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Research Article

Advanced IoT-Based Remote Monitoring and Control for Smart Solar-Powered Irrigation Systems

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Abstract:

In arid regions where water is scarce, effective management of irrigation water for agricultural practices is a major challenge. Integrating IoT technology with modern irrigation systems enables real-time monitoring and data-driven decision-making, significantly improving irrigation efficiency. Therefore, the current study aims to improve water use in these environments by integrating cutting-edge Internet of Things (IoT) technology into modern subsurface irrigation systems. Considering the urgent need for sustainable date palm farming in arid regions, the study focuses on developing and validating an innovative IoT-based system for remote monitoring and controlling solar-powered smart subsurface irrigation (SSI) systems. This SSI system operates under two distinct irrigation scheduling strategies: volumetric soil sensor-based irrigation scheduling (VSS-BIS) and evapotranspiration-based irrigation scheduling (ET-BIS). The SSI system performance was evaluated against the traditional bubbler irrigation (TBI) system. The SSI features an independent sensor network that collects real-time data based on soil moisture in VSS-BIS and based on climatic conditions in ET-BIS. This data is managed through the ThingSpeak cloud platform, which supports algorithmic analysis, generates event-triggered alerts for users, and sends instructions to IoT devices based on the specific irrigation approach. The SSI system with VSS-BIS followed by ET-BIS proved to be significantly more efficient than TBI, reducing water consumption by 62.3% and 58.2%, respectively. The average annual water use of SSI with VSS-BIS, ET-BIS, and TBI was found to be 28.91, 32.51, and 68.81 m^3/palm tree, respectively. The water use efficiency (WUE) was highest with SSI using VSS-BIS (1.83 kg/m^3), followed by ET-BIS (1.56 kg/m^3), and much lower with TBI (0.62 kg/m^3). This result was because the VSS-BIS method consistently maintained the volumetric water content close to field capacity, improving root zone conditions. This study confirms the beneficial effect of IoT application for date palm irrigation management, especially in combination with the VSS-BIS, demonstrating its effectiveness for irrigation water conservation in arid climates.

Keywords:
Cutting-edge technology; Date palm; Sensors; Evapotranspiration; Water conservation; Sustainability; Arid regions

1. Introduction

In arid regions, where water resources are increasingly strained, efficient irrigation water management for agricultural practices denotes a formidable challenge (Ahmed Mohammed et al., 2020). Drought poses a significant challenge to agricultural productivity, with its severity escalating across many cultivated regions globally. Consequently, enhancing water efficiency stands as a fundamental goal in the pursuit of sustainable agriculture (Mohammed, Riad, et al., 2021).

The date palm (*Phoenix dactylifera* L.) thrives in arid and semi-arid regions where water resources are scarce (Shadeed, 2013). Despite the challenges posed by water scarcity in these areas, inefficient irrigation practices persist in date palm orchards, leading to the depletion of precious groundwater sources (Baig et al., 2020). The most of existing irrigation systems utilize a fixed schedule for water application, irrespective of the actual water needs of the plants, posing a considerable challenge for irrigation water management (Calera et al., 2017). Effective irrigation scheduling plays a vital role in achieving optimal crop yields. However, with traditional surface irrigation methods, making frequent adjustments to irrigation depth and frequency is impractical due to implementation complexities. These variations in irrigation depth can be perplexing for producers, making it challenging to adjust the irrigation schedule accordingly (Pereira, 1998). Soil sensor-driven irrigation scheduling represents an applicable solution tailored to field-specific parameters, suggesting a significant contribution to making informed decisions regarding irrigation water scheduling (Sagheer et al., 2021).

Soil moisture measurement involves assessing the moisture level in the soil through either direct or indirect means. Control entails interpreting these measurements and implementing actions that offer the greatest benefit. One direct method involves utilizing a device known as a tensiometer, which gauges the amount of tension or negative pressure within the soil. Another method is the gravimetric technique, considered the gold standard, although it's impractical for regular soil moisture monitoring due to its slow nature. Conventional time domain refractometry (TDR) measurements provide estimates of average soil moisture and the bulk electrical conductivity of the surrounding medium by analyzing the travel time of a reflected electromagnetic wave within a wave guide/TDR probe inserted into the soil (Graeff et al., 2010).

Schmitz and Sourell (2000) attempted to assess the measurement uncertainty of various commercially available sensors including granular matrix, electro conductivity, and time-domain reflectometry sensors. Their findings revealed significant scattering over time, leading the researchers to advise against scheduling irrigations solely based on these instruments without considering the considerable uncertainty associated with their measurements. In contemporary soil moisture measurement methods, numerous types of sensors have been defined and classified by Jorapur et al. (2015). Capacitive, resistive, densiometric, hygrometric, and other indirect measurement techniques have been developed (Susha Lekshmi et al., 2014). Some of them have been miniaturized; e.g., polymer-based resistive method (Liu et al., 2008), micro-machined beam, micro-tensiometer (Jackson et al., 2008) and heat-pulse (Valente et al., 2004) methods.

Moghaddam et al. (2010) proposed a method employing a smart wireless sensor to achieve optimal measurements of soil moisture profiles from the surface to deeper layers using in-situ sensors. This system integrates feedback and control within a dynamic physics-based hydrologic and sensor modeling framework. Their findings indicated that the synchronized operation of sensors guided by the control policy leads to significant reductions in resource consumption.

Due to the substantial advancements in artificial inelegance (AI), internet of things (IoT), and sensor technology for precision agriculture, their implementation brings about significant advantages for both plant growth and the saving of irrigation water (Mohammed et al., 2023; Nam et al., 2020). In a study by the authors (Abba et al., 2019), an IoT-based monitoring and control system for irrigation was introduced, with a focus on ensuring adequate water supply for specific domestic crops in India. The system employed a pumping mechanism to deliver the required water to the soil. However, it lacked the integration of a flow meter to accurately measure the volume of water applied.

The objective of the current study is to develop and validate an innovative IoT-based system for remote monitoring and controlling solar-powered smart subsurface irrigation (SSI) systems for date palm irrigation in arid regions by comparing the performance of two different irrigation scheduling strategies, volumetric soil sensor-based irrigation scheduling (VSS-BIS) and evapotranspiration-based irrigation scheduling (ET-BIS), against the traditional irrigation method.

2. Materials and Methods

3.1. Study Area

The experimental study was conducted in an arid region at the experimental farm of the Date Palm Research Center of Excellence (Latitude: 25.26121 ° N and Longitude: 49.70841 ° E), King Faisal University, Saudi Arabia for one year from 1 January to 31 December 2022. The irrigation water used during the experiment had electrical conductivity, pH, and total dissolved solids values of 0.94 ± 0.16 dS m^{-1}, 7.91 ± 0.87, and 781 ± 50.11 mg L−1, respectively. The bulk density, field capacity, pH, electrical conductivity, and hydraulic conductivity of the soil in the study area were 1.59 ± 0.14 g cm^{-3}, 16.87 ± 0.59 %, 7.8 ± 0.97, and 3.25 ± 0.12 dS m^{-1}, and 4.76 ± 0.15 cm h^{-1}, respectively.

3.1. Description of the Irrigation System

A single solar-powered pumping system was employed for the irrigation setups, including a solar-powered irrigation control unit, two water pumps a water source, water solenoid valves, pressure regulator, valves, a pressure gauge, and water flow meters. In the evapotranspiration-based irrigation scheduling (ET-BIS), the solar-powered irrigation control unit incorporated four digital programmable timers, electronic circuits, and power sources for the valves and timers. Figure 1 displays the main components of the developed irrigation system and the irrigation units distribution around the date palm tree.

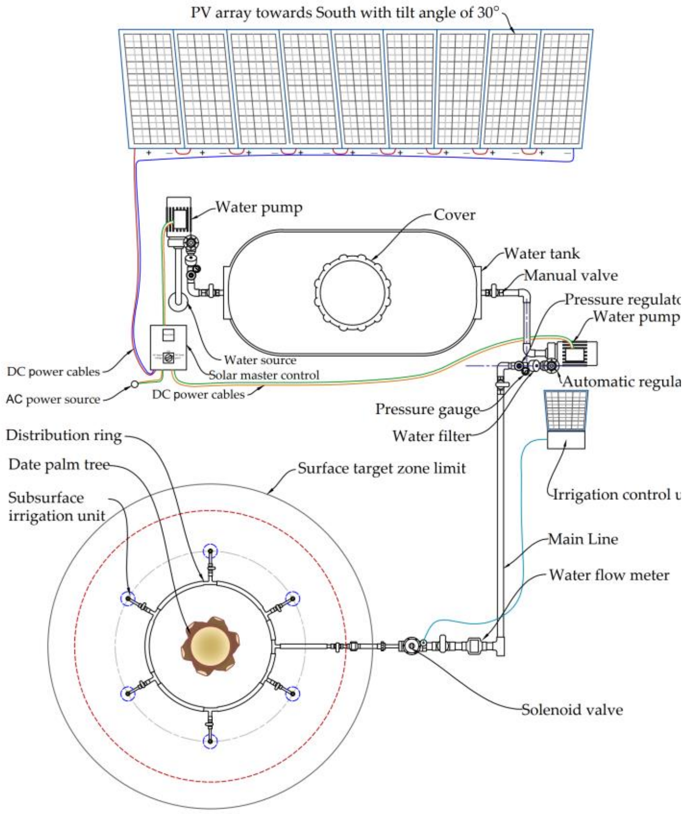

Figure 1. The main components of the irrigation system and the irrigation units' distribution around the palm tree.

The irrigation network comprised mainlines measuring 5 cm in diameter, sublines with a diameter of 2.5 cm, and a distribution ring with a diameter of 1.25 cm, all fabricated from high-density polyethylene material. For water infiltration, disc filters were installed to cleanse the water before it entered the tank and before being pumped into the irrigation networks. Furthermore, manual water valves were employed to manage the flow of irrigation water, serving as backup control measures during system malfunctions and for maintenance tasks. Pressure regulators were employed to prevent water hammering, maintain optimal pressure levels, minimize water leakage, and stabilize pressure fluctuations within the connecting irrigation networks. These pressure regulators, crafted from high-quality copper, featured a connector size of DN25 (2.5 cm). The solenoid valves-controlled water flow based on the irrigation schedule, operating at a voltage of 24 V, with a valve thread size of 2.5 cm, and a working water pressure range of 0.03 - 1.72 MPa. Multiple pressure gauges were employed to monitor irrigation water pressure during operation, ensuring that the required amount of water reached each palm tree at the specified time. The irrigation water pumps utilized were of the Self-priming JET pump type, featuring a mono-phase power supply, power rating of 1100 W, 220-240 V, maximum flow rate of 2.100 m^3/h, maximum working pressure of 6 bar, and constructed from stainless steel.

In this system, 6 subsurface irrigation units were employed for each palm tree, as shown in Figure 1. These subsurface irrigation unit comprised two perforated pipes constructed from polyvinyl chloride (PVC) and encased with a filtering cloth to hinder the intrusion of fine soil particles into the unit, as illustrated in Figure 2. These units were connected to the distribution ring, which was then linked to the subline. Each subsurface irrigation unit consisted of two perforated pipes filled with light volcanic gravel sandwiched between them. The outer pipe had 12.5 cm diameter and 35 cm length, featuring slotted surfaces measuring 0.2 cm in width, 4.0 cm in length, and tilted at a 30° angle.

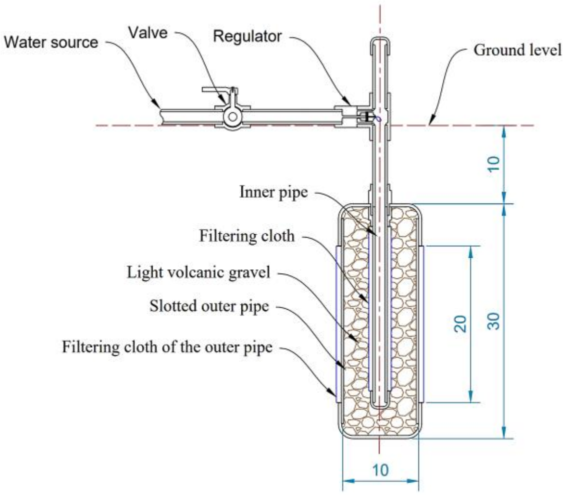

Figure 2. Schematic diagram for the used subsurface irrigation unit.

3.2. IoT System Architecture

Figure 3 displays the hardware components and devices related to a smart irrigation system. The hardware components include relays, contactors, and the ESP8266 Wi-Fi module, which facilitates the automation and connectivity of the system. Additionally, the figure features the Arduino Mega microcontroller, sensors for environmental data collection, PV modules for solar power generation, batteries for energy storage, inverters for DC/AC conversion, charge controllers for managing power flow, as well as valves, pumps, and an irrigation network for water distribution. These components were integrated for the operation and control of a modern, IoT-driven irrigation system to enable the efficient and intelligent management of the irrigation process in the volumetric soil sensor-based irrigation scheduling (VSS-BIS).

Figure 3. Hardware components and Devices in a Smart Irrigation System

3.3. Experimental Layout

In the current study, we developed and implemented the solar-powered smart subsurface irrigation (SSI) system to maintain soil moisture content near field capacity while optimizing irrigation water usage. An experiment was performed to assess the impact of SSI on date palm yield and water productivity. Volumetric soil sensor-based irrigation scheduling (VSS-BIS) and evapotranspiration-based irrigation scheduling (ET-BIS) were utilized as essential tools for irrigation scheduling decisions, customized based on plant characteristics and field attributes. The study applied full-grown date palm trees (Phoenix dactylifera L.) of the Khalas variety, aged 14 years. The VSS-BIS and ET-BIS methods were compared with traditional surface irrigation (Control) in a randomized complete block design. The irrigation amount in VSS-BIS was controlled based on soil volumetric water content using VH400 sensors (Vegetronix, Inc., Riverton, USA) and a cloud platform and IoT system, with hysteresis operated to minimize relay and conductor switching. In ET-BIS, irrigation was selected based on calculated crop evapotranspiration (ETc) and target soil area, with 60% of ETc applied following recommendations of (Ahmed Mohammed et al., 2020).

The amount of irrigation water requirement (IWR) for each irrigation system was estimated based on the target deficit irrigation percentage, ETc of the study area, and the target irrigation area as the following equation:

$$\mathrm{IWR} = \frac{\mathrm{ET_c} \times \mathrm{A}_i}{1000\ (1 - \mathrm{LR})} \qquad 1$$

where IWR is the irrigation water requirement (m^3/palm/day), Et_c is the crop evapotranspiration (mm/day), A_i is the target irrigation area of each date palm tree, LR is the leaching requirement (LR = 0.2). The ETc was determined according to the following equation:

$$\mathrm{ETc} = \mathrm{Kc} \times \mathrm{ETo} \qquad 2$$

where Kc is the crop factor (the average Kc was 0.95) (Ahmed Mohammed et al., 2020; FAO, 2008), and ETo is the reference evapotranspiration (mm/day). The ETo was calculated using FAO software (CropWat 7) according to Penman-Monteith equation (Clarke et al., 2001).

3.4. Statistical Analysis

The statistical analysis employed analysis of variance (ANOVA) to analyze data using IBM SPSS version 26 (SPSS Inc., Chicago, USA). The significant differences among the means at level of $P < 0.05$, was determined using Tukey Test.

3. Results

3.1. Data Description

Figure 4 displays the volumetric soil water content within the controlled subsurface irrigation system utilizing the VSS-BIS method throughout the year 2020 at the experimental site. The volumetric soil water content was maintained within the specified range, bounded by the Min Setpoint of 15% and the Max Setpoint of 30%. Figure 5 shows the meteorological parameters measured from 1-January 2022 to 31 December 2023, using the cloud-based IoT platform developed in the current study. The Al-Ahsa region experiences extremely hot, dry summers and mild to cool winters. December exhibited the lowest average temperature, followed by January and November. Summer temperatures began to rise from May onwards, peaking in June, July, and August. The highest maximum temperatures occurred in June and July, while the lowest were recorded in December and January. The lowest average monthly relative humidity was observed in May and June, while the highest was in November, with intermediate levels in January and December. Solar radiation was highest in May and June, followed by July, with the lowest levels in November and December. Wind speed peaked in April and May and was lowest in January and December.

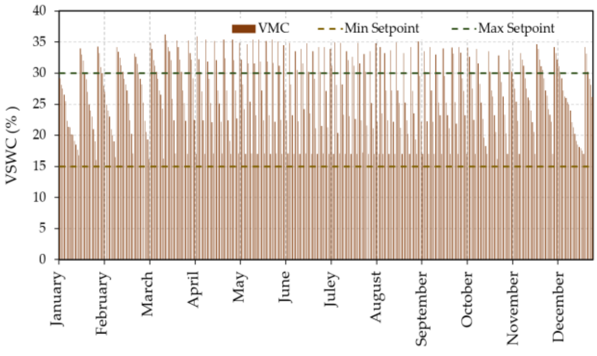

Figure 4. The measured volumetric soil water content (VSWC) in the controlled subsurface irrigation system using VSS-BIS method throughout the year 2022 at the experimental site using the cloud-based IoT platform.

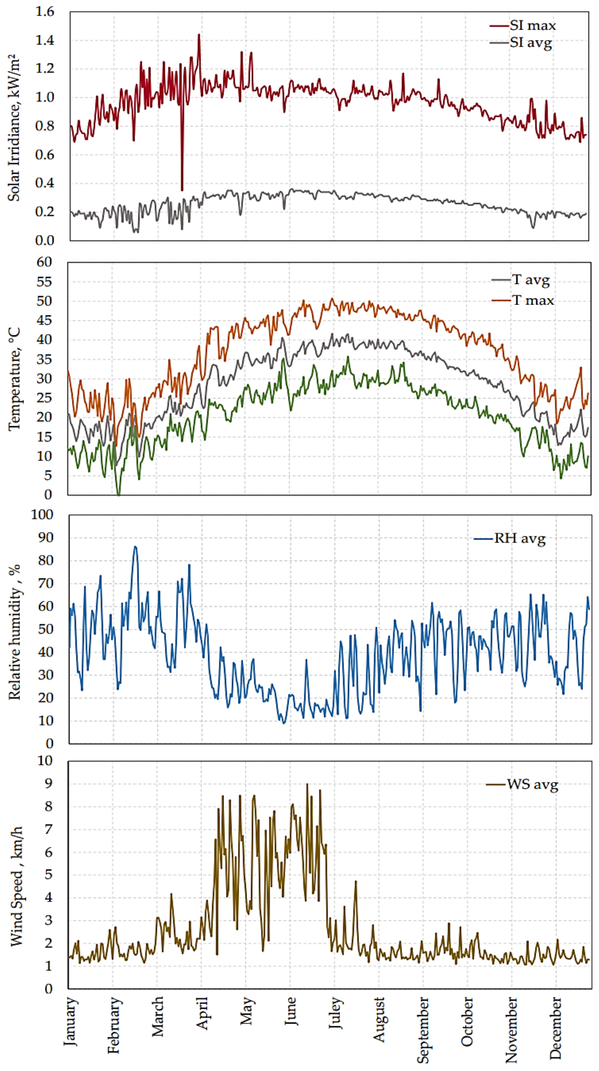

Figure 5. The meteorological parameters measured from January 1, 2022, to December 31, 2023, using the cloud-based IoT platform.

3.2. Applied Irrigation Water

Figure 6 displays the average crop evapotranspiration (ETc) and applied irrigation water (AIW) at 60%, ETc from 1-January 2022 to 31-December 2023. ETc was lowest during the winter months (January, February, November, and December) but peaked during the summer months (April, May, June, July, August, and September). Similarly, the highest water application occurred in summer, with reduced amounts during winter.

Figure 7 shows the average AIW for the date palm trees under investigation, as well as the cumulative water consumption over a year within the implemented controlled SSI system using the (VSS-BIS) method. The average annual cumulative water consumption was found to be 28.91 m^3. In the VSS-BIS method, irrigation intervals varied throughout the study period based on soil VSWC conditions.

Figure 8 shows the average AIW for the date palm trees under investigation, as well as the cumulative water consumption over a year within the implemented SSI system using the ET-BIS method. The average annual cumulative water consumption was found to be 32.51 m^3.

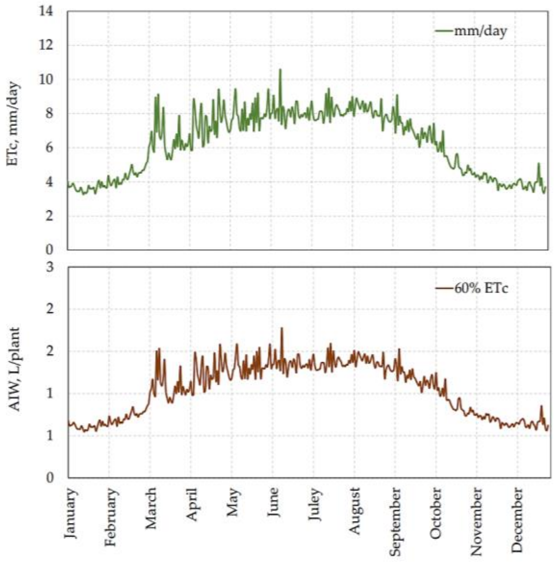

Figure 6. Average daily ETc and applied irrigation water (AIW) from January 1, 2022, to December 31, 2023.

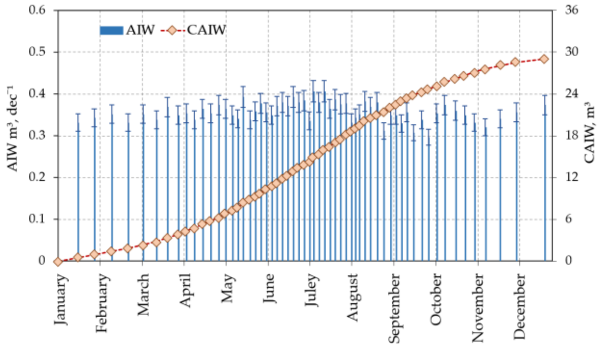

Figure 7. The average volume of applied irrigation water (AIW) and the average cumulative volume of water applied (CAIW) throughout the year 2022 at the experimental site, employing the designed controlled SSI system with the VSS-BIS method.

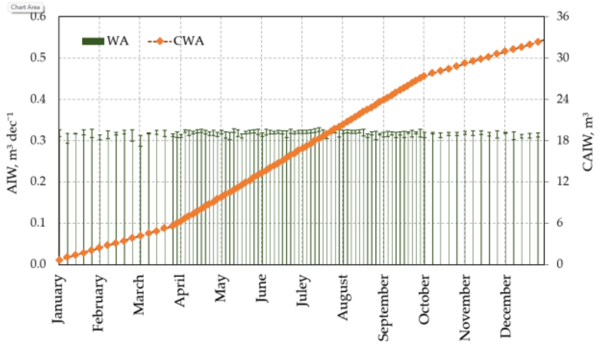

Figure 8. The average volume of applied irrigation water (AIW) and the average cumulative volume of water applied (CAIW) throughout the year 2022 at the experimental site, employing the SSI system with the ET-BIS method.

The SSI system employing VSS-BIS significantly ($p < 0.05$) succeeded in being notably more effective than TBI, reducing water usage by 62.3%, while employing ET-BIS resulted in a reduction of 58.2%. On average, the annual water consumption per palm tree was determined to be 28.91 m^3 with SSI using VSS-BIS, 32.51 m^3 with ET-BIS, and significantly higher at 68.81 m^3 with traditional bubbler irrigation. In general, the yearly cumulative application of irrigation water for date palm trees utilizing the designed CSIS with either S-BIS or T-BIS fell below the range documented by (Ahmed Mohammed et al., 2020; Alnaim et al., 2022; Mohammed et al., 2023; Mohammed, Riad, et al., 2021; Mohammed, Sallam, et al., 2021).

3.3. Yield and Water productivity

Table 1 shows the comparative impact of the VSS-BIS and ET-BIS methods implemented within the designed SSI against the traditional bubbler irrigation method on the studied date palm yield, applied irrigation water, and water productivity. Significant differences ($P < 0.05$) were observed in terms of cumulative applied irrigation water, total marketable yield of date palm, and water productivity across the SSI with VSS-BIS, ET-BIS, and traditional methods. The VSS-BIS and ET-BIS methods showed the highest marketable yield and water productivity, while the lowest values were observed with traditional surface irrigation. Notably, date palm trees irrigated using the SSI with the VSS-BIS method showed a substantial reduction in applied irrigation water compared to the ET-BIS and traditional surface irrigation methods.

Table 3. The applied irrigation water (AIW, m3/palm/year), total yield of date palm trees (Yield, kg/palm), and water productivity (WP, kg/m3) within the experimental season of 2022 under the VSS-BIS and ET-BIS methods of the controlled subsurface irrigation system CSSI system and traditional surface irrigation (Control).

Parameters	**Irrigation methods**		
	CSSI		**(Control)**
	VSS-BIS	ET-BIS	
AIW	28.91 ± 1.04^{A}	32.51 ± 0.98^{B}	68.81 ± 0.36^{C}
Yield	52.87 ± 2.83^{A}	49.94 ± 2.13^{B}	42.45 ± 3.12^{C}
WP	1.83 ± 0.12^{A}	1.56 ± 0.14^{B}	0.62 ± 0.29^{C}

Figures with the same letter in each row are non-significant at $P < 0.05$.

In this investigation, irrigation scheduling relied on volumetric water content sensors within the SSI employing VSS-BIS. This approach aimed to mitigate the risk of emitter flow rates surpassing the soil's capacity to evenly distribute irrigation water within the functional root zone. This contrasts with the utilization of constant irrigation depth, which can be determined and estimated through computer programs or practical insights gleaned from prior research endeavors (Ahmed Mohammed et al., 2020; Al-Muaini et al., 2019; Intrigliolo & Castel, 2010). The smart irrigation system demonstrated enhancements in both water productivity and date palm yield. While employing a constant irrigation depth can streamline and simplify irrigation processes, failing to apply the actual depth of irrigation water uptake often leads to either excessive or inadequate irrigation (Alikhani-Koupaei et al., 2018; Allen et al., 1998; Egea et al., 2012). Furthermore, traditional subsurface irrigation systems pose challenges in effectively controlling irrigation water, as they rely on estimating water requirements from historical evapotranspiration data rather than real-time weather conditions. This underscores the necessity of employing IoT technology to monitor crucial weather parameters like solar radiation intensity, temperature, relative humidity, and wind speed for accurate real-time evapotranspiration estimation. Consequently, our study ensured effective management of the subsurface irrigation system to prevent issues such as water deficit, reduction in date palm yield and quality, or over-irrigation by implementing controlled SSI with ET-BIS.

4. Conclusions

The integration of modern automatic irrigation sensors and devices is critical for enhancing traditional irrigation systems and promoting water conservation. These systems, enriched with contemporary water-saving technologies, have undergone further advancements aimed at enhancing water productivity. This research proposes a solution to address and mitigate the drawbacks of water-saving subsurface irrigation methods through the application of IoT technology, which facilitates improved control over system operations. Moreover, the utilization of subsoil irrigation systems for water applications often lacks adequate monitoring, management, and evaluation of irrigation events. In the current study, irrigation scheduling relied on volumetric water content sensors within the CSIS with S-BIS to mitigate the risk of emitter flow rates exceeding the soil's capacity to distribute irrigation water in the root zone effectively. Further studies are needed to explore the effects of contemporary irrigation systems on various fruit tree species and diverse soil compositions.

Author Contributions: Conceptualization, M.M. and A.D.; methodology, M.M.; software, M.M.; validation, M.M. and A.D.; formal analysis, M.M.; investigation, M.M.; resources, M.M.; data curation, M.M.; writing—original draft preparation, M.M. and A.D.; writing—review and editing, M.M. and A.D.; visualization, M.M.; supervision, M.M.; project administration, M.M.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare that there is no conflict of interest.

References

Abba, S., Namkusong, J. W., Lee, J. A., & Crespo, M. L. (2019). Design and performance evaluation of a low-cost autonomous sensor interface for a smart iot-based irrigation monitoring and control system. In *Sensors (Switzerland)* (Vol. 19, Issue 17). https://doi.org/10.3390/s19173643

Ahmed Mohammed, M. E., Refdan Alhajhoj, M., Ali-Dinar, H. M., & Munir, M. (2020). Impact of a Novel Water-Saving Subsurface Irrigation System on Water Productivity, Photosynthetic Characteristics, Yield, and Fruit Quality of Date Palm under Arid Conditions. *Agronomy*, *10*(9), 1265. https://doi.org/10.3390/agronomy10091265

Al-Muaini, A., Green, S., Abou Dahr, W. A., Kennedy, L., Kemp, P., Dawoud, M., & Clothier, B. (2019). Water use and irrigation requirements for date palms on commercial farms in the hyper-arid United Arab Emirates. *Agricultural Water Management*, *223*, 105702. https://doi.org/10.1016/j.agwat.2019.105702

Alikhani-Koupaei, M., Fatahi, R., Zamani, Z., & Salimi, S. (2018). Effects of deficit irrigation on some physiological traits, production and fruit quality of ‘Mazafati’ date palm and the fruit wilting and dropping disorder. *Agricultural Water Management*, *209*, 219–227. https://doi.org/10.1016/j.agwat.2018.07.024

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *FAO Irrigation and Drainage Paper No. 56 - Crop Evapotranspiration. January 1998.*

Alnaim, M. A., Mohamed, M. S., Mohammed, M., & Munir, M. (2022). Effects of Automated Irrigation Systems and Water Regimes on Soil Properties, Water Productivity, Yield and Fruit Quality of Date Palm. *Agriculture (Switzerland)*, *12*(3), 343. https://doi.org/10.3390/agriculture12030343

Baig, M. B., Alotibi, Y., Straquadine, G. S., & Alataway, A. (2020). Water resources in the kingdom of Saudi Arabia: Challenges and strategies for improvement. *Global Issues in Water Policy*, *23*, 135–160. https://doi.org/10.1007/978-3-030-29274-4_7

Calera, A., Campos, I., Osann, A., D’Urso, G., & Menenti, M. (2017). Remote sensing for crop water management: From ET modelling to services for the end users. In *Sensors (Switzerland)* (Vol. 17, Issue 5). https://doi.org/10.3390/s17051104

Clarke, D., Smith, M., & El-Askari, K. (2001). CropWat for Windows (Version 4.2). In *Oak Brook, IL, USA: IHE* (Issue October, p. 43). http://eprints.soton.ac.uk/73992/

Egea, G., González-Real, M. M., Baille, A., Nortes, P. A., Conesa, M. R., & Ruiz-Salleres, I. (2012). Effects of water stress on irradiance acclimation of leaf traits in almond trees. *Tree Physiology*, *32*(4), 450–463. https://doi.org/10.1093/treephys/tps016

Food and Agriculture Organization of the United (FAO) & International Center for Advanced Mediterranean Agronomic Studies (CIHEAM). (2008). Workshop on “ Irrigation of Date Palm and Associated Crops ” Faculty of Agriculture , Damascus University. In *East.*

Graeff, T., Zehe, E., Schlaeger, S., Morgner, M., Bauer, A., Becker, R., Creutzfeldt, B., & Bronstert, A. (2010). A quality assessment of spatial TDR soil moisture measurements in homogenous and heterogeneous media with laboratory experiments. *Hydrology and Earth System Sciences*, *14*(6), 1007–1020. https://doi.org/10.5194/hess-14-1007-2010

Intrigliolo, D. S., & Castel, J. R. (2010). Response of plum trees to deficit irrigation under two crop levels: Tree growth, yield and fruit quality. *Irrigation Science*, *28*(6), 525–534. https://doi.org/10.1007/s00271-010-0212-x

Jackson, T., Mansfield, K., Saafi, M., Colman, T., & Romine, P. (2008). Measuring soil temperature and moisture using wireless MEMS sensors.

Measurement: Journal of the International Measurement Confederation, *41*(4), 381–390. https://doi.org/10.1016/j.measurement.2007.02.009

Jorapur, N., Palaparthy, V. S., Sarik, S., John, J., Baghini, M. S., & Ananthasuresh, G. K. (2015). A low-power, low-cost soil-moisture sensor using dual-probe heat-pulse technique. *Sensors and Actuators, A: Physical*, *233*, 108–117. https://doi.org/10.1016/j.sna.2015.06.026

Liu, J., Agarwal, M., Varahramyan, K., Berney IV, E. S., & Hodo, W. D. (2008). Polymer-based microsensor for soil moisture measurement. *Sensors and Actuators, B: Chemical*, *129*(2), 599–604. https://doi.org/10.1016/j.snb.2007.09.017

Moghaddam, M., Goykhman, Y., Liu, M., Nayyar, A., Teneketzis, D., Entekhabi, D., Li, K., Mahajan, A., & Shuman, D. (2010). A Wireless Soil Moisture Smart Sensor Web Using Physics-Based Optimal Control: Concept and Initial Demonstrations. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *3*(4), 522–535. https://doi.org/10.1109/JSTARS.2010.2052918

Mohammed, M., Hamdoun, H., & Sagheer, A. (2023). Toward Sustainable Farming: Implementing Artificial Intelligence to Predict Optimum Water and Energy Requirements for Sensor-Based Micro Irrigation Systems Powered by Solar PV. *Agronomy*, *13*(4), 1081. https://doi.org/10.3390/agronomy13041081

Mohammed, M., Riad, K., & Alqahtani, N. (2021). Efficient iot-based control for a smart subsurface irrigation system to enhance irrigation management of date palm. *Sensors*, *21*(12). https://doi.org/10.3390/s21123942

Mohammed, M., Sallam, A., Munir, M., & Ali-Dinar, H. (2021). Effects of deficit irrigation scheduling on water use, gas exchange, yield, and fruit quality of date palm. *Agronomy*, *11*(11), 2256. https://doi.org/10.3390/agronomy11112256

Nam, S., Kang, S., & Kim, J. (2020). Maintaining a constant soil moisture level can enhance the growth and phenolic content of sweet basil better than fluctuating irrigation. *Agricultural Water Management*, *238*, 106203. https://doi.org/10.1016/j.agwat.2020.106203

Pereira, L. S. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56 H2Olive3s View project no title View project. *Fao, Rome*, *300*(9), D05109.

Sagheer, A., Mohammed, M., Riad, K., & Alhajhoj, M. (2021). A cloud-based IoT platform for precision control of soilless greenhouse cultivation. *Sensors (Switzerland)*, *21*(1), 1–29. https://doi.org/10.3390/s21010223

Schmitz, M., & Sourell, H. (2000). Variability in soil moisture measurements. *Irrigation Science*, *19*(3), 147–151. https://doi.org/10.1007/s002710000015

Shadeed, S. (2013). Spatio-temporal Drought Analysis in Arid and Semi-arid Regions: A Case Study from Palestine. *Arabian Journal for Science and Engineering*, *38*(9), 2303–2313. https://doi.org/10.1007/s13369-012-0504-y

Susha Lekshmi, S. U., Singh, D. N., & Shojaei Baghini, M. (2014). A critical review of soil moisture measurement. *Measurement: Journal of the International Measurement Confederation*, *54*, 92–105. https://doi.org/10.1016/j.measurement.2014.04.007

Valente, A., Morais, R., Couto, C., & Correia, J. H. (2004). Modeling, simulation and testing of a silicon soil moisture sensor based on the dual-probe heat-pulse method. *Sensors and Actuators, A: Physical*, *115*(2-3 SPEC. ISS.), 434–439. https://doi.org/10.1016/j.sna.2004.04.056

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