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Development and Evaluation of Smart Drip Irrigation System for Egg Plant using Internet of Things

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An optimized irrigation system maximizes agricultural productivity, ensures efficient water use, and reduces off-site effects caused by excess percolation of water. To address the problems associated with conventional irrigation systems, a drip irrigation system that is based on Internet of Things (IoT) technology for automation of irrigation scheduling was developed and tested for Egg Plant (Brinjal) crop in vertisols. The study compared crop performance under two different drip irrigation systems — one based on IoT and the other based on crop evapotranspiration (ETc). An intelligent data collection system, including sensors and a microcontroller was used in the experiment to monitor relative humidity, soil temperature, air temperature, and soil moisture content. The sensors collect data wirelessly transmitted to a cloud server via the IoT, allowing worldwide access from anywhere. The performance of the egg plant crop revealed significantly higher plant height and crop yield (12.05%) under a drip irrigation system utilizing IoT technology, which could be due to the optimum and timely application of water over ETc-based drip irrigation. Along with improved crop performance, water savings of 35.2% were observed as compared to ETc-based drip irrigation. The developed system can be evaluated in a large field with several sensors together along with a mobile app for a user-friendly system.

Keywords: Data acquisition system, IoT, Irrigation, Precision agriculture, Wireless sensor network

Introduction

In modern years, agriculture has undergone a fourth revolution (Agriculture 4.0), as Information and Communication Technology (ICT) has transformed conventional farming practices.[1–4] Industrial Revolution 4.0 began in the automobile sector and has now extended to other sectors, introducing pioneering technologies such as the Internet of Things (IoT), cloud platforms, data science, and artificial intelligence (AI). Every day, massive amounts of data are generated and analyzed due to innovations in these technologies.[5–7] In this perspective, agricultural field operations have tremendous scope to implement such techniques, which can significantly enhance the efficiency of farming practices by enforcing real-time monitoring and control. Agriculture 4.0 seems to be the most current advancement in Precision Agriculture (PA) and is focused on the idea of sustainable agriculture.[8–11] Agriculture 4.0 is encouraged to take significant global advances in boosting food and agriculture system effectiveness and competitiveness, enhancing the quantity, reliability, and affordability of agricultural commodities, climate change mitigation and adaptation, minimizing food insecurity, optimization of energy and resource use in a sustainable approach, and, as a result, dramatically minimizing environmental impact.

In PA, one of the most well-known names is scaling dizzying heights and establishing a benchmark through the use of sensors and the Internet of Things. It is inspired by the need to recognize potential uses, patterns, implementations, and research directions due to a lack of development, network connectivity, operational efficiency, limited water resources, and real-time monitoring of the agricultural field. In contrast, an irrigation management system based on Wireless Sensor Networks (WSNs) can embrace any desirable irrigation scheduling method to satisfy specific environmental considerations.[12] However, since WSNs are still in their beginning phases, they can be inconsistent, vulnerable, and hungry for power, and can lose communications, specifically when put in a hostile environment such as a field of agriculture.[13] In irrigation scheduling based on Wireless Sensor Network (WSN), the water demand for irrigation is determined directly through soil

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moisture condition, either by soil moisture content or by soil water tension.[14] Since the moisture content of the soil is directly related to crop stress, it is crucial in irrigation scheduling.

Very few studies have explored strenuous efforts in developing an autonomous wireless sensing system for crop root zone soil moisture conditions.[15] Few sensors available for irrigation automation are wide-ranging but have restrictions such as complex construction and configuration.[12,16] These systems have several setbacks, including limitations in the size of deployment for monitoring stations influenced by a substantial cabling range of connection; high installation, maintenance, and also repositioning expenses because of substantial cabling, and cable wires that are vulnerable to severe environments, if installed outdoors. The main highlight of this research is to set up an improved system with remote monitoring of environmental factors in an agricultural field and provide information and alarms on the current conditions to the field managers to act while storing the data for future analysis.

Materials and Methods

Study Area

This research has been carried out at the experimental field of ICAR - Central Institute of Agricultural Engineering Bhopal, India. The altitude of the study site is 495 m above mean sea level and lies in the Northern part of Bhopal at 77°24' 10" E, 23°18' 35" N. The soil composition of the area is heavy clay soil, with clay content ranging from 49.7 to 53.7%, while the Field Capacity (FC) ranges from 42.3 to 43.4% (v/w).[17] This region has a humid subtropical climate with cool, dry winters, hot summers, and a humid monsoon season with an average rainfall of 1146 mm. The average maximum temperature recorded was 38.5°C, and the minimum temperature was 11.5°C (observations between 2019 and 2020). Soil samples (0−20 cm soil depth) were collected and analyzed for soil particle size distribution (sand, silt, and clay) using the Bouyoucos hydrometer method. The undisturbed soil sample method was used to calculate bulk density. A pressure plate device was used to estimate FC and the Permanent Wilting Point (PWP).

Working Principle of Smart Irrigation System

The proposed smart drip irrigation system which is based on IoT technology applies the precise amount of water on time to meet the crop's water needs while maintaining field capacity, with maximum soil moisture depletion of 50%.[4,6,18] Sensors were deployed in a crop's root zone in undisturbed soil to attain precision irrigation using an IoT-instilled device.[19] Following the deployment of sensors, determining the Lower Set Point (LSP) and Higher Set Point (HSP) was carried out. The field capacity and wilting point must be known for setting the lower limit in order to start the pump. A field's capacity and wilting point are used for analyzing the available soil moisture content. The lower set point was reached as soon as the available moisture content was depleted by 50%. The soil moisture sensor alerts the controller to turn on irrigation when the soil moisture content drops below the LSP. As a result, water is pumped up to the field capacity when the soil moisture content falls below the HSP. The pump is shut down at HSP by a signal. A schematic view of the functioning of an automatic irrigation control system is shown in Fig. 1.

Developing the System for Data Acquisition

Specifications for Design

A wireless sensor-based smart irrigation system was developed and evaluated in this research work. The system's design was intended for water-resistant, fully wireless, portable, and robust for use in field conditions. Further, the device is powered with solar panels to ease installation and avoid substantial cabling for electricity supply and data communication. The transmitters collect the data from the sensors deployed in the field and send the data to a cloud-based platform through inbuilt Wi-Fi technology.

Elements of the Data Acquisition Module

This data acquisition device has three sensors:

- A capacitive soil moisture sensor (v2.0)
- A soil temperature sensor (DS18B20)
- A temperature and relative humidity sensor (DHT11)

ESP32-WROOM-32 microcontroller reads the output of these sensors and wirelessly transfers the entire observations that were recorded by these sensors using the ESP8266 Wi-Fi Module to an IoT-based platform (ThingSpeak).

The real-time field data were recorded and saved in the cloud server. Users can access the recorded information stored in a cloud server wirelessly by using a website on a device with Internet connectivity or visiting the Internet of Things (IoT) platform website. The field environmental data captured by sensors were used as input information to the

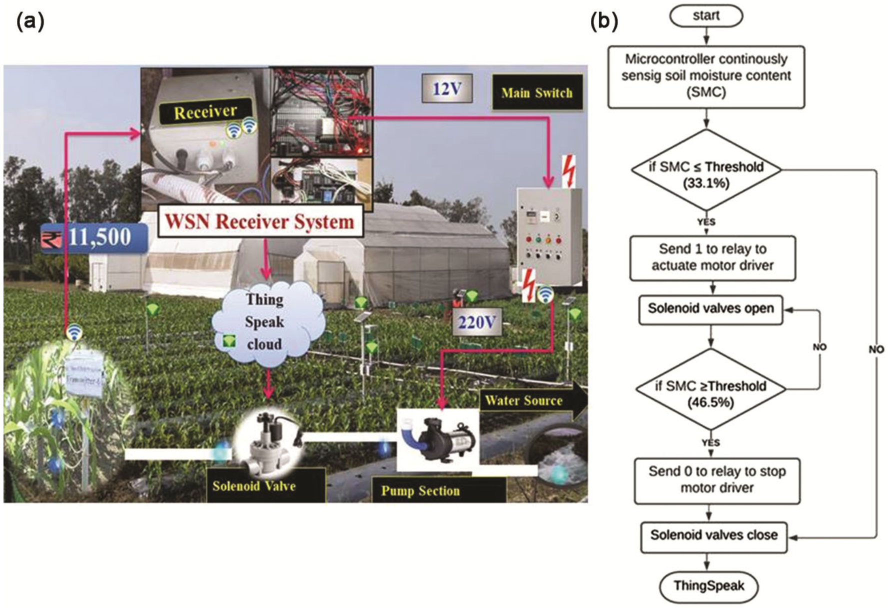

Fig. 1 — A flow chart for the functioning of an automatic irrigation control system

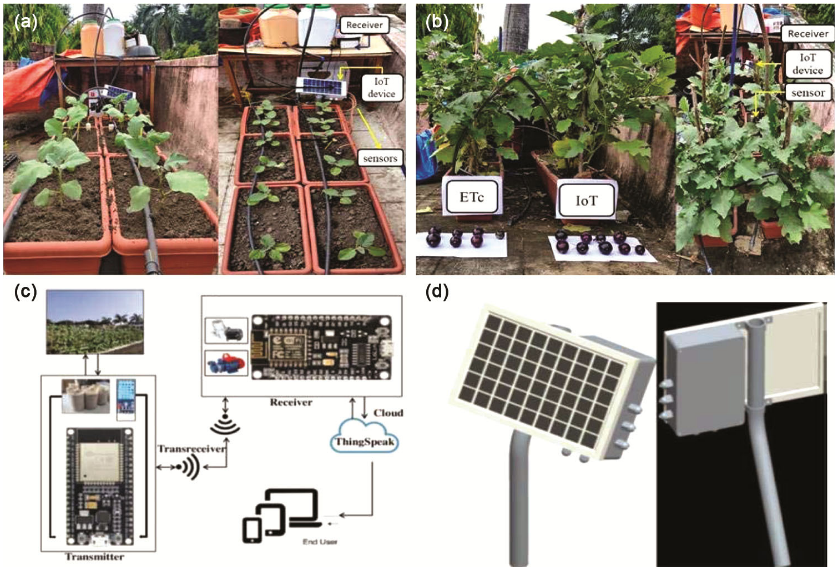

Fig. 2 — (a) General view of bed preparation and transplanting of egg plant (b) Laboratory simulation model development and testing (c) Data transfer from cloud to the user (d) Fully assembled IoT system

automated wireless sensor-based drip irrigation system. Further, the sensors transmit acquired field data from the microcontroller; it acts as a channel for communication of monitoring system data to the cloud server with specific configuration protocols. Message Queuing Telemetry Transport (MQTT) and JavaScript Object Notation (JSON) scripts were chosen for sending sensor node data to the IoT platform (ThingSpeak). The MQTT is a publish protocol-subscribe communication procedure that is designed for connecting to faraway regions with restricted network bandwidth. The JSON is an accessible communication data that provides attribute values and pairs of array data types in human-readable text format to the users. The environmental field data were communicated to the ThingSpeak platform via sensor nodes that are connected to wireless devices that are kept in the agriculture field, establishing a LAN (Local Area Network), as shown in Fig. 2. The designed system is low-cost, multipurpose, and adaptable to most agriculture fields using the plug-and-play technique.

Assembly of the Data Acquisition Unit

The electronic parts were assembled in the IP-65 weatherproof enclosure. Certain dimensions of all components were established, and the appropriate casing was created employing a Computer-Aided Design (CAD) application. Following that, the sensors were secured to the shell. Following that, the custom code is essential to acquire data from the environment via sensors using the Arduino IDE programming interface. The ESP 32 microcontroller uploads all the recorded information to the cloud platform. The transmitter (microcontroller) collects data from various sensors, and the measured values are uploaded to the IoT-based platform (ThingSpeak), which was chosen as a service provided by IoT platform explorers.

Experimental Details

The egg plant plant (*Solanum melongena*) variety MAHY 112 Hybrid was selected because the plant is sensitive to excess soil moisture, high salinity, water stress, and higher temperatures.[20] About three weeks healthy seedlings were transplanted in the well-prepared experimental plots as shown in Fig. 2. When rainfall occurred, the experiment was protected from the plastic sheet so that the interruption of the rain could be prevented during the experiment period. The experiment was conducted from June to October 2021 with two irrigated treatments with three replications; plot sizes of 180 × 45 cm area were used. The treatments were an IoT-based irrigation system and another crop evapotranspiration (ETc)-based irrigation schedule. Two plants of each plot were marked to determine plant morphological parameters. For ETc irrigation treatment, the crop's water requirement is based on the ETc of the crop.[21,22] The irrigation schedules and ET regimes for the study region/field were implemented based on daily calculations of the reference ETc by FAO Penman-Monteith method using CROPWAT 8.0 software.[10] The determination of ETc is done by multiplying reference crop evapotranspiration divided by a crop coefficient (Kc).[22] For considering the crop’s (egg plant) Kc value, FAO 56 was referred.

Crop Growth Parameters

The crop growth observations were recorded at 30, 60, 90, and 120 days after transplanting (DAT) on three randomly tagged competitive plants selected from each treatment for studying various characteristics, i.e. plant height, the number of branches, flowering and yield parameters such as fruit length, fruit size, yield per pot, and yield per plant as shown in Fig. 2. The crop root parameters were also determined at the final harvest; the tagged three plants from each treatment were carefully separated by cutting with roots.

Statistical Analysis

The work efficiency of the drip irrigation system which is based on IoT technology using real-time soil moisture monitoring was compared to those plants irrigated with the ETc (100%). To assess notable variances among various treatments, a paired t-test for two means statistics with an ANOVA analysis was used. To determine whether the subsequent analyses show significant distinctions at a selected significance level of $p = 0.05$.

Results and Discussion

Calibration of the Soil Moisture Sensor

The sensors' calibration was performed according to the widely used protocol described in the reference.[15] Furthermore; the gravimetric sensor calibration method was used to obtain a representative moisture content compared to the sensors' percentage readings at different moisture levels. The appropriate data have been collected and are displayed graphically in Fig. 3.

Performance Evaluation of Developed Data Acquisition Wireless Sensor Network System

Analysis of Functionality

The overall system underwent testing to ensure its capability to acquire data from the environment via sensing devices and communicate it to the cloud server (ThingSpeak). The wireless data-acquiring

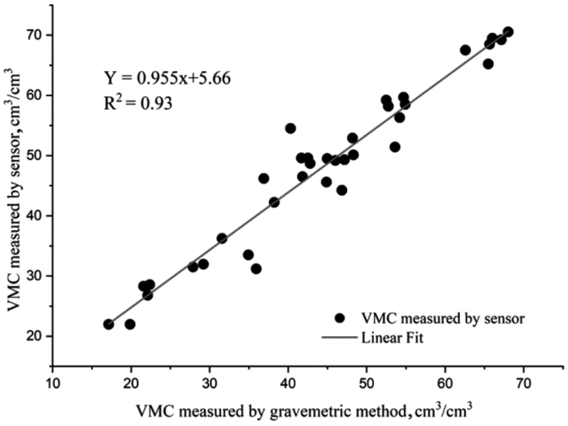

Fig. 3 — Graph showing the calibration of sensor-based soil moisture with the gravimetric method

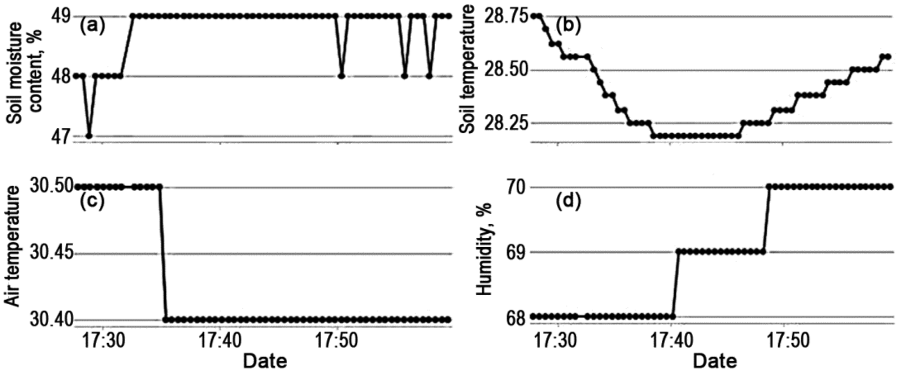

Fig. 4 — ThingSpeak IoT platform displaying environmental parameter data

device was evaluated by connecting to a locally available Wi-Fi dongle network. An internet webpage provided access to the ThingSpeak IoT platform. To observe, the already developed system was made to run for a short duration (a few hours) to mark numerous data points. The sensors successfully recorded and uploaded the environmental data readings to the IoT platform. Judging from the sensor observed, four variables' data is shown in graphs, as shown in Fig. 4. At every 15 to 20 seconds, the field data was transmitted to the IoT platform.

On-site Performance Analysis

A soil moisture sensor was installed 15 cm from the plant in the root zone depth to aid irrigation control. When the moisture level drops below the LSP, the sensor transmits a signal to the ESP 32's Wi-Fi module, which triggers the water pump for field irrigation through a smartphone/computer application. A continuous recording of the variables was transmitted to the ThingSpeak server and could then be accessed through ThingSpeak. The device is connected to the ThingSpeak web service directly to access and analyze cloud-based data in real-time. The representation of moisture content in soil, soil temperature, relative humidity, and air temperature values at different times is presented in Fig. 4. There is a control system for each individual's field channel valves. In the IoT-based analytics platform (ThingSpeak), if the value is 1, the motor is on, and if it is 0, it is off.

The field environmental data acquired through the sensors was systematically monitored and transmitted to the ThinkSpeak server, which can later be monitored via the ThinkSpeak IoT application. In the IoT-based data acquisition unit, sensors continuously recorded observations, namely temperature, humidity, soil temperature, and soil moisture measurements during one cropping season of egg plant. The daily variations in temperature, humidity, soil temperature, and soil moisture content were observed and recorded using different sensors like the DHT11 sensor to monitor and record the measurements about the humidity and temperature. The DS18B20 sensor that was installed for measuring the soil temperature and the volumetric moisture content of the soil, as well as the capacitive soil moisture sensor v2.0, was utilized during the research study, as shown in Fig. 5.

Effect of Irrigation on Growth and Yield of Egg Plant Crop

Growth Response of Above Ground Parts

The effect of the two irrigation methods on plant growth parameters was recorded and analyzed by paired t-test. Analysis details of crop growth parameters are shown in Table 1. The average plant height was recorded as 14.9 cm, 38.5 cm, 51.4 cm, and 54.5 cm for drip irrigation based on senor, whereas for drip irrigation system based on ETc, the average plant height was recorded as 10.7 cm, 34.5 cm, 44.8 cm, and 48.5cm, respectively at 30,60,90 and 120 days. It was observed from paired t-test results that there was a significant effect of irrigation methods on plant height at a 5% level of significance ($p < 0.004$). Irrigation methods had a significant impact on plant height. Sensor-based drip irrigation treatments showed higher plant height than ETc-irrigated treatments. Because of the real-time soil moisture-based irrigation scheduling, plant growth was observed to be higher (54.5 cm) in the drip irrigation treatment based on senor Due to the disrupted operation of the drip irrigation system, the height of plant for treatment using Etc drip irrigation system was reduced (48.5 cm). While the maximum plant height was observed around DAT 65 for sensor-

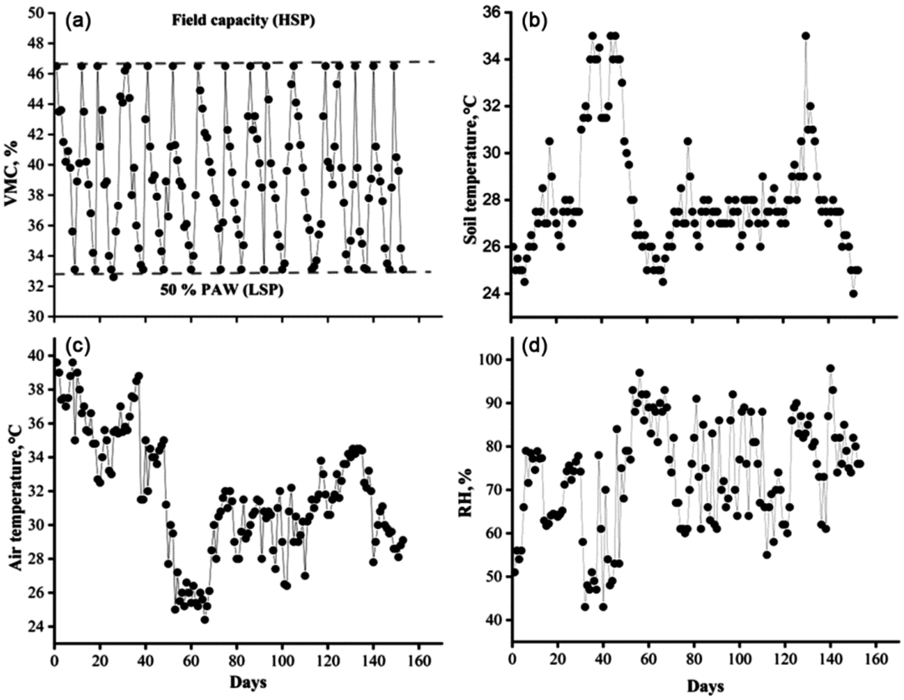

Fig. 5 — Observed and recorded parameter data of field environment on the ThingSpeak IoT-based platform using different sensors (a) Soil moisture sensor reading; (b) Soil Temperature; (c) Air Temperature; and (d) Relative Humidity

Table 1 — Paired t-test statistical performance of treatments for drip irrigation based on senor, ETc

t-test						
	Growth parameters					
Irrigation levels	Plant height (cm)	Number of branches	Fruit length (cm)	Crop root spread (cm)	Root length (cm)	Avg. fruit weight (g)
Sensor, ETc	0.004*	0.006	0.005	0.573	0.188	0.179
	Yield parameters					
Irrigation levels	Avg. fruit weight (g)	Yield per plant (kg)	Yield per pot (kg)	Yield per hectare(t/ha)	Water consumption (mm)	No. of fruits per plant
Sensor, ETc	0.179	0.011*	0.011*	0.043*	0.0182*	0.057

based treatment, the maximum plant height in the ETc drip irrigation treatments was observed around DAT 83. This could be attributed to maintaining sufficient soil moisture within the root zone through the crop growth cycle, leading to improved uptake of water and nutrients, which positively impacts crop growth.[19] Further, observations of the overall performance of plant morphological parameters revealed a significant improvement in sensor-based irrigation compared to ETc-based irrigation systems due to optimal irrigation scheduling, as shown in Fig. 6.

*Indicates significance at ($p < 0.05$), the other values within a table are not significantly different at a significance level of $p > 0.05$.

The number of branches per plant were also recorded during the crop-growing period. However, No significant different was noted at a 5% significance level. The average fruit size, fruit length, crop root spread, and number of fruits per plant were recorded as 36.7 mm, 5.2 mm, 27.6 mm, and 17 for sensor-based drip irrigation treatment. Similarly, average fruit size, fruit length, crop root spread, and number of fruits per plant were also at par in both the treatments. This could be the result of maintaining soil moisture content at field capacity within root zone depth for the whole crop period, leading to improved water and nutrient uptake and overall optimistic impact on crop growth.

Growth Response of Below Ground Parts

Furthermore, the crop root length (26.2 cm) was significantly higher under ETc-based drip irrigation

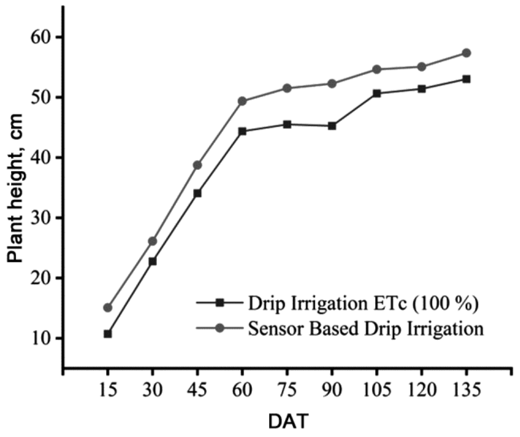

Fig. 6 — Plant height at different DAT under two irrigation regimes

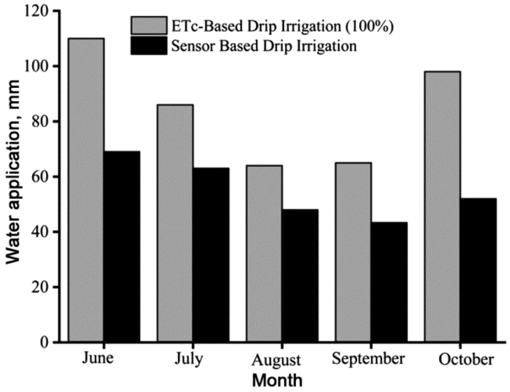

Fig. 7 — The amount of water applied under the two different irrigation treatments

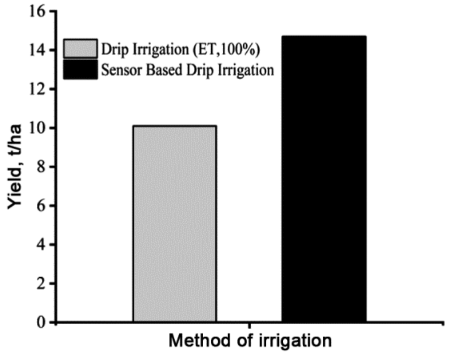

Fig. 8 — Yield for the different irrigation methodologies

treatment followed by sensor-based drip irrigation treatment (23.3 cm), respectively. The results on root length after harvesting were influenced by the effect of irrigation levels. The amount of water applied under the sensor-based drip irrigation treatment was the lowest (274.3 mm), whereas ETc-based drip irrigation treatment resulted in 423.6 mm application as shown in Fig. 7. Sustainably, more water was applied in ETc drip irrigation treatment which corresponds to almost 149.3 mm volume of water of the sensor-based drip irrigation. The total yield was recorded under a sensor-based drip irrigation system (14.4 t/ha) followed by ETc-based drip irrigation (10.6t/ha), as shown in Fig. 8. It was clear from the data that different irrigation methods significantly affected yield. In general, the effect of sensor-based drip irrigation has been confirmed that yields have increased with minimum water input. The primary aim of irrigation in farming is yield optimization and optimal water management.[16,18,23–25] To attain these objectives, it is frequently advised to keep the moisture content of the soil close to field capacity during the crop growing period.

The overall hypothesis of the study revealed that the right time of irrigation events is key to high yield levels.[3,26,27] A non-congenial root environment is created at field potential, resulting in increased water and nutrient uptake and increased growth and yield. Water is readily available to the crop in this situation. The irrigation water demand was directly determined from the moisture content in the soil, via moisture content, in sensor-based drip irrigation scheduling. As a result, since soil water potential is directly related to plant tissue stress, it is essential for irrigation scheduling. Experiments have confirmed that we can achieve outstanding outcomes, including reduced manual labor costs and efficient water usage for irrigation. Advanced sensor-based irrigation scheduling techniques strive to deliver appropriate water amounts to plants at the right times, enhancing irrigation efficiency, plat growth, and yields.[21]

On the other hand, over-irrigation is pricey and must be managed to avoid unfavorable adverse effects such as nitrogen leaching and enhanced pest and disease populations. When kc values were used, the ETc-based irrigation received nearly 149 mm more water than the drip irrigation treatment based on the sensor with the highest yield. Another critical factor demonstrated by measured observations of plant development, such as plant heights, the number of branches, crop yield, and water content of soil measurements, is presumably the appropriate timing of irrigation watering. Consequently, the ETc-based drip irrigation treatment used more water than the drip irrigation system based on sensors, resulting in higher soil moisture content. This was entirely due to improper irrigation timing, which was also evidenced in plant morphological parameter measurements.

Another critical factor is the scheduling of irrigation events. Irrigation is commonly used to maximize production rates by reducing the effects of drought during critical plant development phases.

Yield of Egg Plant

Egg plant yields were generally high for sensor-based drip irrigation treatments in which drip irrigation was automatically triggered at 33.5 percent volumetric soil moisture content at 15 cm soil depth. The automatic irrigation technique provides high yields while using relatively small amounts of irrigation water and tries to avoid timing issues. The potential benefits of drip irrigation scheduling based on sensors include the ease of setting up and maintaining, as well as the great promise for robotization. However, in particular, automation necessitates the use of costly advanced well-maintained irrigation systems and trained individuals

As the prescribed Kc values were used, the ETc-based drip irrigation treatment resulted in a massive over-irrigation of about 423.6 mm in comparison to the wireless drip irrigation treatment based on the sensor showing the maximum yield. Additionally, statistical analysis revealed significant crop yield effects, indicating that any applied irrigation results in excess irrigation because of the humid autumn. Yet another critical factor, as sensor-based drip irrigation treatment indicated by observed improvement in plant growth and water consumption efficiency and soil water potential or contents studies, is the proper irrigation timing operations.

According to the researchers, even separate planting dates in the same geographical area constrain a specific Kc factor curve within the same area. Moreover, the Kc factors are dependent on climatic circumstances, they are not valid universally[8,17,28–31], leading to limited interchange ability of these parameters. Additionally, water balance inefficiencies build with time, necessitating data integration. Irrigation scheduling based on ETc (soil water balance) calculations resulted in inefficient excess irrigation due to improper overstate crop coefficients, highlighting the need for further more reliable and consistent estimations of these coefficients to reduce over-irrigation. As a result, ETc-based drip irrigation was purely due to improper timing, which was also reflected in plant growth and development measurements. The information can also be downloaded to Microsoft Excel format in the drip irrigation system based on IoT technology. The time and parameters variables can be saved for further analysis using the ThingSpeak IoT platform.[32–34] The present research results reveal that sensor-based irrigation, with soil moisture sensors, installed approximately 15 cm from the plant-appropriate root zone depth in clayey soil, obtained significant yields with low irrigation water inputs.

Conclusions

In present study, a wireless smart drip irrigation system that connected to IoT through the wireless soil moisture sensor network using the ESP32 microcontroller was developed and evaluated in Egg Plant crop. The field environmental parameters such as soil moisture content, air temperature, relative humidity, and soil temperature can be obtained for decision-making. The drip irrigation based on the IoT and soil moisture sensor technique saved 35.2% of the water for irrigation, with an increased yield of 12.01% compared ETc-based irrigation. The findings also revealed that a sensor-based drip irrigation technique had a major difference ($p \leq 0.05$) in terms of operating time for pumping, rate of water consumption, over ETc-based drip irrigation. Further, the findings of this project can be extended as advisory services for irrigation to farmers via smart phone app.

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Conflicts of Interest

The authors have no conflict of interest to declare.

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