at P ≤ 0.05

The price of 1 kg of pepper was 15 L.E in the first season and 20 L.E in the second season

### 3.8. The Net Return (NR) and Benefit-Cost Ratio (BCR)

Table 6. Presents the Net Return (NR) in both seasons, SIS consistently achieved higher NR than TIT, demonstrating the economic advantage of smart irrigation. The highest NR was observed at D10 in SIS, with 28623 L.E in 2023–2024 and 43472 L.E in 2024–2025, followed by D0, D20, and D30, respectively. TIT resulted in lower net returns across all treatments, with the lowest values recorded at D30, where both SIS and TIT showed negative returns in the first season -6693 L.E and -5570 L.E, respectively), indicating economic losses at this depth. However, in the second season, D30 in SIS improved slightly, yielding NR of -700 L.E, while TIT remained lower at -2696 L.E. On average, SIS outperformed TIT across all treatments, achieving mean NR values of 8393L.E in 2023–2024 and 18191L.E in 2024–2025, compared to TIT's 6293L.E in 2023–2024 and 14719L.E in 2024–2025

Similar trends are observed in the BCR data, which show that SIS consistently outperformed TIT across all treatments. BCR was observed at D10 in SIS, with 0.74 in 2023–2024 and 0.97 in 2024–2025, D10 in SIS had the highest BCR, demonstrating a significant economic return per unit cost. In contrast, D30 had the lowest BCR values; in the first season, its values were negative (-0.17 for SIS and -0.15 for TIT), indicating monetary losses. The mean BCR values 0.22 in 2023–2024 and 0.43 in 2024–2025 for SIS, and 0.17 in 2023–2024 and 0.37 in 2024–2025 for TIT further confirm SIS's superior financial performance.

SIS consistently achieved higher net return NR than TIT, demonstrating the economic advantage of smart irrigation. The highest NR was observed at D10 in SIS, with 28623 L.E in 2023–2024 and 43472 L.E in 2024–2025.

**Table 6. Net Return and Benefit-Cost Ratio for Different Irrigation Treatments and Techniques in the 1st and 2nd Seasons.**

| Treatment | 1st Season (2023–2024) | | 2nd Season (2024–2025) | |
|---|---|---|---|---|
| | Net Return (L.E) | Benefit-Cost Ratio (BCR) | Net Return (L.E) | Benefit-Cost Ratio (BCR) |
| **Effect of irrigation technique** | | | | |
| SIS | 8393 a | 0.22 a | 18191 a | 0.43 a |
| TIT | 6293 b | 0.17 b | 14719 b | 0.37 b |
| **Effect of irrigation depth (surface and subsurface at 0, 10, 20, and 30 cm)** | | | | |
| D0 | 6700 b | 0.20 b | 15834 b | 0.38 b |
| D10 | 27152 a | 0.74 a | 41268 a | 1.00 a |
| D20 | 2528 c | 0.05 c | 10416 c | 0.25 c |
| D30 | -7009 d | -0.16 d | -1698 d | -0.04 d |
| **Interaction between irrigation depth × technique** | | | | |
| D0 × SIS | 7725 c | 0.20 b | 17120 c | 0.41 b |
| D10 × SIS | 28623 a | 0.74 a | 43472 a | 1.03 a |
| D20 × SIS | 3918 d | 0.10 c | 12872 d | 0.31 c |
| D30 × SIS | -6693 f | -0.17 e | -700 f | -0.02 e |
| D0 × TIT | 7425 cd | 0.20 bc | 14548 cd | 0.36 bc |
| D10 × TIT | 27432 b | 0.74 a | 39064 b | 0.97 a |
| D20 × TIT | 2889 e | 0.00 d | 7960 e | 0.20 d |
| D30 × TIT | -5570 f | -0.15 e | -2696 f | -0.07 e |

Note:
- SIS: Surface Irrigation System; TIT: Traditional Irrigation Technique.
- D0: Surface drip irrigation; D10, D20, D30: Subsurface drip irrigation at 10, 20, and 30 cm, respectively.
- Means within each column followed by different letters are significantly different at $P \leq 0.05$.

The Total Cultivation Cost (TCC) for the traditional irrigation technique (TIT) was **36,850** L.E in the first season and **40,100** L.E in the second season, while for the smart irrigation system (SIS), it was **38,850** L.E and **42,100** L.E, respectively.

## 4.Discussion

The amount of water applied to the pepper crop depends on several factors, including the irrigation system, which is the focus of this research. The Smart Irrigation System (SIS) significantly reduced water application in the first and second seasons, respectively, compared to the Traditional Irrigation Technique (TIT). This reduction was achieved through precise water distribution, minimized evaporation, and real-time soil moisture monitoring, ensuring efficient water use. These findings confirm the effectiveness of SIS in reducing water application while sustaining optimal plant development, consistent with Abdel-Aziz et al. (2016).

Lower consumptive water use in SIS due to efficient water distribution, which minimized deep percolation losses and enhanced water availability for plant uptake Automated and precise irrigation scheduling further optimized crop water uptake and prevented over-irrigation, enhancing water-use efficiency (Zhang et al., 2019). In contrast, the Traditional Irrigation Technique (TIT) exhibited higher consumptive use due to increased surface runoff and deep percolation, leading to significant water losses and reduced irrigation efficiency (Hassanli et al., 2010).

Irrigation efficiency (IE) was significantly higher under the Smart Irrigation System (SIS) compared to the Traditional Irrigation Technique (TIT), primarily due to SIS's automated and real-time water delivery, which prevents over-irrigation (Yao et al., 2021). In contrast, TIT exhibited lower efficiency due to manual water application, increased surface evaporation, and the lack of dynamic adjustments. Deeper irrigation further reduced efficiency due to greater water losses from evaporation, lateral movement, and percolation (Shahrokhnia & Sepaskhah, 2018).

The highest crop yield in the first season was recorded at D10 under SIS, attributed to improved root-zone moisture retention and reduced surface evaporation, consistent with the findings of Rodríguez & Gil (2012) and Yao et al. (2021). Yield in the second season was slightly lower, likely due to seasonal variations in temperature, humidity, or soil conditions (Patanè et al., 2011). Conversely, the lowest yield was observed at D30 under TIT, likely resulting from inefficient water distribution and reduced oxygen availability in deeper soil layers (Seidel et al., 2015; Fernández et al., 2020).

Regarding water productivity (WP), the higher WP observed in SIS at D10 aligns with Li et al. (2018), who reported that smart irrigation increases crop yields, thereby enhancing water productivity. Conversely, the low WP at D30 under TIT was likely due to inefficient water use, deeper infiltration losses, and increased nutrient leaching beyond the root zone (Hassanli et al., 2010). D10 achieved the highest WP for both SIS and TIT, supporting the findings of Yao et al. (2021), who noted that subsurface drip irrigation (SSDI) minimizes evaporation and deep percolation. In contrast, the lowest WP was recorded at D30, likely due to increased water losses at greater depths (Seidel et al., 2015).

SIS also improves energy efficiency by optimizing water use (Lopez et al., 2021). The lowest energy productivity (EP) was recorded at D30 for both SIS and TIT, as deeper irrigation requires more energy and results in less efficient water uptake (Patanè et al., 2011). Energy productivity followed similar trends across both seasons, confirming the advantages of shallow irrigation for SSDI. The increase in EP at D10 can be attributed to optimal soil moisture at this depth, which ensures adequate water availability in the root zone while preventing excessive percolation (Rodríguez & Gil, 2012). Additionally, applying water below the surface reduces evaporation (Yao et al., 2021). Enhanced root efficiency under shallow subsurface irrigation supports stronger root development and improves water uptake (Fernández et al., 2020).

The decline in EP at D30 may be due to excessive irrigation depth, which reduces water accessibility for the crop's root system (Seidel et al., 2015). Furthermore, the higher energy demand for pumping water to greater depths increases overall energy consumption, thereby reducing energy productivity (Lopez et al., 2021). Overall, D10 (shallow subsurface irrigation) consistently yielded the best results in terms of yield, water productivity, and energy efficiency, whereas deeper irrigation at D30 resulted in lower productivity across all parameters.

The high net returns and benefit-cost ratios (BCR) at D10 indicate that subsurface irrigation at this depth optimally balances water use efficiency and crop yield (Yao et al., 2021). Negative NR and BCR values at D30 in the first season suggest that deeper irrigation may restrict water availability in the upper root zone, negatively affecting crop growth (Kandelous & Šimůnek, 2010). However, improved NR at D30 in the second season implies that root system adaptation and enhanced soil moisture retention may have mitigated these effects over time. The overall increase in net returns and BCR in the second season underscores the role of favorable climatic factors and efficient irrigation management in improving economic outcomes.

## 5. Conclusion

This study demonstrates that smart irrigation systems (SIS) significantly outperform traditional techniques (TIT) by reducing water use by 27% while maintaining or increasing crop yields. Subsurface drip irrigation at 10 cm depth (D10) was the most effective, improving water productivity by over 30% and energy productivity by 34% over two seasons. D10 also yielded the highest economic returns, confirming its viability for resource-scarce regions. The findings support wider adoption of SIS to enhance efficiency, sustainability, and profitability in agriculture. Future research should investigate the long-term impacts of SIS on soil health, economic feasibility, and its integration with technologies such as precision fertigation, renewable energy, and remote sensing to further optimize resource use in agriculture.

**Declarations**

**Ethics approval and consent to participate**

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**References**

Abd El-Aty MS, Kamara MM, Elgamal WH, Mesbah MI, Behiry SI, Abo-Marzoka SA (2023). Influence of foliar supplied of some biostimulants on physiological, agronomic characters and water productivity of rice under water deficit and normal conditions. Egypt. J. Soil Sci., 63(4): 455–464.

Abdel-Aziz, A. A. (2016). Effect of intelligent irrigation technique on water use efficiency for cucumber and pepper crops in New Salhia Area, Egypt. *Journal of Soil Science*, 56(4), 761-773.

APHA American Public Health Association. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association, American Water Works Association, & Water Environment Federation.

Broner, I. Irrigation Scheduling [WWW Document]. Crop Ser. Available online: https://extension.colostate.edu/docs/pubs/crops/04708.pdf (accessed on 5 May 2024).

Chauhan, S. S., & Sharma, P. (2021). *Assessment of crop water use and irrigation efficiency using soil moisture sensors for precision irrigation.* Agricultural Water Management, 245, 106650. https://doi.org/10.1016/j.agwat.2020.106650

Dong, Y. Irrigation scheduling methods: Overview and recent advances. In *Irrigation and Drainage-Recent Advances*; InTech Open: Rijeka, Croatia, 2022. Available online: https://www.intechopen.com/chapters/83834 (accessed on 1 June 2024).

El-Sawy; S.M., M.A. Marwa, A.F. El-Shafie, A.E. Hamza, H.E. Jun and Sun Zhaojun (2022). Effect of irrigation scheduling on yield, quality and water use efficiency of potato plants grown under deficit irrigation conditions. Middle East J. Agric. Res.,11(2): 693-711.

EL-Sayed, M., Gebreel, M., Elglaly, A. M. and Abdelhalem, A. K. (2022). Potato productivity in response to furrow irrigation practices, rabbit manure rates, and potassium fertilizer levels., Egypt. J. Soil Sci., 62(4): 335 – 348.

Estefan G, Sommer R, Ryan J (2013). Methods of soil, plant, and water analysis: A manual for the west, Asia and North Africa region. ICARDA,Beirut, Lebanon.

FAO. *FAOSTAT: Food and Agriculture Data.* Food and Agriculture Organization of the United Nations, 2023, https://www.fao.org/faostat.

Fernández, J. E., Alcon, F., Diaz-Espejo, A., Hernandez-Santana, V., & Cuevas, M. V. (2020). Water use indicators and economic analysis for on-farm irrigation decisions: A case study of a super high-density olive tree orchard. *Agricultural Water Management,* 237, 106074.

Gardner, W.H. (1986). Water content. *Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods* (2nd ed.), Klute, A. (Ed.), pp. 493-544. American Society of Agronomy.

Gohar, A. A., and Ward, F. A., 2013. Mitigating impacts of water shortage on Egyptian agriculture: a catchment scale analysis. Water Policy, 15(5), 738-760.

Gomez, K. A., & Gomez, A. A. (2016). *Statistical Procedures for Agricultural Research* (2nd ed.). John Wiley & Sons.

Hassanli, A. M., Ebrahimizadeh, M. A., & Beecham, S. (2010). The effects of irrigation methods with effluent and irrigation scheduling on water use efficiency and crop yield in an arid region. Agricultural Water Management, 97(3), 731-736.

https://extension.colostate.edu/docs/pubs/crops/04716

Johnson, R., Miller, D., & Thomas, P. (2018). Optimizing irrigation schedules for sustainable water use in agriculture. *Journal of Irrigation Science*, 36(4), 289–301.

Kabir, M.Y.; Nambeesan, S.U.; Bautista, J.; Díaz-Pérez, J.C. Effect of Irrigation Level on Plant Growth, Physiology and Fruit Yield and Quality in Bell Pepper (Capsicum Annuum L.). Sci. Hortic. 2021, 281, 10990.

Kandelous, M. M., & Šimůnek, J. (2010). Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D. Agricultural Water Management, 97(7), 1070–1076.

Koech, R.; Langat, P. Improving irrigation water use efficiency: A review of advances, challenges and opportunities in the Australian context. *Water* 2018, *10*, 1771. https://doi.org/10.3390/w10121771.

Kwon, Y.B.; Lee, J.H.; Roh, Y.H.; Choi, I.-L.; Kim, Y.; Kim, J.; Kang, H.-M. Effect of Supplemental Inter-Lighting on Paprika Cultivated in an Unheated Greenhouse in Summer Using Various Light-Emitting Diodes. Plants 2023, 12, 1684

Li, X., Zhang, Q., & Wang, Y. (2005). Impact of irrigation methods on crop yield and water use efficiency. *Agricultural Water Management, 72*(1), 45-59.

Li, Y., Zhao, L., Kang, S., & Li, F. (2018). Effect of smart irrigation scheduling on water productivity and economic benefits of greenhouse vegetables. Irrigation Science, 36(1), 27-38.

Liao, R.; Zhang, S.; Zhang, X.; Wang, M.; Wu, H.; Zhangzhong, L. Development of smart irrigation systems based on real-time soil moisture data in a greenhouse: Proof of concept. Agric. Water Manag. 2021, 245, 106632.

Lopez, J., García, M., & Martínez, R. (2021). Energy performance analysis of irrigation systems in greenhouse environments. *Journal of Agricultural Engineering*, 72(4), 345-356. https://doi.org/10.1016/j.jae.2021.04.004

Ministry of Agriculture. *Annual Agricultural Statistics Report.* Ministry of Agriculture and Soil Reclamation, Egypt, 2023.

Mukherjee, S.; Dash, P.K.; Das, D.; Das, S. Growth, yield and water productivity of tomato as influenced by deficit irrigation water management. Environ. Process. 2023, 10, 10.

Naroua, I., Sinobas, L. R., & Calvo, R. S. (2014). Water use efficiency and water productivity in the Spanish irrigation district "Río Adaja". *International Journal of Agricultural Policy and Research*, 2(12), 484-491.

Parkash, V.; Singh, S. A review on potential plant-based water stress indicators for vegetable crops. Sustainability 2020, 12, 3945

Patanè, C., Tringali, S., & Sortino, O. (2011). Effects of deficit irrigation on biomass, yield, water productivity, and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. *Scientia Horticulturae*, 129, 590–596.

Pereira, L. S., Cordery, I., & Iacovides, I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural Water Management*, 108, 39-51.

Rasheed, M.W.; Tang, J.; Sarwar, A.; Shah, S.; Saddique, N.; Khan, M.U.; Imran Khan, M.; Nawaz, S.; Shamshiri, R.R.; Aziz, M.; et al. Soil Moisture Measuring Techniques and Factors Affecting the Moisture Dynamics: A Comprehensive Review. *Sustainability* 2022, *14*, 11538. https://doi.org/10.3390/su141811538.

Richards L A (1954). Diagnosis and improvement of saline and alkaline soils (p. 60). Washington: US Department of Agriculture Hand Book. https://doi.org/10.1007/s13201-022-01590-x

Rodríguez, A., & Gil, J. (2012). Water-saving potential and mechanisms of subsurface drip irrigation: A review. *Agricultural Water Management*, 104, 80-87.

Seidel, S. J., Schütze, N., Fahle, M., Mailhol, J. C., & Ruelle, P. (2015). Optimal Irrigation Scheduling, Irrigation Control and Drip Line Layout to Increase Water Productivity and Profit in Subsurface Drip-Irrigated Agriculture. Irrigation and Drainage, 64(4), 501-518.

Shahrokhnia, M. H., & Sepaskhah, A. R. (2018). Water and nitrate dynamics in safflower field lysimeters under different irrigation strategies, planting methods, and nitrogen fertilization and application of HYDRUS-1D model. *Environmental Science and Pollution Research*, 25, 8563–8580. https://doi.org/10.1007/s11356-017-1184-7.

Sparks, D. L., Page, A. L., Helmke, P. A., & Loeppert, R. H. (Eds.). (2020). *Methods of soil analysis: Part 3—Chemical methods* (SSSA Book Series No. 5). ACSESS

Steduto, P.; Hsiao, T.C.; Fereres, E.; Raes, D. Crop Yield Response to Water; FAO: Rome, Italy, 2012; FAO Irrigation and Drainage Paper 66

Tolba, R. A., S. M. Abou-Shleel, M. A. El- Shirbeny and Z. F. Fawzy (2023)Assessment of Potato Growth and Yield under Smart Irrigation Egypt. J. Soil Sci. Vol. 63, No. 4, pp: 553-569 (2023)

Tzanakakis, V.A.; Paranychianakis, N.V.; Angelakis, A.N.Water supply and water scarcity. Water **2020**, 12, 2347.

Walters, S. A., and Jha, A. K., 2016. Sustaining Chili Pepper Production in Afghanistan through Better Irrigation Practices and Management. Agriculture, 6(4):1-10.

Wang, J.; Klein, K.K.; Bjornlund, H.; Zhang, L.; Zhang, W. Adoption of improved irrigation scheduling methods in Alberta: An empirical analysis. *Can. Water Resour. J.* 2015, *40*, 47–61. https://doi.org/10.1080/07011784.2014.975748.

Wu, Y.; Yan, S.; Fan, J.; Zhang, F.; Zhao, W.; Zheng, J.; Guo, J.; Xiang, Y.; Wu, L. Combined effects of irrigation level and fertilization practice on yield, economic benefit and water-nitrogen use efficiency of drip-irrigated greenhouse tomato. Agric. Water Manag107401 ,262 ,2022.

Yang, F.; Wu, P.; Zhang, L.; Wei, Y.; Tong, X.; Wang, Z. Effects of subsurface irrigation types on root distribution, leaf photosynthetic characteristics, and yield of greenhouse tomato. Sci. Hortic. 2024, 328, 112883.

Yao, J., Qi, Y., Li, H., & Shen, Y. (2021). Water-saving potential and mechanisms of subsurface drip irrigation. Chinese Journal of Eco-Agriculture, Vol. 29, No. 6, 1076-1084 ref. 75 ref.

Zhang, Y., Guo, Z., Shao, X., Zhang, Y., & Wang, H. (2019). Energy consumption and efficiency evaluation of smart irrigation systems: A case study from China. Environmental Science and Pollution Research, 26(8), 7452-7464.