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Water management using internet of things with surface and sub-surface drip irrigation systems

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ABSTRACT

Proper irrigation management, particularly for water-sensitive plants, ensures long-term productivity. Combining a low-cost sensor with the Internet of Things (IoT) offers a promising solution for accurately monitoring soil moisture levels in the root zone of plants. This technology empowers on-demand irrigation, significantly reducing the need for human involvement. An IoT-based, precise monitoring system was developed to cultivate green beans within a greenhouse. Three irrigation levels, 100%, 80%, and 60%, and two irrigation systems, surface (SDI) and subsurface (SSDI) drip irrigation, were compared to assess which level and irrigation system increased in green bean yield and water use efficiency (WUE) under greenhouse conditions. The experiment was conducted at El-Sharkia governorate, Egypt, at latitude 30.416667° N and longitude 31.639833° E. during the winter season of 2022-2023, planting on 25 October 2022, and last harvesting on 14 March 2023.The results revealed that SSDI outperformed (SDI) regarding of green bean yield. The results indicate that (SSDI) enhances average green bean yield by approximately 11% compared to (SDI) for both full and deficit irrigation treatments. The average green bean yields are 26.844 and 30.156 t ha^{-1} for SDI and SSDI, respectively. Additionally, SSDI demonstrated superior WUE compared to SDI, particularly under deficit irrigation conditions. These results suggest that SSDI, coupled with an irrigation treatment of 80% ETc, can maximize green bean yield while optimizing WUE. The productivity reached 33.614 t ha^{-1}, and the seasonal water use value was 262.5 mm/season, while the WUE was 12.81 kg/m^3. In regions facing water scarcity, implementing SSDI strategies that involve a 60% reduction in ETc throughout the entire growing season could be a viable approach in the greenhouse. The productivity reached 32.466 t ha^{-1}, and the seasonal water use value was 206.5 mm/season, while the WUE was 15.73 kg/m^3. Therefore, the combination of Internet of Things technology, SSDI system, and deficit irrigation practices of 80% can enhances both WUE and green bean yield under greenhouse conditions, particularly in water-scarce regions.

1. Introduction

Agriculture is a vital sector of most economies, accounting for a significant portion of gross domestic product (GDP) and ensuring food security (World Bank, 2020d). However, agriculture is also a major water user, consuming 70% of the world's freshwater resources to irrigate 25% of the world's croplands (FAO, 2020a; Khokhar, 2017). Climate change and population growth are putting additional pressure on resources essential for agricultural production, such as water availability (Ungureanu et al., 2020). By 2050, the world population is projected to reach 9.7 billion, which will increase the demand for nutritious food and water resources (FAO, 2020a). The Food and Agricultural Organization (FAO) predicts that irrigated food production will increase by more than 50% by 2050. This will require a 10% increase in water withdrawn for

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agriculture, but only if water productivity improves (FAO, 2020b).

Green bean (Phaseolus vulgaris L.) belongs to the Fabaceae family and is cultivated worldwide due to its high nutritional value (Mehrasa et al., 2022). The rise in temperature causes an increase in evapotranspiration and plant water demand. Higher evapotranspiration has a negative influence on food output, especially for water-sensitive plants like green beans. Green beans are a popular and water-intensive vegetable. It is well known that green beans are sensitive to drought and overwatering (Rai et al., 2020). The world production of green bean (*Phaselous vulgaris L.*) in 2020 was 4,310,733 metric tons. Egypt produced 265,000 tons of green beans in 2020, ranking 7th globally (FAOSTAT, 2022).

IoT-based irrigation uses sensors and real-time data to optimize water use, boosting food production and saving water. This helps farmers manage resources better and combats the global water crisis (Blessy et al., 2023; Kumar et al., 2023; Vaishnavi et al., 2023). Using IoT technology in irrigation operations not only decreases labor needs but also saves up to 90% more water than traditional irrigation methods. Furthermore, employing microcontrollers, IoT systems combining soil moisture sensors have considerable promise. Soil moisture reading systems based on capacitive sensors linked to microcontrollers have been employed in monitoring networks for real-time soil moisture evaluation (Romano, et al.,2022). By using low-cost sensors and controlling modules, IoT-based solutions make the difficult work of irrigation easier and more precise. The device can assist in obtaining an accurate assessment of soil moisture in the plant root zone and applying the appropriate percentage of water at the appropriate time. Water stress can harm metabolic processes and photosynthetic apparatuses, resulting in reduced crop development (Wan et al., 2021).

Micro irrigation methods, like drip irrigation, are highly effective for vegetable cultivation. These systems excel at minimizing water waste thanks to their efficient water application and targeted delivery directly to the plant root zones (Sun et al., 2013). Subsurface drip irrigation (SSDI) is a type of drip irrigation that delivers water and fertilizer directly to the root zone of crops through a network of buried emitters. In recent years, many studies have shown that SSDI can reduce deep seepage, soil evaporation, and weed growth, while increasing crop water productivity (WP) (Yao et al., 2021). In a subsurface drip irrigation (SSDI) system, the depth of the laterals, the spacing of the emitters, the spacing of the laterals, the discharge rate of the emitters, and the system pressure all play an important role in managing the irrigation system and affecting the distribution of moisture in the soil and the delivery of the required amount of water to the plants (Badr and Abuara, 2013).

The total amount of water a crop needs to sustain its maximum evapotranspiration (ETc) rate is known as crop water requirement. It is determined by subtracting the water obtained from rainfall and soil water from ETc. The water needed to maintain ETc is technically referred to as the "net" crop water requirement, while the "gross" crop water requirement takes into account additional irrigation to account for salinity and application uniformity. crop water requirements are "net" crop water requirements. Since greenhouses receive no rainfall and seasonal soil water extraction is negligible, it can generally be assumed that the crop water requirement of greenhouse-grown crops is equivalent to ETc because the soil is constantly maintained close to field capacity due to frequent drip irrigation (Fernández et al., 2005). Deficit irrigation is an irrigation strategy that delivers a reduced amount of water to crops, controlled by a water stress indicator or as a percentage of the crop's full water requirements throughout the growing season. The goal is to achieve a uniform water deficit throughout the crop cycle to avoid severe water stress at any particular time, which could have negative consequences (Fernandes-Silva et al., 2018).

Water use efficiency in irrigated agriculture is the percentage of water withdrawn for irrigation that is actually used by the plants (FAO, 2020a). Water use efficiency is a unitless measure that can be applied to plants, fields, irrigation schemes, basins, and entire countries. In the field of agronomy, water use efficiency is commonly defined as the crop yield per unit of water used to produce that yield (Ullah et al., 2019).

The main objectives of this study:

- Using the Internet of Things (IoT) to optimize irrigation water management with surface and subsurface drip irrigation systems.
- Increase the water use efficiency and yield production.

2. Materials and methods

2.1. Field Experiment

The field experiment was carried out at the SEKEM Company for Biodynamic Agriculture in Belbeis city, Sharkia Governorate, Egypt, at latitude 30.416667° N, longitude 31.639833° E, and a mean altitude of 9.6 m above sea level. during the winter season 2022–2023, planting on 25 October 2022, and last harvesting in 14 March 2023.Three soil samples from each profile were collected at depths of 0-15 cm, 15-30 cm, and 30-45 cm. The samples were air-dried and passed through a 2 mm sieve to obtain the fine soil for analysis. The soil texture analysis of the experimental field revealed that the soil belongs to the loamy sand class. Table 1 present the soil physical analysis of the experimental site. The characteristics were measured in the laboratory of Soil, Water

& Environment Research Institute, Agricultural Research Center, Ministry of Agricultural, El-Giza, Cairo, Egypt.

Experimental designs are illustrated in Table 2, where experiments were laid out in a split plot design. The dimensions of the experimental area are 23 x 9.5 m, divided into three plots. Each plot is equal to 23 x 2.5 m, which is divided into two subplots: sub-plot (1) is the surface drip irrigation system (SDI), and sub-plot (2) is the sub-surface drip irrigation system (SSDI). Each subplot equals 23 x 1.25 m. Fig. 1 shows a schematic sketch of the field experimental area to plant the green bean (Phaseolus vulgaris L.) irrigated by two irrigation systems and three water irrigation requirements. We were harvested by hand to determine the green bean (Phaseolus vulgaris L.) yield (t/ha). The experiment was repeated three times with the same plot. The total experimental area was 71×9.5 m^2.

Three irrigation water application rates were used to irrigate the green bean crop at (100%, 80%, and 60%) of the calculated irrigation water requirement. Table 2 shows the experiment Treatment.

Table 1

Soil physical analysis of experimental site.

Depth (cm)	Percentages soil particles (%)			Texture	Bulk Density (g/ cm^3)	Field capacity (%)	Wilting point (%)	Available Water (%)
	Sand (%)	Silt (%)	Clay (%)					
0-15	84.72	7.17	8.11	Loamy Sand	1.54	17.53	6.81	10.72
15-30	85.24	6.81	7.95	Loamy Sand	1.56	17.28	6.77	10.51
30-45	86.26	6.51	7.23	Loamy Sand	1.59	17.12	6.63	10.49
AV	85.41	6.83	7.76	Loamy Sand	1.56	17.31	6.74	10.57

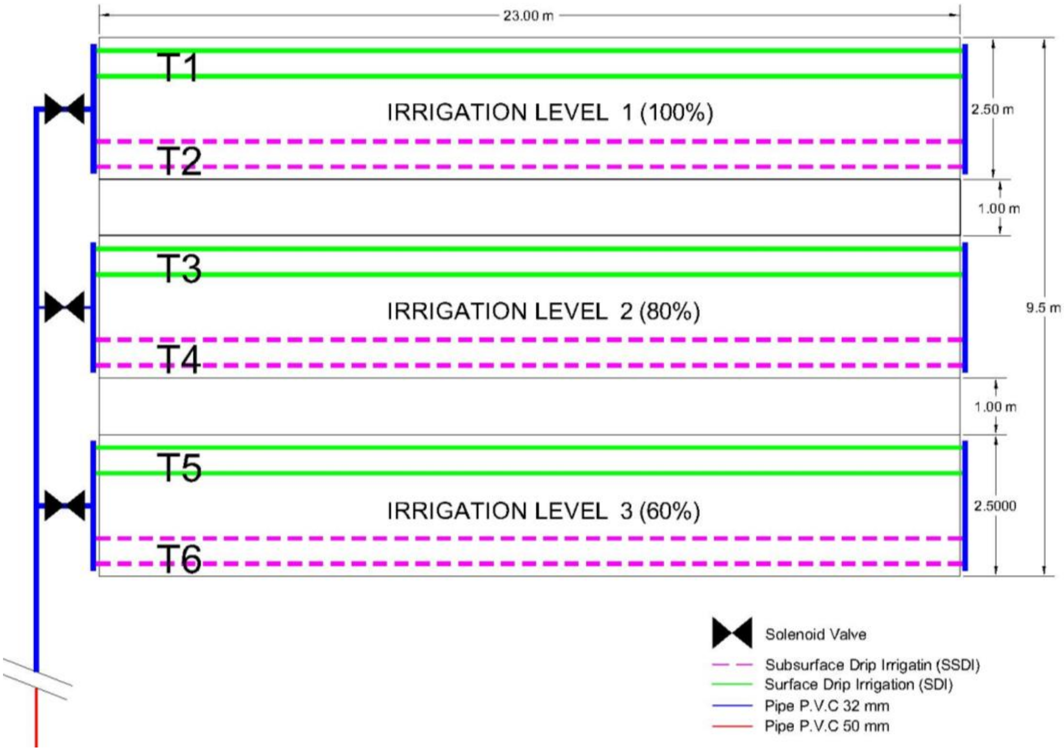

Fig. 1. Schematic sketch of field experimental area.

Table 2

Experiment treatments.

Experiment Treatment	Water treatments					
	100% of the irrigation water requirement		80% of the irrigation water requirement		60% of the irrigation water requirement	
	SDI	SSDI	SDI	SSDI	SDI	SSDI
	T1	T2	T3	T4	T5	T6

2.2. *Drip irrigation system components*

The irrigation system was set up in the field before planting the seeds. The irrigation network consists of the following components:

1) Control head: Located at the water source, it comprises a 2"/2" centrifugal pump driven by an electric motor (pump output of 20 m^3/h and 26 m lift), a 2" screen filter (120 mesh), a backflow prevention device, a pressure regulator, pressure gauges, a flow meter, and control valves.
2) Main line for the experiment: PVC pipes with a diameter of 50 mm to transport water from the source to the submain line.
3) Submain line: PVC pipes with a diameter of 32 mm to convey water from the main line to the manifolds.
4) Manifold lines: PVC pipes with a diameter of 32 mm connected to the submain line through 1" control valves.
5) Lateral lines: PE tubes with a diameter of 16 mm connected to the manifolds through fittings installed on the manifold lines.
6) Emitters: These emitters were integrated into 16 mm PE tubes (emitter discharge of 3.4 L h^{-1} at an operating pressure of 1 bar and spaced 30 cm apart). For the subsurface drip-irrigated plots, the drip lines were buried at a depth of 15 cm.

2.3. *Components of the IoT-based monitoring and irrigation system*

The Internet of Things model was used in the permanent and continuous monitoring of plants through various measurements, including air temperature, air humidity, and soil moisture. Two units were used in the experiment. The first unit was an internet of things unit for data collection, and the second was a special irrigation control unit. This work proposes a novel cloud-based Internet of Things (IoT) solution aimed at optimizing water management for green bean cultivation. By leveraging the combined capabilities of cloud computing and IoT technology, the system seeks to achieve precise control of irrigation systems, ensuring efficient water utilization and maximizing green bean yield. Our monitoring of the internet of things is shown in Fig. 2. The proposed solution utilizes various sensors to automatically monitor crucial parameters influencing green bean growth and water requirements. This data is then uploaded to the cloud platform, where it undergoes real-time analysis. Based on the collected information, the system helps the user intelligently schedule the application of optimal water amounts over variable periods, employing a sensor-based irrigation scheduling approach.

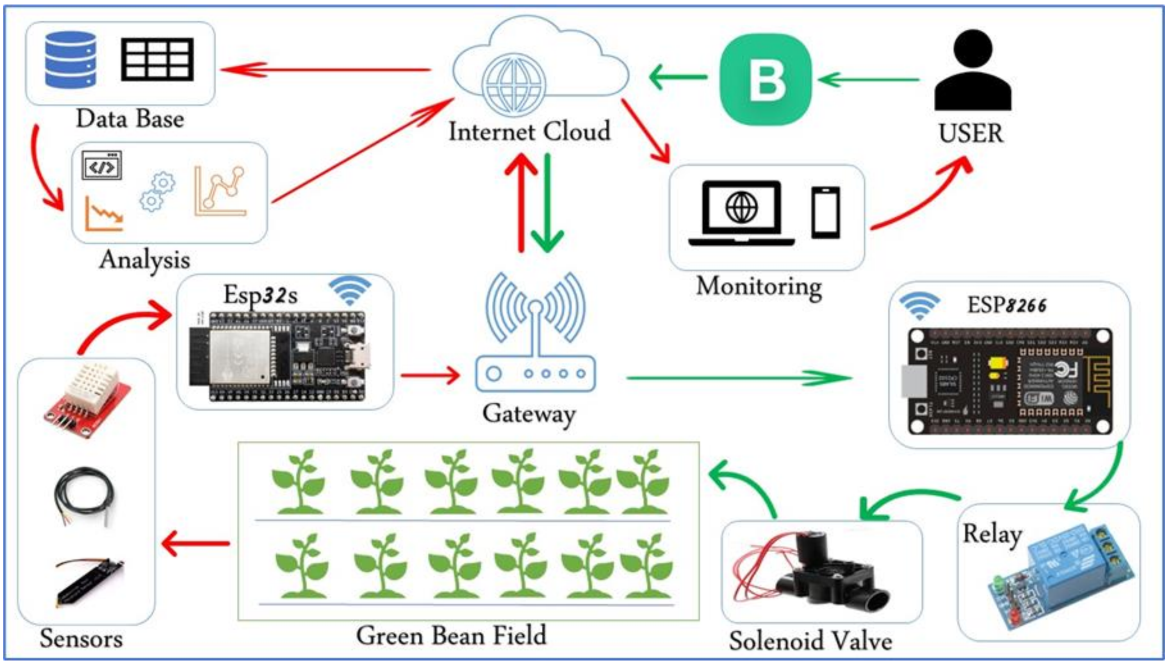

Fig. 2. Components of the IoT-based monitoring and irrigation system.

The internet of things unit part consists of an ESP32-S board, a digital-output relative humidity and temperature sensor/module (DHT22), a capacitive soil moisture sensor, a waterproof project box, and a power supply. The irrigation unit part consists of an ESP 8266 board, a solenoid valve, relay four channels, and a power supply. The TP-link my-fi was used to connect to the internet network.

- ESP32-S board: The ability to employ a large number of sensors with the chosen CPU was critical, as was connection, ease of programming, and board cost. Given the arguments raised above, the ESP32-WROOM-32 microcontroller was an excellent option for final selection. The Esp ressif SMD ESP32-WROOM-32 microcontroller is included on the 38-pin ESP32 development board. This board enables the efficient and cost-effective control of various types of sensors, modules, and actuators via WIFI and BLUETOOTH for Internet of Things ("IoT") projects. It contains a micro-USB Type B port for charging and programming the ESP32, and it also has a USB controller integrated inside the UART CP2102.

- Sensor digital-output relative humidity and temperature sensor/module (DHT22): The DHT22's technical specs are as follows: Model DHT22, power supply 3.3-6V DC, output signal digital signal via single-bus, operating range humidity 0-100%RH; temperature -40 to 80Celsius, and humidity accuracy +-2%RH (Max +-5%RH); temperature +-0.5Celsius.
- Sensor capacitive soil moisture sensor: The Capacitive Soil Moisture Sensor Module calculates the quantity of soil moisture by sensing variations in capacitance to measure the soil's water content. The Capacitive Soil Moisture Sensor has the following technical specifications: Operating Voltage 3.3 to 5.5V, Operating Current 5mA, Output Voltage at 5V is about 1.5V to 3V, Sensor Probe L x W (PCB) 98 x 23mm.
- ESP 8266 board: NodeMCU is an open-source development board and firmware based on the commonly used ESP8266-12E Wi-Fi module.The following are the board's specifications: Arduino-style (software-defined) hardware IO, programmable Wi-Fi module Can be programmed using the simple and powerful Lua programming language or the Arduino IDE, and can connect to the internet to collect or post data.
- solenoid valve: To manage the opening and stopping of irrigation water, solenoid valves were employed. The experiment has one solenoid valve for each treatment. The following are the basic characteristics of the solenoid valve specifications: Size of the valve: 1 in. Inline valves are used. Plastic is the material used. Flow rates range from 0.05 to 9 m3/hr. Pressure range recommended: 1.5 to 10 bar.

2.4. Determination of water application

Climate data, including air temperature, air humidity, rainfall, wind speed, and sunshine hours, was used to calculate evapotranspiration (ETo) and water usage. Outside of the greenhouse, during the growing season (October to March), maximum temperatures ranged from 14.9 to 36.01°C, while minimum temperatures ranged from 4.17 to 19°C. Humidity levels varied from 24% to 80%.

Crop evapotranspiration (ETc) was estimated for each day using reference evapotranspiration (ETo) multiplied by a green bean crop coefficient (Kc). Crop coefficients vary depending on the crop and its stage of growth. In this study, crop growth was divided into four stages, which were as follows (Allen et al., 1998): Initial stage, Developmental stage, Mid-stage, and Late-season stage.

$$\mathrm{ET_c} = \mathrm{ET_o} \times \mathrm{K_c} \qquad \text{... [1]}$$

The reference evapotranspiration (ETo) was determined by the FAO Penman-Monteith equation, was used for 24-hour ETo estimates using daily or monthly mean data (Allen et al., 1998), as shown in Equation:

$$\mathrm{ET_o} = \frac{0.408\,\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma \frac{900}{\mathrm{T} + 273} \mathrm{u_2}\,(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma\,(1 + 0.34\,\mathrm{u_2})} \qquad \text{... [2]}$$

where:

ETo: Reference evapotranspiration, (mm.day^{-1}),
Rn: Net radiation at the crop surface, (MJ.m^{-2}.day^{-1}),
G: Soil heat flux density, (MJ.m^{-2} day^{-1}),
T: Mean daily air temperature at 2 m height, (°C),
u_2: Wind speed at 2 m height, (m.s^{-1})
e_s: Saturation vapor pressure, (kPa),
e_a: Actual vapor pressure, (kPa)
e_s-e_a: Saturation vapor pressure deficit, (kPa)
Δ: Slope vapor pressure curve, (kPa.°C^{-1}),
γ: Psychrometric constant, (kPa.°C^{-1}).

The water application time was calculated as in the following equation:

$$\mathrm{Ti} = \frac{\mathrm{ETc} \times \mathrm{A}}{\mathrm{q}} \qquad \text{... [3]}$$

where:

Ti : is the irrigation time (min),
ETc: is the plant evapotranspiration (mm/period irri.)
A: is the dripper irrigate area (m^2) and
q: is dripper flow rate (m^3 /min).

2.5. Yield reductions and water-saving determination

The reductions in total green bean yield and water savings were determined by calculating the percentage decrease in yield and irrigation water use compared to a control treatment. The equations used for these calculations were based on the method described by Ismail (2010).

$$\text{Reduction in yield} = 100 - \left(\frac{\text{yield of T4, T3 T5, T6 or T2}}{\text{T1}} \times 100\right) \qquad \text{... [4]}$$

$$\text{Water saving} = 100 - \left(\frac{\text{water consumption of T4, T3, T5, T6 or T2}}{\text{T1}} \times 100\right) \quad \dots [5]$$

Where:

T1: A full irrigation water requirement (control treatment).

2.6. Irrigation water use efficiency (IWUE)

Irrigation water use efficiency (IWUE) was calculated by dividing the yield in kilograms per hectare (kg.ha^{-1}) by the total seasonal irrigation volume applied per hectare in cubic meters per hectare (m^3. ha^{-1}). It was expressed in units of kilograms per cubic meter (kg m^{-3}) (Ertek et al., 2006).

2.7. Green bean quantity parameters

The total yield of green beans was determined in tons per hectare (ton.ha^{-1}).

The total green bean yield per hectare was calculated based on the yield per plot using the following formula:

$$\text{Yield} = \frac{\text{weight of greenbean} \times 10000}{\text{plot area} \times 1000} \quad \dots [6]$$

3. Results and discussions

3.1. Determine of ET$_o$ in greenhouse

The temperature and humidity data were recorded in real-time using our cloud-based Internet of Things (IoT) system every hour of every day throughout the experiment to modify the reference evapotranspiration. Fig. 3A depicts the daily temperature (°C), while Fig. 3B shows the percentage of relative humidity.

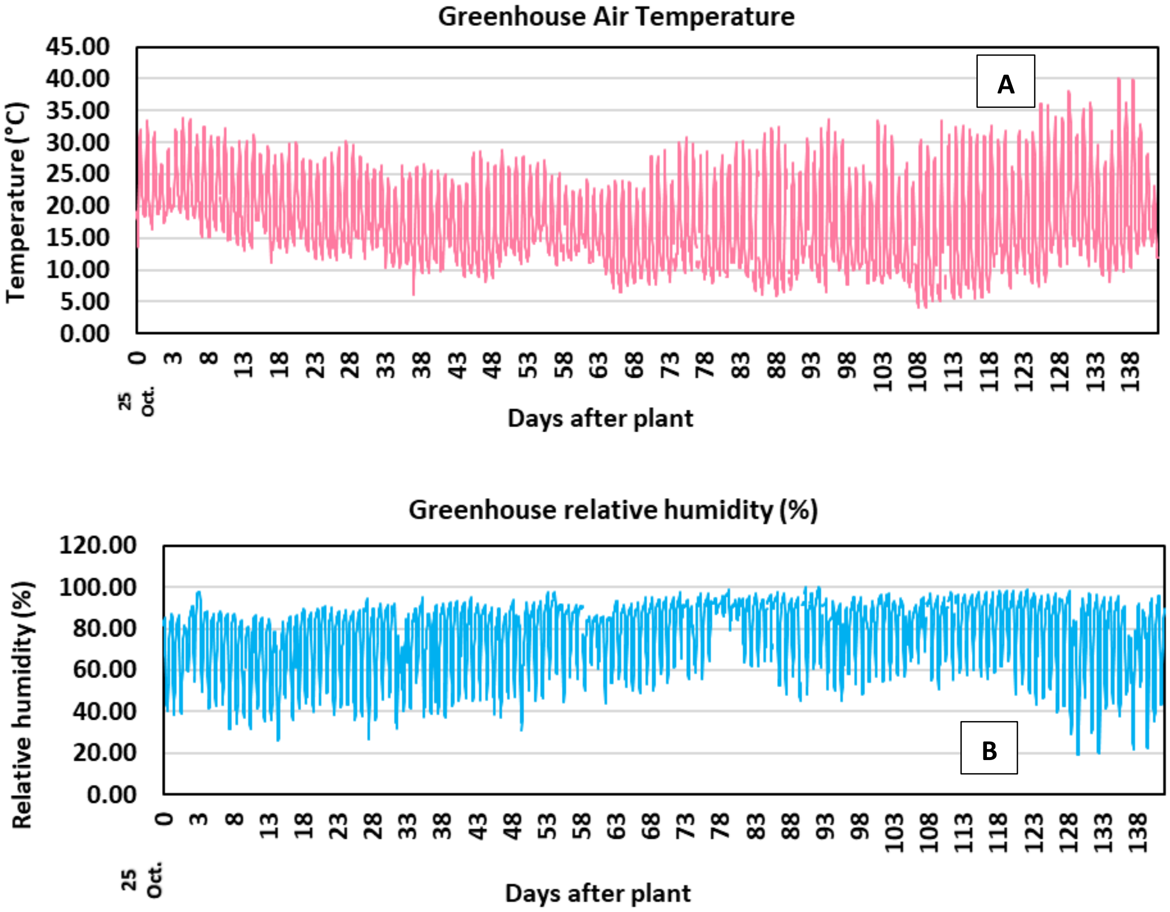

Fig. 3. Daily average Temperature and humidity data in greenhouse.

The data illustrates that the highest daily average temperature was recorded on days 9 March, 11 March, and 2 March after planting, reaching 40.07°C, 39.82°C, and 38.01°C, respectively. In contrast, the lowest daily average temperature occurred on days 9 Febr, 12 Febr, and 14 Febr after planting, with values of 4.15°C, 5.10°C, and 5.46°C, respectively. These findings are depicted in Fig. 3A.

Fig. 3B reveals that the highest daily average relative humidity was observed on days 24 Jan, 23 Febr, and 1 March after planting, reaching 99.1%, 98.7%, and 98.0%, respectively. Conversely, the lowest daily average relative humidity was recorded in 2 March, 5 March, and 10 March, with values of 19.00%, 19.80%, and 21.70%, respectively. The data also indicates that the highest daily average temperature was recorded at 12 AM, 1 PM, and 11 AM, reaching 40.07°C, 39.75°C, and 38.8°C, respectively. Conversely, the lowest daily average temperature occurred at 6 AM, 5 AM, and 4 AM, with values of 4.15°C, 4.16°C, and 4.52°C, respectively. The highest daily average relative humidity was observed at 5 AM, 6 AM, and 7 AM, reaching 99.1%, 99.1%, and 98.3%, respectively. In contrast, the lowest hourly average relative humidity was recorded at 12 PM, 1 PM, and 2 PM, with values of 19.00%, 19.00%, and 19.90%, respectively. The Penman-Monteith equation was used to compute the reference evapotranspiration, which was then adjusted using this equation: $Eto_{modify} = Eto \times 0.6$ as shown in Fig. 4, This observation is consistent with the findings of (Fernández et al., 2010), who observed that, as compared to outdoor-grown vegetable crops that get irrigation, greenhouse-grown vegetable crops had a much lower seasonal ETo due to reduced evaporative demand within the greenhouse. Because of a reduction in solar radiation (40% on average) and much reduced wind speeds of 0.1-0.3 m s^{-1} or less, evaporative demand within the greenhouse can be as low as 60% of that outside.

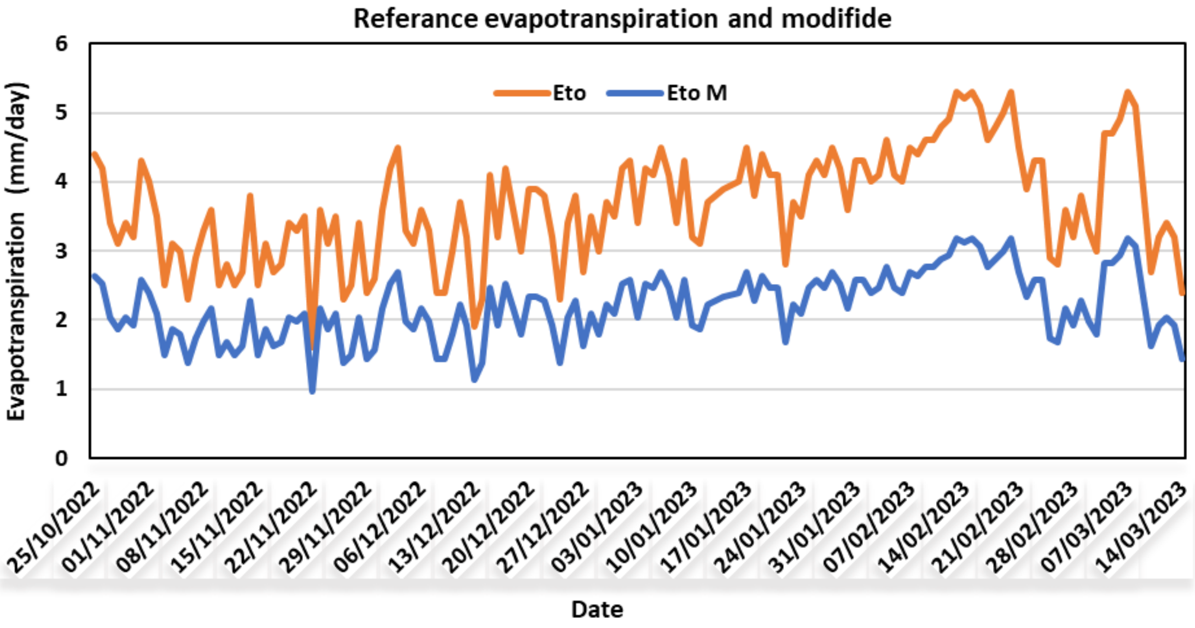

Fig. 4. Daily average Reference evapotranspiration and modified.

The results in Table 3 demonstrated that the total Et_c for green beans in a greenhouse with drip irrigation was 306.02 mm during the entire growth period. The amount of ET_c was the highest at the midseason stage, which accounted for 68.55%of total ET_c.

Table 3
ET_c in different green bean stage in greenhouse.

Plant stage	Initial	Development	Mid	Late	Total
ETc (mm)	14.69	44.79	209.76	36.78	306.02

3.2. *Effect of treatments on the soil moisture content*

The soil moisture data was recorded in real-time using our cloud-based Internet of Things (IoT) system every hour of every day throughout the experiment to modify the water application. The soil moisture content was measured at two depths in the soil profile: 0-20 cm and 20-40 cm. The average soil moisture content for each depth was calculated. Fig. 5 shows the average soil moisture content values as a percentage under different irrigation treatments for two types of irrigation systems: surface drip irrigation (SDI) and subsurface drip irrigation (SSDI). Soil water content readings were taken from planting until the end of the growing season. The average soil moisture content was calculated for each stage of crop growth: planting (initial stage), development, mid-season, and harvest. Soil moisture content was directly related to the amount of water applied at full or deficit-irrigated treatments and irrigation systems. Initially, soil moisture content was higher in all treatments due to the irrigation amount applied before planting to replenish the soil profile to field capacity. All treatments at the initial stage received almost the same amount of water (100% of ET$_c$). The average soil moisture content in the root zone area for the initial stage was 17.9% for T1 and 18.2% for T2, with an average depletion (p) of 45%. The soil water depletion fraction for a crop without water stress (p) represents the proportion of the total available soil water that the crop can withdraw from its root zone before experiencing water stress. This fraction is 45% for green bean crop (Allen et al., 1998).

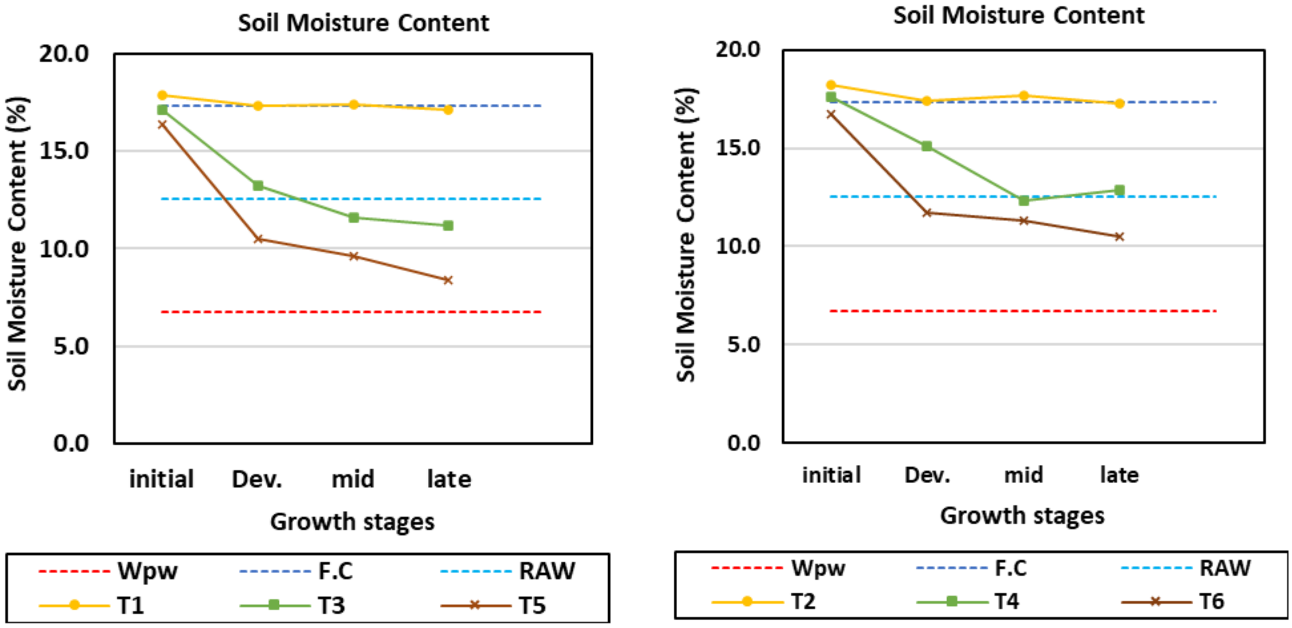

Fig. 5. Comparison of average soil moisture content values, under different irrigation treatments for the (SDI) and (SSDI) systems throughout the growth stages.

The results demonstrate that for all irrigation treatments, there were also differences between the soil moisture content of the plots irrigated with the subsurface drip system and those irrigated with the surface drip system during the development, mid-season, and harvest periods. Subsurface drip irrigation (SSDI) maintained a higher soil moisture content and the lowest percentage depletion compared to surface drip irrigation (SDI). This is attributed to the reduction in evaporation from the soil surface by placing the drip line under the soil surface.

Subsurface drip irrigation minimizes evaporative loss, in agreement with EI-Awady et al. (2003), who reported that evaporation decreased with increasing drip line depth. Under full irrigation (100% ETc), soil moisture content was significantly higher than under deficit treatments for both irrigation systems. Soil water content data can help explain the water stress among different treatments. In treatments T1 and T2, the soil moisture content remained close to field capacity (F.C) throughout the entire growth cycle. In contrast, under treatments T3 and T4, the soil moisture content stayed near the Readily Available Water (RAW) level for the entire growth cycle. For treatments T5 and T6, the soil moisture content fell below the RAW line, indicating mild water stress.

3.3. Effect of treatments on the green bean yield

The data in Fig. 6 and Table 4 demonstrate that subsurface drip irrigation (SSDI) resulted in higher green bean yields compared to surface drip irrigation (SDI). The average green bean yields exhibited a statistically significant difference between surface drip irrigation (26.844 ton.ha^{-1}) and subsurface drip irrigation (30.156 ton. ha^{-1}).

The findings indicate that subsurface drip irrigation (SSDI) enhances average green bean yield by approximately 11% compared to surface drip irrigation (SDI) for both full and deficit irrigation treatments. This yield improvement is likely attributed to the higher soil moisture content maintained under SSDI compared to SDI. These results concur with those reported by other researchers for surface and subsurface drip irrigation systems (Al-Mansor, A. N., 2015; Amor, 2007; Machado et al., 2003).

The data revealed more distinct differences between treatments in surface drip irrigation (SDI) and subsurface drip irrigation (SSDI). The overall green bean yield exhibited significant variation under SDI for treatments T1, T3, and T5, ranging from 25.425 to 28.719 and 26.390 t ha^{-1}, respectively. Similarly, under SSDI for treatments T2, T4, and T6, the total yield varied considerably, spanning from 24.390 to 33.614 and 32.466 t ha^{-1}, respectively. The highest yield, reaching 28.719 t ha^{-1} for SDI and 33.614 t ha^{-1} for SSDI, was observed in treatments T3 and T4, which received 80% of ETc irrigation. This outcome can be attributed to the varying amounts of water applied to different treatments. The initial treatment (100% ETc) received the highest water input, while the third treatment (60% ETc) received the least.

On the other hand, results show the highest increase in green bean yield (32.2% and 27.7%) respectively) for T4 and T6, compared with T1 and the lowest green bean yield with the water treatment T2 (100% ETc). this is due to the T2 under over irrigation.

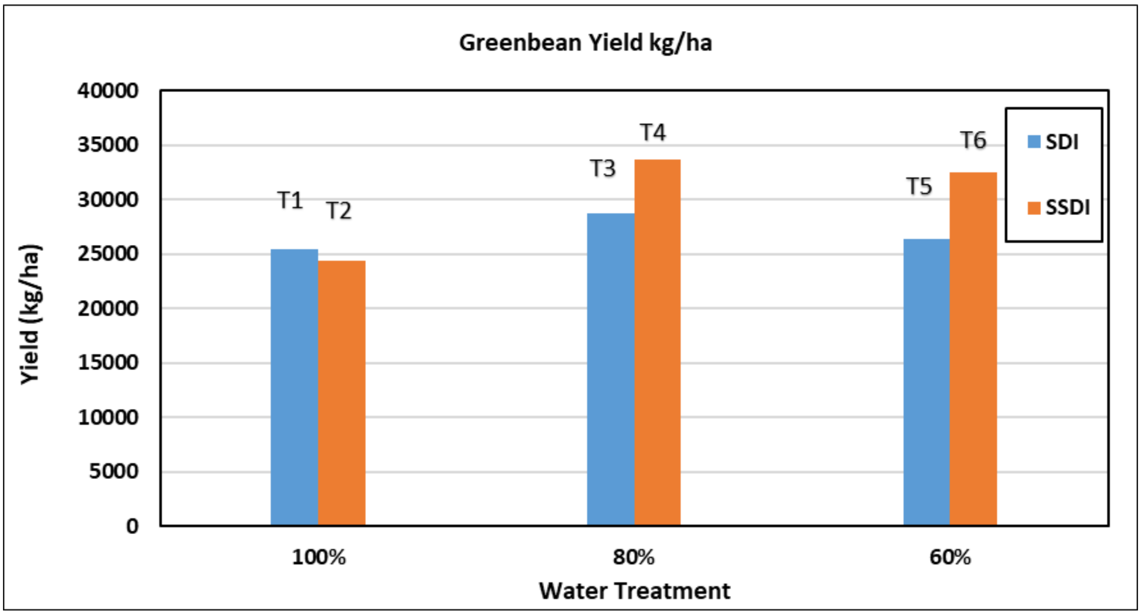

Fig. 6. The green bean yield under different water treatment and irrigation system.

Table 4
The green bean yield under different water treatment and irrigation system

Water treatment	100%	80%	60%	Average
SDI	T1	T3	T5	26.844
Yield (ton.ha^{-1})	25.425	28.719	26.390	
SSDI	T2	T4	T6	30.156
Yield (ton.ha^{-1})	24.390	33.614	32.466	

3.4. Effect of treatments on irrigation water use efficiency (wue)

The data in Table 5 clearly demonstrates that there was an interaction between irrigation type (SDI and SSDI) and irrigation water level (100%, 80%, and 60%) on in green bean crops. The average amount of irrigation water applied under the two trickle irrigation systems varied depending on the irrigation water level, with the highest application (3185 m^3.ha^{-1}) observed under full irrigation (100% ET$_c$) and the lowest application (2065 m^3/ha) observed under deficit irrigation (60% ET$_c$). The values also exhibited significant variation across the different irrigation treatments, ranging from 7.66 kg.m^{-3} to 15.73 kg.m^{-3}. The highest value was achieved under SSDI with the lowest water level (T6, 60% ETc), reaching 15.73 kg.m^{-3}. Conversely, the lowest value was recorded under SSDI with the highest water level (T2, 100% ET$_c$), at 7.66 kg.m^{-3}. Overall, tended to increase with decreasing irrigation water levels, indicating that deficit irrigation strategies can improve water use efficiency in green bean production.

The water applied in SDI was the same as that in SSDI treatment. It is possible to save water by improving its use efficiency in processing green bean, but water should be applied to the crop (80% ET$_c$), to achieve an adequate yield, minimizing yield losses. These results are in agreement with the previous findings in green bean cultivated under deficit irrigation treatments (Buyukcangaz, H et al., 2008). It is possible to save water by improving its use efficiency in green bean to achieve an adequate yield. The amount of water saved can be used to provide other areas to increase the green bean yield.

Table 5

Irrigation water use efficiency with different water treatment and irrigation system

Water treatment	100% of the irrigation water requirement		80% of the irrigation water requirement		60% of the irrigation water requirement	
	T1	T2	T3	T4	T5	T6
Total water applied (m^3.h^{-1}.season^{-1})	3185	3185	2625	2625	2065	2065
Yield (ton.ha^{-1})	25.425	24.390	28.719	33.614	26.390	32.466
kg.m^{-3}	7.98	7.66	10.94	12.81	13.78	15.73

4. Conclusions

This study investigates the efficacy of an IoT-based monitoring system coupled with a low-cost sensor for optimizing green bean irrigation within greenhouses. Combining a low-cost sensor with the Internet of Things (IoT) offers a promising solution for accurately monitoring soil moisture levels in the root zone of plants. For cultivating green beans within a greenhouse, an IoT-based, precise monitoring system was developed. Specifically, the study aims to:

- Compare three irrigation levels: 100%, 80%, and 60% of perceived water requirement, to identify the most beneficial level for green bean yield under greenhouse conditions.
- Assess the impact of two irrigation systems, surface drip irrigation (SDI) and subsurface drip irrigation (SSDI), on green bean yield and Water Use Efficiency (WUE).
- Evaluate the effectiveness of the IoT-based monitoring system in accurately measuring soil moisture levels in the root zone and facilitating precise irrigation control.

This research was conducted during the winter season of 2022-2023, between planting on October 25, 2022, and final harvest on March 14, 2023. The experiment took place at the SEKEM Company for Biodynamic Agriculture in Belbeis city, Egypt, located at 30.416667° N latitude, 31.639833° E longitude, and 9.6 m above sea level.

This experiment was conducted under greenhouse conditions; deficit irrigation was applied throughout the entire growing season of green beans. The findings revealed that:

- On average, SSDI increased green bean yield by approximately 11% compared to SDI, the average green bean yields are (26.844 t ha^{-1}) and (30.156 t ha^{-1}) for SDI and SSDI, respectively. regardless of whether full irrigation or deficit irrigation was used.
- Under treatment 80% and SSDI (T4) the green bean yield was highest, with values of (33.614 t ha^{-1}).
- Under treatment 100% and SSDI (T2) the green bean yield was lowest, with values of (24.390 t ha^{-1}).
- Under treatment 60% and SSDI (T6) the highest, with values of (15.73 kg/m^3).
- Under treatment 100% and SSDI (T2) the lowest, with values of (7.66 kg/m^3).
- The T4 treatment (80% ETc) with SSDI is considered a more practical and beneficial option for farmers to optimize by conserving water and boosting yield.

In regions with limited water resources, implementing SSDI strategies that involve a 60% reduction in ETc throughout the entire growing season could be a viable approach. Deficit irrigation, which prioritizes water conservation over maximum yield, is a suitable irrigation technique for green bean production in such areas. SSDI has demonstrated superior irrigation water use efficiency (WUE) compared to SDI, making it a more effective water management strategy.

Therefore, in the context of water scarcity, the combination of SSDI technology and deficit irrigation practices enhance both and green bean yield under greenhouse conditions. This approach offers a sustainable and efficient solution for green bean production in regions facing water resource challenges.

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إدارة المياه باستخدام إنترنت الأشياء مع أنظمة الري بالتنقيط السطحي وتحت السطحي

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الملخص العربي

يوفر الجمع بين أجهزة الاستشعار منخفضة التكلفة وإنترنت الأشياء (IoT) حلاً واعدًا لمراقبة مستويات رطوبة التربة بدقة في منطقة جذور النباتات. تعمل هذه التكنولوجيا على المساعدة في الري حسب الطلب، مما يقلل بشكل كبير من الحاجة إلى المشاركة البشرية. ولزراعة الفاصوليا الخضراء داخل البيوت المحمية، تم تطوير نظام مراقبة دقيق قائم على إنترنت الأشياء. في هذه الدراسة تمت مقارنة ثلاثة مستويات للري هي ١٠٠٪ و٨٠٪ و٦٠٪ ونظامين للري، هما الري بالتنقيط السطحي (SDI) والرى بالتنقيط تحت السطحي (SSDI) لتقييم المستوى ونظام الري الذي يشير إلى الزيادة في محصول الفاصوليا الخضراء وكفاءة استخدام المياه (WUE) في ظل ظروف البيوت المحمية. أجريت التجربة بشركة سيكم للزراعة الحيوية بمدينة بلبيس، محافظة الشرقية، مصر، عند خط عرض

٣٠,٤١٦٦٦٧° شمالاً، وخط طول ٣١,٦٣٩٨٣٣° شرقاً، وبمتوسط ارتفاع ٩,٦ متر فوق سطح البحر. خلال الموسم الشتوي ٢٠٢٢-٢٠٢٣م، وتمت الزراعة في ٢٥ أكتوبر ٢٠٢٢م، وآخر حصاد في ١٤ مارس ٢٠٢٣م.أظهرت النتائج أن الري بالتنقيط تحت السطحي يتفوق على الري بالتنقيط السطحي من حيث إنتاجية الفاصوليا الخضراء. وتشير النتائج إلى أن الرى بالتنقيط تحت السطحى يعزز متوسط إنتاجية الفاصوليا الخضراء بحوالي ١١٪ مقارنة مع الرى بالتنقيط السطحى لكل من معاملات الري الكامل والناقص. متوسط إنتاج الفاصوليا الخضراء هو ٢٦,٨٤٤ طن/هكتار و ٣٠,١٥٦ طن/هكتار للرى بالتنقيط السطحى والرى بالتنقيط تحت السطحى على التوالي.بالإضافة إلى ذلك، أظهرت النتائج أن الرى بالتنقيط تحت السطحي أدى إلى زيادة كفاءة استخدام المياه مقارنة بالتنقيط السطحي فى ظل ظروف الري الناقص. كما تشير النتائج إلى أن الرى بالتنقيط تحت السطحي، إلى جانب مستوى الري بنسبة ٨٠٪ يزيد من إنتاجية الفاصوليا الخضراء مع تحسين كفاءة استخدام المياه. وصلت الإنتاجية إلى ٣٣,٦١٤ طن/هكتار بينما بلغت كفاءة استخدام المياه ١٢,٨١ كجم/م^{٣}.كما أشارت النتائج إلى أنه في المناطق التي تواجه ندرة المياه، يكون تنفيذ استراتيجيات الري بالتنقيط تحت السطحى مع معاملة الري ٦٠٪ خلال موسم النمو بأكمله نهجًا قابلاً للتطبيق في الصوبات الزراعية حيث وصلت الإنتاجية إلي ٣٢,٤٦٦ طن/هكتار، في حين أن كفاءة استخدام المياه هو ١٥,٧٣ كجم/م^{٣}.ومن خلال ماسبق فإن الجمع بين نظام الري بالتنقيط تحت السطحي واستراتيجية الري الناقص يعزز كلاً من كفاءة استخدام المياه وإنتاجية الفاصوليا الخضراء في ظل ظروف الصوب الزراعية خاصة في المناطق التي تعاني من ندرة المياه.