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ORIGINAL PAPER

IoT-based smart drip irrigation scheduling and wireless monitoring of microclimate in sweet corn crop under plastic mulching

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Abstract

Precision irrigation with IoT-based decision-making technologies has proven effective in optimizing agricultural production irrigation. The Internet of Things (IoT) is crucial for monitoring the real-time data from sensors and automatically activating irrigation systems. This study evaluated the effectiveness of a drip irrigation system based on IoT and soil moisture sensors in a field experiment with sweet corn between 2020 and 2022. There were nine treatments with three replications: ETc-based drip irrigation (ETc 100%) and IoT-based drip irrigation scheduling with two soil moisture levels under three mulches: black plastic mulch, silver plastic mulch, and control (bare soil). IoT-based drip irrigation scheduling (100% FC) applied irrigation when soil moisture reached a lower threshold ($\leq$33.1%) and ended when the field capacity was reached ($\geq$43.5). With IoT-based drip irrigation scheduling (80% FC), irrigation was applied when the soil moisture content reached the threshold ($\leq$33.1%) and ended when the field capacity reached 80% ($\geq$34.8). Growth variables (root biomass, yield, corn length, cob weight, and water productivity) were compared for each irrigation method. Results showed that the ET-based irrigation method was easier to implement with less infrastructure and could result in lower yields than the IoT-based drip irrigation method with 100% FC. Grain and stalk yields increased by more than 12.05% and 14.97% for the IoT irrigation with 100% Field Capacity (FC). It was found that IoT-based drip irrigation with 100% FC and 80% FC used 12.7% and 24.5% less irrigation water, respectively. Additionally when compared to other two irrigation methods IoT-based drip irrigation with 100% FC, resulted in 12.8% increase in marketable yield. The results show that the developed IoT system can potentially

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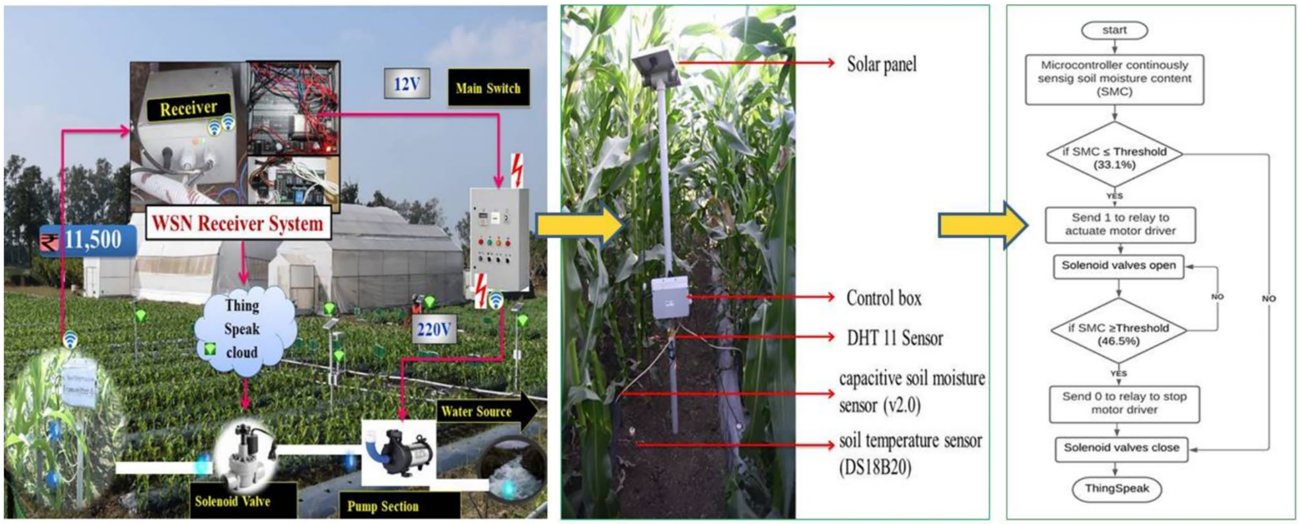
monitor the microclimate of plants in real time under different conditions of using plastic mulch. The IoT system is rugged and water-resistant, making it suitable for outdoor agriculture. Solar panels power the system, so there is no need for cabling and sensor nodes can be efficiently monitored. Research conducted on the IoT system shows that it can record and display environmental parameters to users via the cloud (ThingSpeak).

Graphical abstract



Introduction

The agricultural sector consumes most of the freshwater resources in the world's arid and semiarid regions, resulting in significant water scarcity and depletion (Krishnan et al. 2020). In most regions of the world, agriculture is still practiced without concern for sustainability and effective use of water resources. In addition to rapid population growth, current water scarcity will exacerbate existing water availability challenges for agriculture, leading to food insecurity for future generations (Imran et al. 2019). The global population is expected to reach 8 billion by 2025 and nearly 10 billion by 2050 (Chakraborty et al. 2022; Krishnan et al. 2020). Climate change will also lead to rainfall variability, ultimately threatening water supplies for irrigation (Khanna and Kaur 2019). In India, climate change has adverse impacts on agriculture, and the overuse of natural resources and poor coping mechanisms are a concern when meeting the food needs of an ever-growing population. Demand and competition for freshwater from various industries, including domestic and industrial, are leading to a decline in the supply of irrigation water in Indian agriculture (Pathak et al. 2019). To mitigate this, farmers should use the minimum amount of water required to meet their yield goals and ensure adequate water supply for future generations (Imran et al. 2019; Kim et al. 2008).

The agricultural sector is undergoing a dramatic transformation, driven by digital technologies that appear to be extremely promising and will enable us to reach the next level of farm efficiency and productivity (Boursianis et al. 2022). In recent years, agriculture has experienced a fourth revolution (Agriculture 4.0) as information and communication technology (ICT) has been merged with traditional agricultural techniques (Boursianis et al. 2022). Industrial Revolution 4.0 began in the automotive sector and has now spread to other industries, notably introducing disruptive technologies: the Internet of Things (IoT), cloud platforms, data science, and artificial intelligence (AI) (Kovács and Husti 2018; Rose and Chilvers 2018; Trendov et al. 2019). Huge amounts of data are generated and analyzed every day due to technological innovations. From this perspective, agricultural field operations have tremendous opportunities to implement such techniques that can significantly improve the efficiency of farming practices through real-time monitoring and control (Mehta et al. 2021; Trivedi et al. 2022; Liu et al. 2017; Zambon et al. 2019). Agriculture 4.0 appears to be the most current advancement in precision agriculture (PA) and focuses on the idea of sustainable agriculture. Agriculture 4.0 is expected to make significant progress globally in increasing the effectiveness and competitiveness of the food and agriculture system, improving the quantity, reliability, and affordability of agricultural products, mitigating and adapting to climate change, minimizing food insecurity, optimizing energy and resource use in a sustainable approach, and consequently drastically minimizing environmental impacts (Kumar et al. 2023; Krishnan et al. 2020; Imran et al. 2019).

From the emergence of the concept of precision agriculture in the 1990s (Heuvel 1996) to the present day, agriculture has sought to improve the efficiency of irrigation and agricultural production and to address the shortage of agricultural labour through advances in smart agricultural technology (Tian et al. 2021). In precision irrigation (PI), water is applied to a crop's root zone at the right time, amount, and place using an effective method. A precision irrigation system increases crop productivity and water use efficiency (WUE) at a lower energy cost per irrigation (Rajwade et al. 2018). Wired and wireless smart drip irrigation systems with soil moisture sensors can apply a precise amount of water to the right place at the right time. This can be done by using smart strategies to improve precision. The smart irrigation monitoring drip systems are very effective techniques to determine how much water needs to be applied based on the amount of water lost by the plant. A precisely planned irrigation system can maximize water use efficiency (WUE). Wireless sensor networks (WSNs) can improve real-time database monitoring (Jabro et al. 2020; Kumar et al. 2020, 2023, 2024; Vinod et al. 2022). Installing sensors near the top of the active root system is critical for optimizing precision irrigation and irrigation scheduling (Boursianis et al. 2022).

The ET-based irrigation systems calculate plant water use based on evapotranspiration, which is influenced by atmospheric factors such as humidity, air temperature, wind speed, and solar radiation (Kranz et al. 2012). Field studies on biblical hyssop (Snyder et al. 2015; Bhar & Kumar 2019), maize, and sweet corn (Irmak et al. 2016) have successfully used ET-based irrigation. Most precision irrigation techniques are based on the Penman–Monteith method (FAO-56) (Allen 1998), in which ETc: crop evapotranspiration is estimated by multiplying ETo: crop evapotranspiration by Kc: a specific crop coefficient in the equation. The effectiveness of this technique is mainly due to its low complexity, high reliability, and adaptability (Zotarelli et al. 2009). Nevertheless, the method is uncertain when calculating the water required to satisfy the various parameters that can affect Kc (Allen 1998). A thorough understanding of soil hydrodynamic properties and local optimization based on thorough field experiments (Tzounis et al. 2017a, b) is essential. According to Rodriguez-Ortega et al. (2017), estimating ET_O at a regional scale is difficult because there are insufficient weather stations. If soil and crop water status are used to schedule irrigation, especially for field crops, then a significant improvement in irrigation scheduling is needed. This method can easily determine the amount of water to be applied based on its principles. However, due to the time lag and sometimes inaccurate crop coefficients, irrigation techniques based on ET require the estimation of local climate data (ETo), contributing to overall uncertainty (Masmoudi et al. 2011).

IoT-based smart irrigation technology measures soil moisture in the root zone of plants, which is decomposed by plant roots at an evaporation rate until a wilting point is reached. Soil moisture sensors can determine the timing of irrigation and irrigation stops in real-time (Cardenas and Dukes, 2010; Dursun and Ozden, 2011; Garcia et al. 2009). The amount and timing of irrigation can be estimated based on available soil moisture (Tzounis et al. 2017 a, b; Khanna and Kaur 2019). Many studies have been conducted using soil moisture status to schedule irrigation in papaya (Migliaccio et al. 2010), tomato (Zotarelli et al. 2009), and bell pepper (Sharma et al. 2021). It is a simple method and can be automated with commercially available systems. Soil moisture sensor-based scheduling has several drawbacks, including soil moisture heterogeneity in the root zone, difficulty representing the entire root zone, and the need to calibrate sensors for different soil types (Jones 2006). However, previous agricultural monitoring systems have suffered from issues restricting growth. Agricultural monitoring systems of the early days used wired data acquisition systems, which connected the sensor units to monitoring centers via wires. Due to the wiring connection range, such systems have a limited deployment size for monitoring points; they require extensive cabling, which leads to high installation, maintenance, and relocation costs; and the cables are easily damaged if placed outdoors in adverse conditions (Kumar et al. 2020, 2023; Vinod et al. 2022). In the present research work, we have developed an IoT system that uses wireless sensor networks (WSNs) technology to overcome previous wired sensor system issues.

Drip irrigation and plastic mulch are commonly used in high-value crops to produce high-quality plants. The use of plastic mulch in agriculture, known as plastic culture, has increased dramatically worldwide since 2000 (Kyrikou and Briassoulis 2007; Yadav et al. 2023). Plastic mulch is used in all climates, seasons, and soil types because it offers numerous benefits, such as increasing soil temperature (Kasirajan and Ngouajio, 2012). (Almeida et al. 2015) shows the effectiveness of plastic mulch in reducing soil evaporation and improving crop water efficiency. Evidence shows that mulches increase soil moisture compared to bare soil (Chakraborty et al. 2008; Zhao et al. 2014a, b). Plastic mulch films have gained popularity because they improve vegetable yield and quality (Daz- Pérez and Batal, 2002; Lee & Park 2020). Plastic mulches alter plants' microclimate by changing plants' energy balance and reducing water evaporation (Liakatas et al. 1986; Tarara 2000; Li et al. 2016).

However, previous versions of agricultural monitoring systems have been plagued by flaws that have limited the expansion of this industry. Initial agricultural monitoring systems adopted wired data collecting systems, where the sensor units were interconnected to the monitoring center through electrical wiring. These systems have several limitations, including limited accessibility for locations for monitoring due to the wired connection range, expensive installation, maintenance, and shifting expenses due to extensive wiring, and vulnerability of outdoor cables to damage in adverse environments (Kumar et al. 2020, 2023; Vinod et al. 2022). These data-gathering units are not suitable for outdoor usage for long periods due to their lack of ruggedness. They are specifically developed for use in controlled conditions, such as greenhouses or food factories (Kumar et al. 2020, 2023, 2024; Vinod et al. 2022). Existing approaches of sensor-based irrigation systems do not focus on efficient energy consumption; smart technologies like IoT are used to capture information and transfer data wirelessly to the cloud server. Earlier versions of wireless networks used radio frequency (RF) technology and Bluetooth. RF and Bluetooth communications were replaced by ZigBee and wireless local area network (WLAN) technologies based on low-cost, low-power, and adequate data rate requirements.

In this study, an IoT-based smart drip irrigation system was developed, designed, and implemented for a two-year field trial to evaluate the smart drip irrigation system under different mulching conditions. This study aimed to compare the ET and IoT-based drip irrigation scheduling methods and assessing their effects on morphometric parameters, water use, and water productivity of sweet corn under different mulching conditions. The developed system saves fresh water through efficient utilization and supports smart energy consumption. The implemented system uses Internet of Things (IoT) technology and a collection of sensors to effectively capture field observations and determine their irrigation requirements. The system is deployed with a cloud-based application interface for continuous monitoring and management of the effective irrigation system. The robust and weatherproof casing enables its utilization in outside agricultural areas, while a solar power source eliminates the requirement for cables and minimizes the regular maintenance of sensor nodes. Solar energy to replenish the battery effectively addresses the issue of power scarcity. The designed system can effectively and reliably address the aforementioned critical challenges.

Materials and Methods

Study area

The study area is located in ICAR—Central Institute of Agricultural Engineering (CIAE), in Bhopal, India (77o 24′ 10" E, 23o 18′ 35" N; 495 MSL) (Fig. 1). Sweet corn (Zea mays var. KSCH – 972, hybrid) grown in this field trial is usually sown in early spring and requires warm soil temperatures (20–30 °C) for optimal development. Sweet corn is usually grown over a long period to ensure a constant supply of fresh corn. Sweet corn varieties generally mature 70 to 100 days after sowing. Evidence shows that optimal irrigation strategies can result in high crop yields (over 20,000 kg/ha) as well as improved water efficiency and minimal water losses (y Garcia et al. 2009); however, improper irrigation practices can result in low yields and economic losses (Archana et al. 2016; Dukes and Scholberg 2005; Mubarak 2020).

The experimental site has a subtropical climate, with dry, hot summers from (March to June) followed by monsoons (July to September) and cold winters the rest of the year. Annual rainfall averages 1146 mm. According to Rao

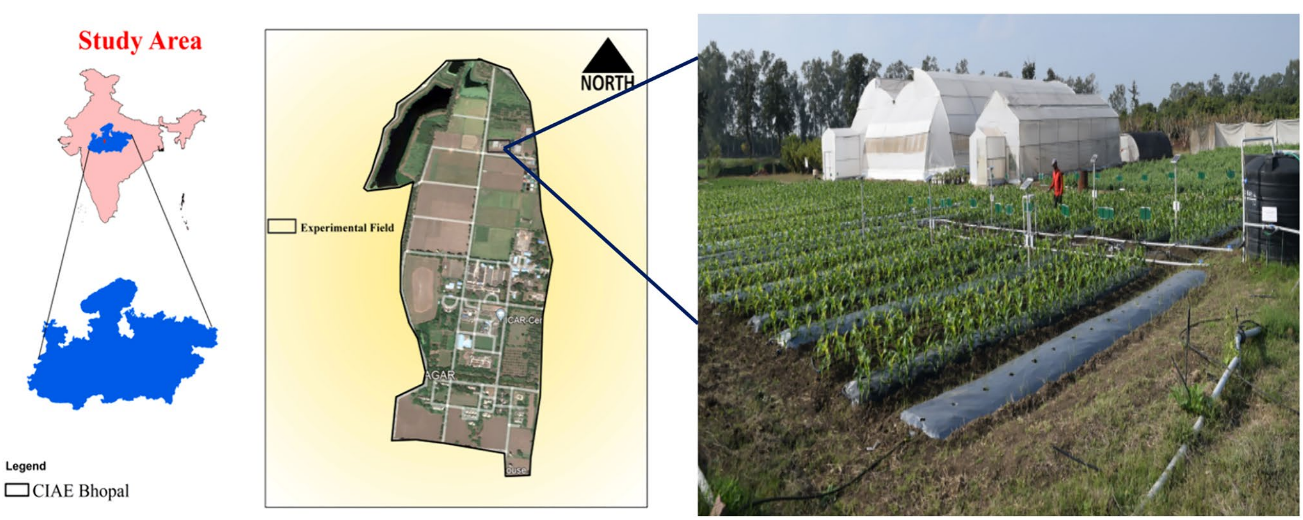


Fig. 1 Location map of the study area in Central Institute of Agricultural Engineering PFDC farm- Bhopal, Madhya Pradesh—India

et al. (2021), the average maximum temperature was 39.5 degrees Celsius, and the minimum temperature was 11.5 degrees Celsius (observations between 2019 and 2020). Daily crop evapotranspiration (ETc) was calculated as a factor of grass-reference crop evapotranspiration (ET_O) and crop coefficient (Kc) using FAO Penman–Monteith equation in CROPWAT 8.0 software (Allen 1998) (Fig. 2).

The soil of the experimental site was a non-calcareous Vertisol with 16% sand, 30% silt, and 54% clay. The soil had a pH of 7.94, electrical conductivity of 0.2 dS/m, CaCO3 of 2.83%, and organic carbon content of 0.62% (Kumar et al. 2020, 2023, 2024; Vinod et al. 2022). Saxton and Rawls (2006) used the model to estimate the water properties of the soil (the permanent wilting point was about 31 percent, field capacity was 43.5 percent, and saturation was 49.7 percent). In this experiment, bulk density was calculated using the cylinder method and was reported as 1.42 g/cm^3.

Sweet corn cultural practices

Seeds were sown in the last week of December (Zea mays var. KSCH – 972, hybrid) with a germination rate of 90%. Seeds were buried at a depth of 5–6 cm. Nitrogen, phosphorus, and potassium fertilizers (NPK ratio 15:15:15) were applied at 250 kg/ha. Weeds were hand-weeded for the first 40 days of DAS, and a 2,4-D herbicide concentration of 50 cm^3 in 12 l of water (4.58 cc/L water) was applied to the entire field 40 days after sowing (DAS). The experimental plants were irrigated with the same amount of water until the seedlings emerged. Sweet corn plants were irrigated after emergence according to the recommended irrigation treatments.

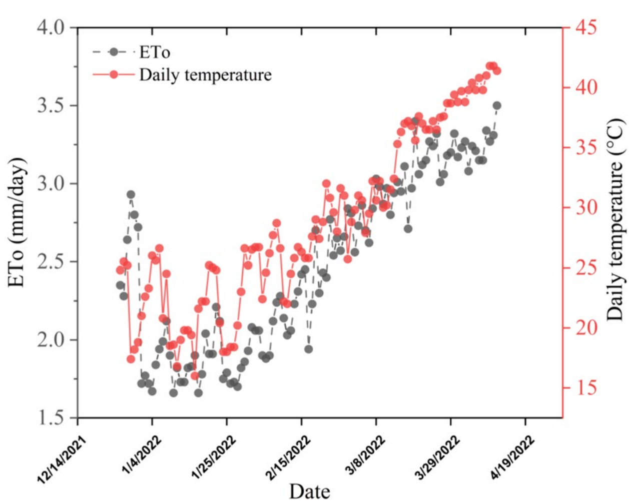


Fig. 2 Temperature (°C) and ETO during the crop growing period at the meteorological station, CIAE, from January to April 2022

Experimental design

Two experiments were conducted using two different irrigation scheduling methods for the various subplots. The soil moisture sensor (IoT-based drip irrigation system) and evapotranspiration-based methods (ETc-based drip irrigation system) were used. There were nine treatments and three replications in the experiment, totaling 27 experimental plots with a size of 8 m × 1 m and a spacing of 1 m to avoid disturbance. Figure 3 shows the layout and distribution of the experimental plots. The experiment was conducted in a split-plot design with nine treatments, namely, T1- Black mulch IoT with 100% field capacity (FC), T2- Silver mulch IoT with 100% FC, T3- Without mulch IoT with 100% FC, T4- Black mulch IoT with 80% FC, T5- Silver mulch IoT with 80% FC, T6- Without mulch IoT with 80% FC, T7- Black mulch 100% ETc, T8- Silver mulch 100% ETc, T9- Without mulch 100% ETc. The ET treatments were irrigated with a control system according to the daily calculations of the ET_C. When the plant was in the early growth stages, irrigation was scheduled at an average interval of 2 days, followed by three days. A total of 20 self compensating drippers were tested at a pressure of 100 kPa (1 bar), and an average discharge rate of 2.3 l/h was observed. The test diagrams are shown in Fig. 3.

Irrigation scheduling

To determine plant evapotranspiration (ETc) in an ET-based drip irrigation system, the ETo of the experimental plot was multiplied by the plant coefficients (Kc) at the beginning, middle, and end (0.61, 1.15, and 1.05, respectively) (Asiimwe et al. 2022). Irrigation intervals varied according to ETc, a factor of plant growth stage, and seasonal meteorological phenomena. Irrigation methods for IoT-based drip irrigation were 100% field capacity (FC) and 80% FC. The IoT-based drip irrigation scheduling was configured using upper (field capacity) and lower thresholds (50% Plant Available Water, (PAW)). The motor relay module was activated, and solenoid valves were actuated to start irrigation events based on the soil moisture thresholds in each treatment. The valves were closed when the volumetric soil moisture content (VMC) reached the higher threshold, as shown in (**Fig.** 4).

Suitable sensor positions

The sensors were installed at sensitive and suitable locations in the plant's root zone. Soil moisture or tension varies in three dimensions (Soulis et al. 2015). According to Shock and Wang, (2011), these dimensions include soil moistening by irrigation/rainfall, soil drying by evaporation, and water removal in the root zone for plant

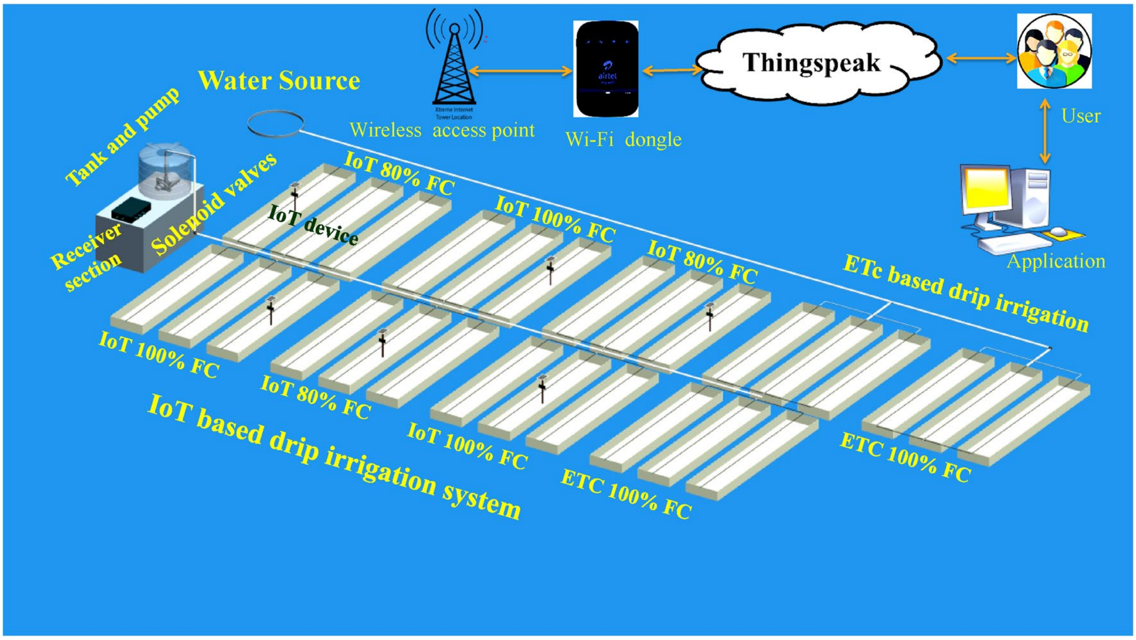
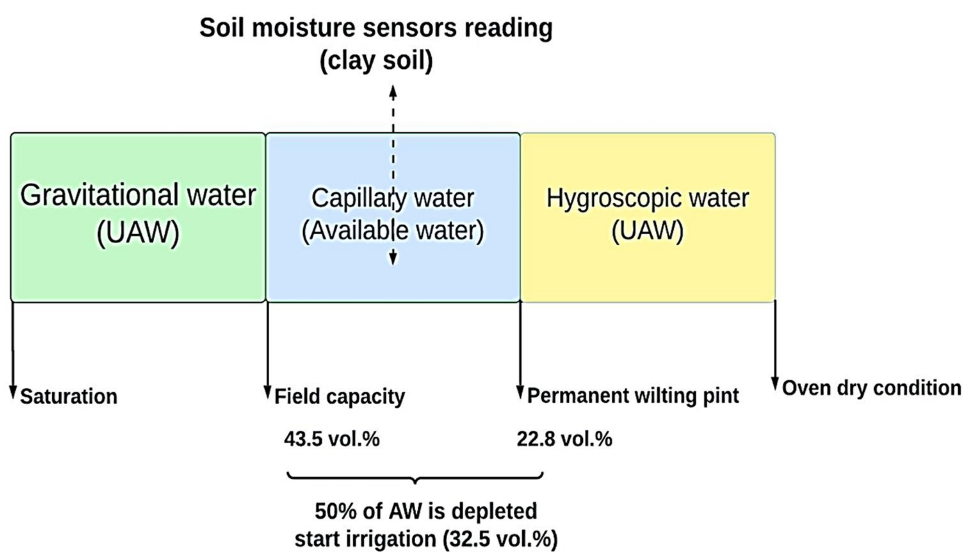


Fig. 3 CAD model for irrigation system layout and experimental design for the IoT-based and ETc-based experiments

Fig.4 Schematic representation of water types in soil and soil-water limits for clay soil. AW and UAW stand for available water and unavailable water, respectively.



transpiration. The interaction of these dimensions has been critical to installing soil moisture sensors. In a study by Soulis et al. (2015), soil moisture sensors were recommended to be placed at the top of the active root system, near drippers, and below the soil surface. In all cases studied, the best location for soil moisture sensors was 11 cm from the drip line and 10 cm below the surface. The irrigation efficiency of sensors placed at 20 cm depth is generally lower when the sensors are placed deeper in the soil profile, resulting in more frequent irrigations (Soulis et al. 2015). Twelve capacitive soil moisture sensors v2.0 (DFRobot, China) were installed at two depths (10 and 15 cm) as part of the IoT-based smart drip irrigation system. The soil moisture content (SMC) was measured using a capacitive soil moisture sensor v2.0 (Accuracy: ± 2%) (Kumar et al. 2023). The voltage level of the capacitance varies between 1.2 and 3.0 V. The capacitive soil moisture sensor has the advantage of being made from a material that is long-lasting and resistant to corrosion. The receiver unit was connected to six 24VAC solenoid valves for different irrigation treatment.

IoT-based data acquisition system

Wireless sensor networks or stand-alone sensor nodes can be used depending on the field requirements. The field data collection system contains three sensors: a capacitive soil moisture sensor (v2.0), a soil temperature sensor (DS18B20), and a temperature and humidity sensor (DHT11). The output of this sensor is read by an ESP32-WROOM-32 microcontroller, which wirelessly transmits the recorded data to an IoT platform (ThingSpeak) using an ESP8266 Wi-Fi module (Kumar et al. 2020, 2023; Vinod et al. 2022). An IP-65 enclosure was used to create a data acquisition device that could house all system components. The components were integrated within the IP-65 enclosure, with a small hole at the bottom to expose the DHT11 sensor to the surroundings. The bottom portion of the hole was skirted to prevent rainwater from entering. To ensure waterproofing, the upper and bottom components were screwed and soldered together with another rubber O-ring. The bottom portion of the enclosure was pole-mounted to elevate the device above the ground level and prevent flooding. The rugged and water-resistant box allows it to be used in outdoor agricultural fields, and a solar power supply eliminates the need for wiring and reduces sensor node maintenance. Solar energy, which recharges the battery, can be used to solve the power shortage (Vinod et al. 2022; Kumar et al. 2023), and a flowchart of the process is shown in (Fig. 5).

Soil Moisture Measurements and Sensor Calibration

A v2.0 capacitive soil moisture sensor was calibrated and used in each test treatment to ensure appropriate sensor–soil contact. The ThingSpeak IoT platform collected soil moisture data at 5-min intervals. To represent the active root zone of maize observed at 30–35 cm (Wiesler and Horst, 1994), sensors were installed at 10 and 15 cm depths. A total of 12 soil moisture sensors were used to measure soil moisture at 10 and 15 cm depths throughout the growing season for each treatment. The solenoid valves and water pump are programmed to activate if the soil moisture content exceeds the threshold limit. A continuous monitoring of soil moisture values was sent to the ThingSpeak server (Jones 2006; Dabach et al. 2015). Gravimetric moisture content, a ratio of soil moisture to soil dry matter, was then calculated for the soil sample. The soil was dried in an oven at 105° C for 24 h to determine soil moisture content. Standard methods were used to estimate bulk density. Volumetric water content was calculated by multiplying the gravimetric moisture content by the bulk density of the soil. A linear regression model was developed to estimate soil moisture content based on gravimetric moisture content and soil moisture sensor

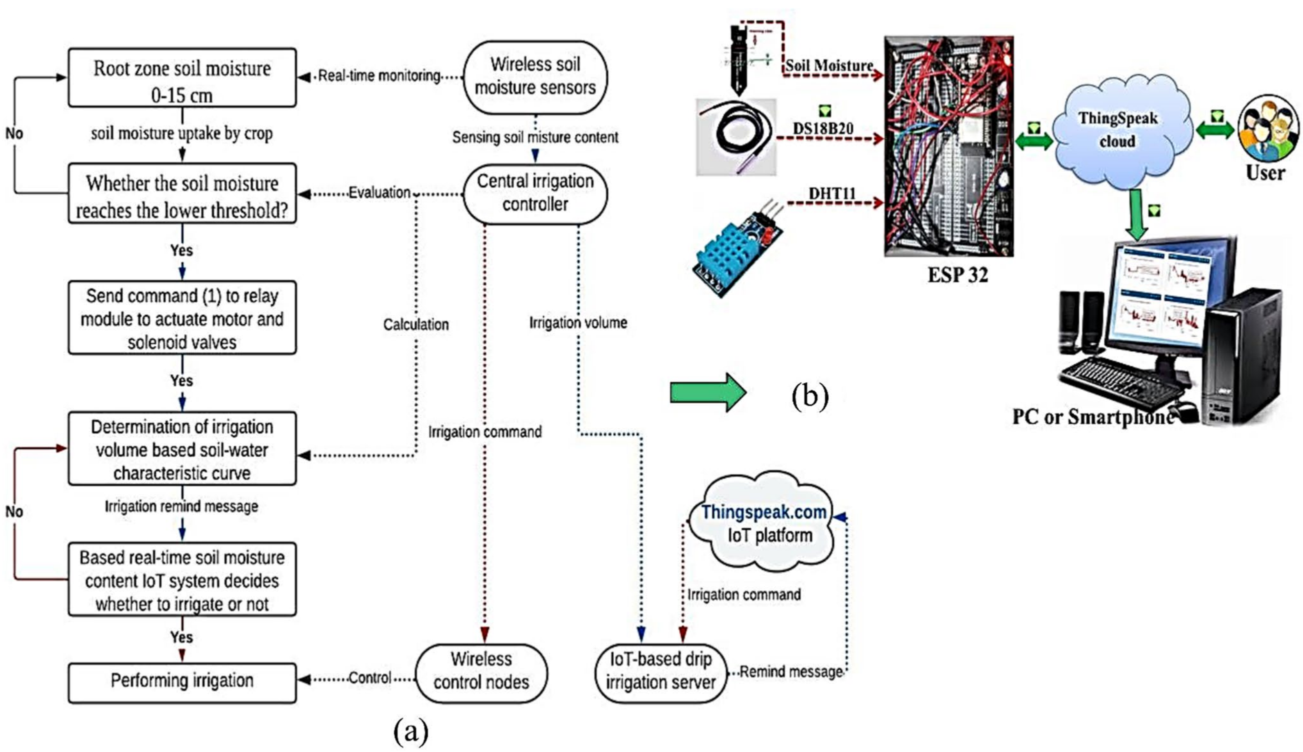


Fig. 5 Workflow of the proposed IoT-based smart drip-based irrigation system

readings. The soil moisture content was determined directly by implementing the linear regression model into the system's software.

Measured Parameters and Statistical Analysis

The growth parameters of sweet corn, such as plant height, number of leaves, cob weight, cob length, and root biomass, were directly measured for five plants from the middle two rows within each treatment on the day of harvest 9at. The calculated parameters were grain yield, stover yield, SPAD values, and water productivity (WP). WP measures biophysical gain in terms of water consumed. The ratio of fresh and dry biomass of cob yield to cumulative ETc or total water consumed (WU) is used to calculate WP (Fereres and Soriano, 2006) tukey test for means comparison with origin pro. Software statistical package version 22 was used to examine the effects of the irrigation levels studied. Least Significant Difference (LSD) was used to calculate significant differences between group means at a significance level of p 0.05.

Results and Discussion

Calibration and feasibility of the IoT system

In the ICAR Central Institute of Agricultural Engineering laboratory, the capacitive soil moisture sensors v2.0 were calibrated using the moisture content measured by the oven-dry method before installation in the corn test plot. Forty-eight soil samples were collected from a depth of 20 cm to determine soil moisture content and compared to the soil moisture sensor readings. In the Vertisol, which consisted of 16% sand, 30% silt, and 54% clay, the bulk density was 1.42 g/cm^3. Thus, the soil moisture sensors were calibrated with an accuracy error of about ± 2–3%. In Fig. 6, the linear regression equation with the highest coefficient of determination ($R^2 = 0.92$) was used for calibration. Overall, the IoT system functioned properly throughout the irrigation period.

Only a few instances of data loss in the IoT system were reported. Six IoT systems were found to have an average data loss rate of 4.51%. Some signal loss may have occurred because the receiver unit was housed in a box with no window to the field. This can be improved if the receiver unit is installed outdoors where it is less obscured. Signal loss occurs when a component, such as a transmitter unit, receiver unit, server, or Things Speak (IoT) platform, is disconnected.

Nevertheless, the acquisition system was only moderately affected as data was uploaded at a frequency of two minutes with no prolonged data loss. All six batteries of the IoT transmitters were charged by solar cells and had sufficient power throughout the experiment. Due to the persistent cloudy and rainy weather, all six IoT transmitters experienced voltage drops. In the open field, the battery voltage was constantly above 4.0 V throughout the experiment,

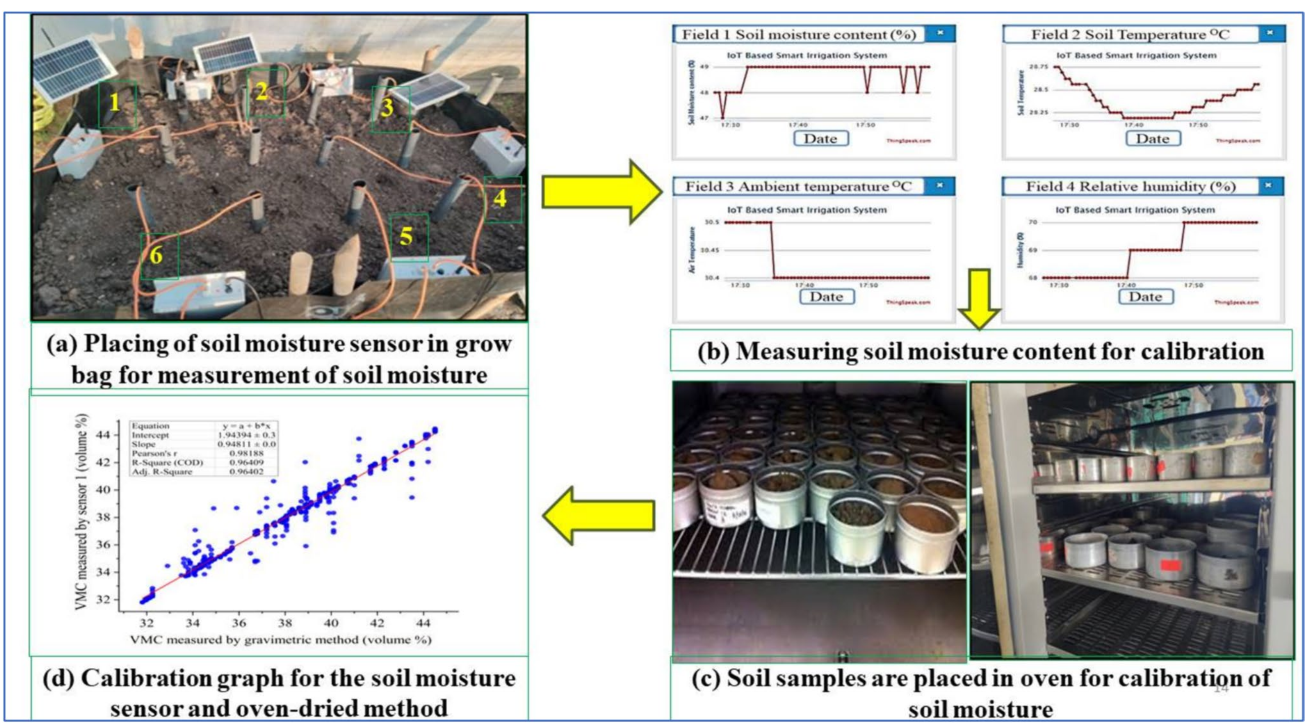


Fig. 6 Calibration curve for capacitive soil moisture sensors v2.0 and oven dry method

showing that the 5,000 mAh LiPo battery and solar panel can support the IoT transmitters in the open field.

Solenoid valves and pump control

Irrigation was successfully controlled with an IoT-based drip irrigation system by monitoring the status of the pump and solenoid valves. The cloud application (ThingSpeak) notifies the end-user when soil moisture thresholds are reached. The solenoid valves and pump operation are automatically controlled based on real-time soil moisture content, and irrigation begins when soil moisture content falls below a predetermined threshold. In the IoT platform (ThingSpeak), the status of the pump and solenoid valves were displayed as 'green' lights and a signal, respectively (Fig. 7).

The solenoid valves close when the soil moisture content reaches the field capacity, and the status indicates zero. The pump automatically stops irrigating the field when the solenoid valves are closed. IoT-based wireless data monitoring systems were turned on and installed in the field experiment (Fig. 8).

Soil moisture monitoring with the IoT-based drip irrigation system

For the two IoT-based soil moisture treatments (SM), the cumulative irrigation water volume was 393.6 mm for the irrigation treatment of 100% FC and 356.24 mm for the irrigation treatment of 80% FC. Measuring soil moisture in the IoT-based drip irrigation treatment of 80% FC showed that irrigation was close to a threshold of 32.2%, 27.9% of the manageable allowable depletion (MAD). For IoT-based drip irrigation at 100% FC, soil moisture remained within permissible limits at an average of 38%. In this treatment, it took an average of 2 days for the next irrigation event to occur. Irrigation at 100% FC corresponded to 50% MAD before the next irrigation schedule. The IoT devices were directly connected to the IoT analytics platform web service

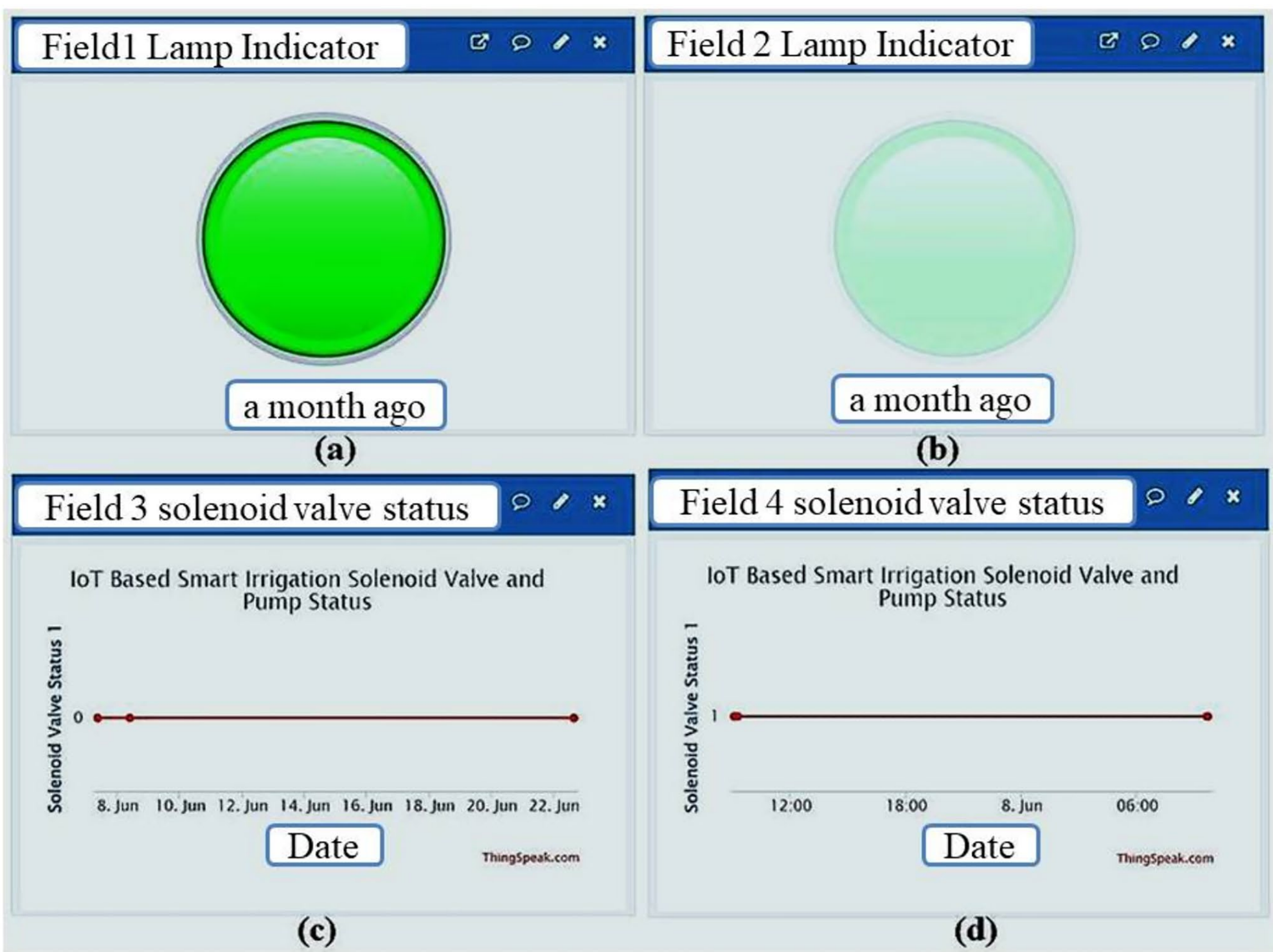


Fig. 7 **a** Field 1 chart status indicating motor ON, **b** Field 2 chart status indicating motor OFF, **c** Field 4 chart 0 value indicating solenoid valve OFF, and **d** Field 6 chart one value indicating solenoid valve ON

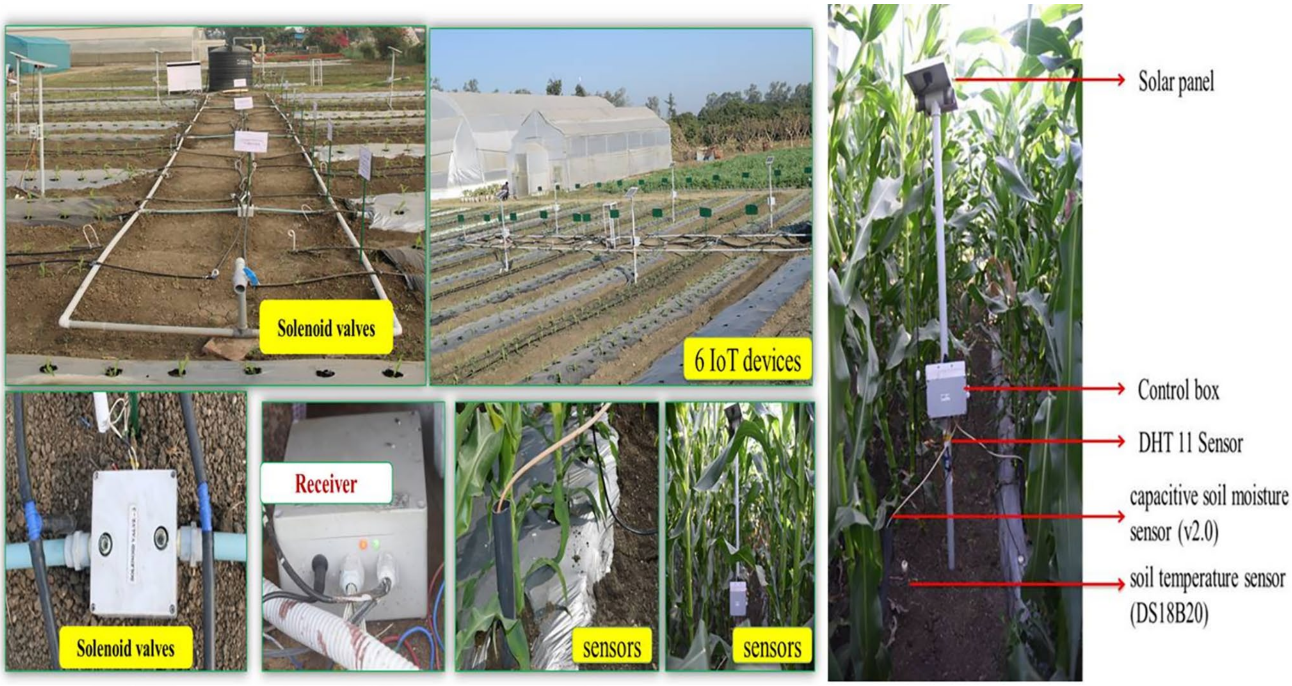


Fig. 8 IoT-based wireless data monitoring systems in a full-scale field experiment

(ThingSpeak) to access and analyze live cloud data such as soil moisture values, soil temperature, relative humidity, and temperature at different times (Fig. 9).

The sensors were placed at a depth of 15 cm below the soil surface and maintained at a constant depth throughout the growing season. At a depth of 15 cm, the soil moisture sensors were used to determine how much irrigation should be applied. When soil moisture reached ≤ 33.1%, a notification was sent to the cloud, and the solenoid valves were opened remotely, automatically triggering the irrigation pump. When the sensors detected a soil moisture of ≥ 43.5%, a notification was sent to the cloud, and the irrigation pump and solenoid valve were turned off.

An IoT-based drip irrigation system (80% FC) controls the pump and solenoid valves based on real-time soil moisture. Once the soil moisture sensor threshold consumes 50% of the water available to the plant (31.5%), the solenoid valve is opened. Once the soil moisture content reaches 80% of the soil moisture sensor's field capacity (34.8%), the pump is turned off, and the solenoid valves are closed. The continuously measured volumetric soil moisture data is uploaded to the IoT platform using "ThingSpeak.com" (see Fig. 10).

Soil moisture analysis in ET-based drip irrigation scheduling

Monitoring soil moisture in the ETc-based drip irrigation experiment was critical for interpreting yield and biomass responses. In the ETc 100% treatment, a cumulative 443.7 mm of irrigation water was applied. In the ETc-100% irrigation treatment, soil moisture measurements indicated that volumetric moisture content (VMC) often exceeded field capacity after irrigation, causing irrigation water to percolate below 25 cm. In ETc-based drip irrigation, it was observed that bare soil had the lowest moisture content (mean = 39.12%) compared to silver and black mulch treatments. In both experimental years, the black mulch had the highest moisture content (mean = 41.23%), followed by the silver mulch (mean = 40.24%), as shown in (Fig. 11).

The results are in close agreement with those of Chakraborty et al. (2008), Zhao et al. (2014a, b), Kader et al. (2017), Ogundare et al. (2015), and Bakr et al. (2015), who showed that mulches have a beneficial effect on soil moisture regime by controlling surface evaporation and conserving soil moisture. Different mulches can retain soil moisture at different rates depending on soil type and climatic conditions. Mulches improve the soil's ability to retain moisture and soil structure and suppress weed growth. In general, mulched soil retains more moisture than bare soil (without mulch) Ogundare et al. (2015). Ashrafuzzaman et al. (2011) found that transparent plastic mulch provided the highest soil moisture (21.1%), followed by black plastic mulch (20.4%) and blue plastic mulch (19.2%) and control (bare soil) (14.6%).

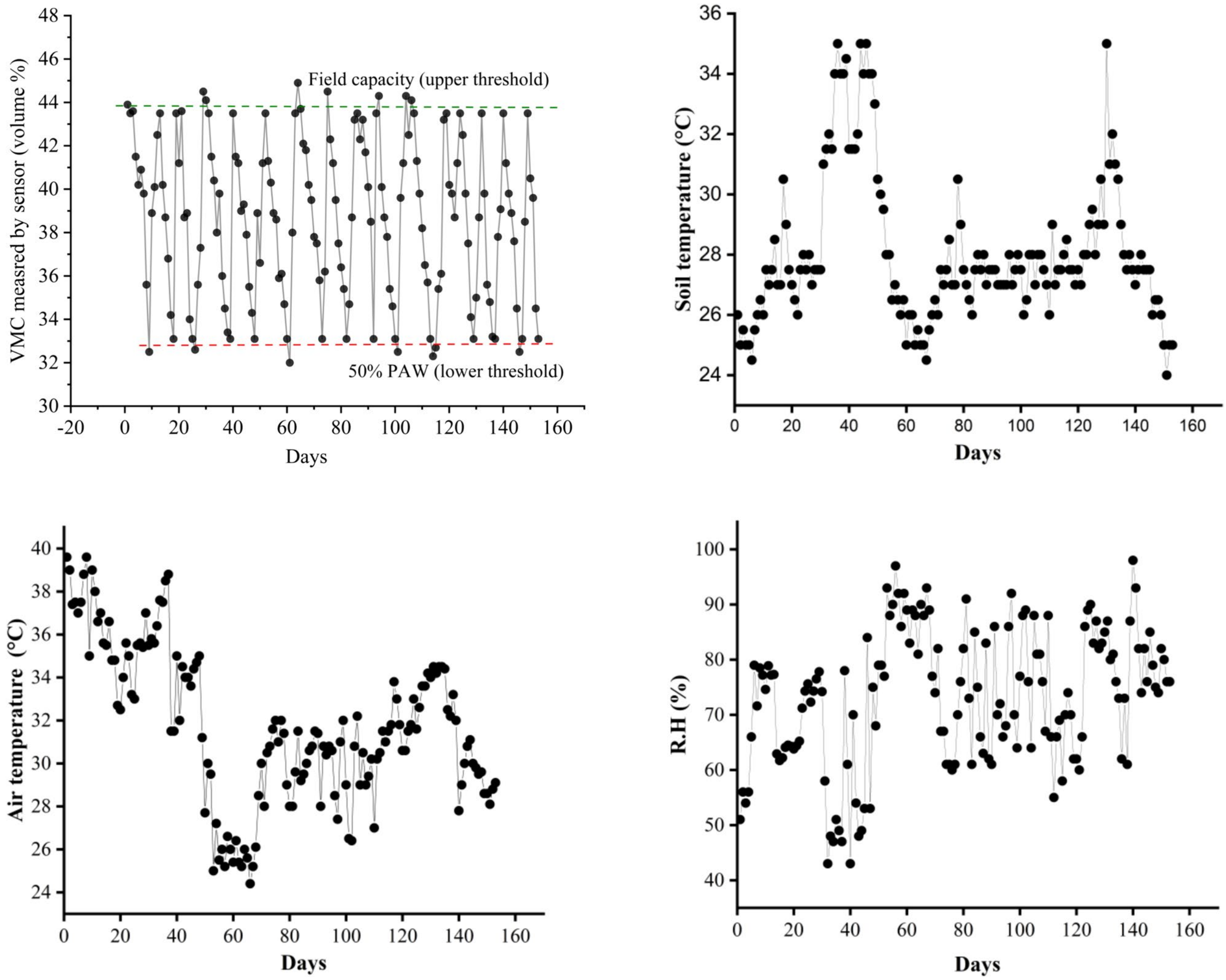


Fig. 9 During the experiment, daily average soil moisture, air temperature, relative humidity (RH), and soil temperature sensor readings of treatment IoT-based drip irrigation (100% FC)

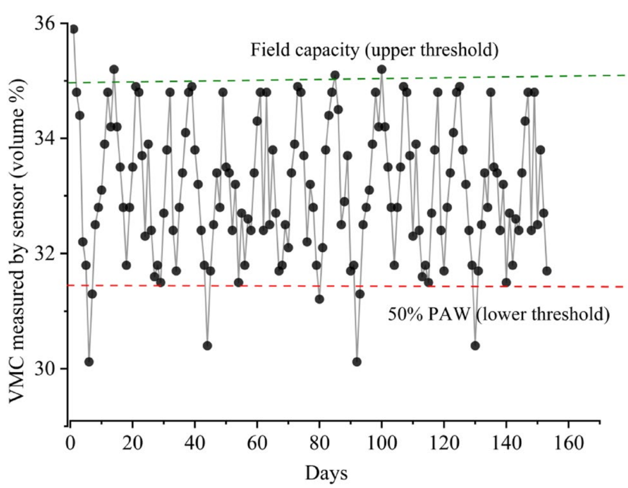


Fig. 10 Daily average soil moisture sensor readings of treatment IoT-based drip irrigation (80% FC) during the experiment

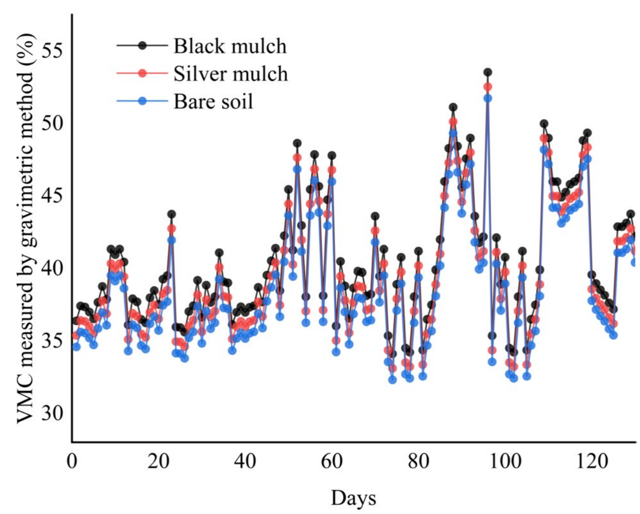


Fig. 11 Daily average soil moisture readings were measured with ETC-based drip irrigation (100%) during the experiment

Soil temperature analysis with IoT and ETc-Based drip irrigation scheduling

For all three treatments, mean seasonal root zone temperature (RZT) was highest under the black mulch treatment, followed by the silver mulch treatment, and lowest under the bare soil treatment. Maximum seasonal RZT was highest under black mulch and lowest under silver mulch treatment and bare soil. Minimum seasonal RZT was highest under the black mulch treatment and lowest under the silver mulch and bare soil treatments (**Fig.** 12). Under the different mulch conditions, the average daily RZT was measured with soil temperature sensors (DS18B20) placed 15 cm below the soil surface. The soil temperature sensors collected real-time data transmitted to the ThingSpeak IoT platform, as shown in (**Fig.** 12).

As a result of IoT-based drip irrigation (100% FC) during the winter season, mean soil temperature at 15 cm depth ranged from 21.24 ^{O}C to 28.63 ^{O}C under black mulch, 20.04 ^{O}C to 26.89 ^{O}C under silver mulch, and 19.86 ^{O}C to 26.14 ^{O}C under bare soil (**Fig.** 12). The mean seasonal soil temperature under IoT-based drip irrigation (80% FC) ranged from 20.84 ^{O}C to 28.23 ^{O}C under black mulch, followed by silver mulch (19.3 ^{O}C to 27.18 ^{O}C) and bare soil (19.76 ^{O}C to 27.24 ^{O}C). For drip irrigation based on ET_C, the average soil temperature was significantly higher under black mulch (21.04 ^{O}C to 28.56 ^{O}C), followed by silver mulch (19.87–27.32 ^{O}C) and bare soil (19.70 ^{O}C to 27.46 ^{O}C). There were no significant differences in soil temperature due to the interaction effect. In contrast, the highest soil temperatures were observed in the black mulch treatment (28.63 ^{O}C) and the lowest in the bare soil treatment (27.14 ^{O}C). The nutrient-converting microorganisms' enhanced activity may have impacted sweet corn yield due to the warmer soil under plastic mulch during the winter months.

Applied water in the various treatments

During the growing season, applied water depths (mm) were compared at 10-day intervals for IoT-based and ETc-based drip irrigation. (The first row in Table 1 shows an irrigation of 20 mm immediately after seeding to bring the soil to its capacity.) Drip irrigation with 100% ETC applied the highest amount of water, followed by drip irrigation with 100% FC and 80% FC with IoT. During the growing season, irrigation water used in ETc-based treatments increased exponentially with ETo (Allen 1998). Compared to ETC-based drip irrigation, IoT-based drip irrigation with 100% FC and 80% FC used 12.7% and 24.5% less irrigation water, respectively.

In addition, IoT-based drip irrigation with 100% FC provided 12.8% higher marketable yield than ETc and IoT-based drip irrigation with 80% FC plots. No significant differences were found between ETc and IoT-based drip irrigation with 80% FC. As a result of our study, the IoT irrigation system proved to be a very efficient tool for precise irrigation management of sweet corn in plastic culture. The batteries were sufficiently charged by the solar panels attached to the transmitters. Sensor data were recorded in real-time and displayed in the IoT platform ThingSpeak. Irrigation was successfully performed by controlling the solenoid valves based on soil moisture. Although there was no significant degradation in monitoring sensor data and controlling the valves, the IoT system had an average data loss rate of 4.51%, possibly due to the indoor placement of each component and disconnection. In future studies, the signal strength and path loss will be investigated more to address the signal loss issues.

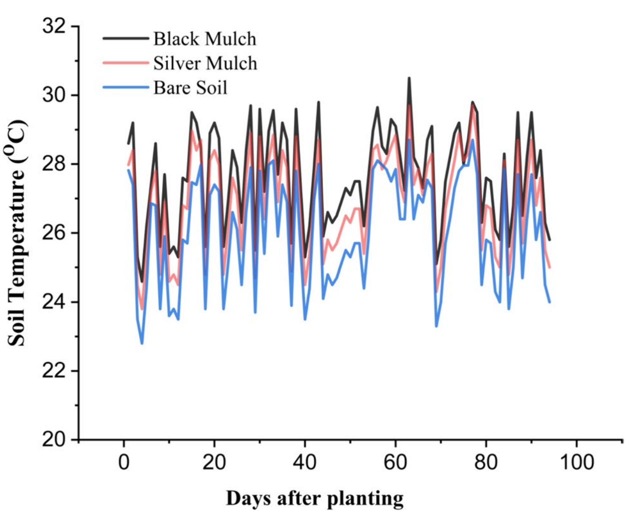


Fig.12 Seasonal averages of daily root zone temperatures (RZT) as influenced by plastic film mulch treatments.

Table 1 Water is applied (mm) for different irrigation schedules over the growing season (days)

Days after planting	ET_C-based drip irrigation	IoT-based drip irrigation	
	100% ET_C	100% FC	80% FC
0	20	20	20
10	17.2	13.7	12.33
20	26.4	22.2	19.98
30	37.7	32.5	29.25
40	43.9	39.9	35.91
50	51.8	44.7	40.23
60	53.1	47.3	42.57
70	57.7	56.7	51.03
80	64.2	53.9	48.51
98	71.7	62.7	56.43
Total (mm)	443.7	393.6	356.24
Water saved (%)	-	12.72	24.55

As a result, IoT-based drip irrigation can improve water use efficiency and crop sustainability. In addition, the IoT-based drip irrigation system could be used for precision and automatic crop irrigation applications using capacitive soil moisture sensors (v2.0).

Impact of irrigation schedules on crop growth

Impact on plant height

The amount of applied water and average soil moisture during the season significantly affected plant growth parameters. It was found that IoT-based drip irrigation with 100% FC treatments with lower water application significantly affected the average plant height. The IoT treatment with 100% FC black mulch had a higher average plant height than the ETc treatment with 100% or the IoT treatment with 80% FC (Table 2). For the IoT-based drip irrigation treatments, sweet corn in the 80% treatment had significantly lower plant height than the other treatments. Plant heights were significantly different in the IoT with 100% FC compared to ETc with 100% and IoT with 80% FC. For both irrigation schedules, the IoT with 100% FC drip irrigation system with black mulch had the highest plant height, followed by silver mulch and bare soil, with 4.49%, 1.1%, and 1.62% more than the ETc with 100% irrigation schedule and the IoT with 80% FC irrigation schedule, respectively. The results of this study were consistent with those of previous studies that had shown similar effects of irrigation applications on aboveground biomass (Kresovic et al. 2016).

Cob length

IoT-based drip irrigation with 100% FC black mulch treatment resulted in longer cob lengths; ET100% and IoT with 80% FC each had the lowest cob length averages. Mean cob lengths showed no significant differences between ETc100% and IoT with 80% FC. At a significance level of 0.05, the piston lengths in the IoT treatment with 100% FC significantly differed from the mean values of the other treatments. Cob length in the IoT treatment with 100% FC and black mulch was substantially greater (8.7%) than in the IoT irrigation with 80% FC and the ETc irrigation with 100%. Table 2 shows that the same letter indicates no significant difference among the three treatment means, while another letter indicates a substantial difference among the three treatment means at $p < 0.05$.

Impact yield responses toward irrigation treatments

In the present study, the level of irrigation, the colour of plastic mulch, and their interactions were found to affect crop yield significantly. IoT-based drip irrigation at 100% FC resulted in considerably higher yields than other irrigation levels, while yields were lowest for ETc at 100% and IoT at 80% FC. Black colour mulch produced the highest yield among plastic colour mulches. The minimal yield was recorded in the control treatment (bare soil). The interaction effect of IoT 100% FC with black mulch treatment resulted in a higher yield than silver-coloured and bare soil treatments. In the present study, a drip irrigation system using black plastic mulch combined with IoT 100% FC treatment promoted plant growth. In the mulched plots, yields increased due to water conservation, improved microclimate below and above the soil surface, and improved weed control, especially with silver/black plastic mulch (Kader et al. 2017). As a result of IoT-based drip irrigation with 100% FC treatments, grain yield and stalk yield were significantly affected. Table 3 shows that the highest grain and stalk yields were obtained in irrigation treatments IoT with 100% FC, which were more than 12.05% and 14.97% higher than irrigation treatments ETc with 100% and IoT with 80% FC. The results indicated that an IoT based smart drip irrigation with 80% FC with limited supply of water, depending on its

Table 2 Effects of irrigation on the morphometric characteristics (plant height and cob length) of field-grown sweet corn at harvest in different irrigation treatments

Irrigation Scheduling type	Irrigation treatment	Plant height (cm)	Cob length (cm)
IoT—100% FC	Black mulch	211.53 ± 0.55^{a}	26.85 ± 0.60^{a}
	Silver mulch	186.23 ± 0.49^{d}	26.49 ± 1.14^{ab}
	Bare soil	185.13 ± 0.49^{ef}	25.27 ± 0.95^{ab}
IoT—80% FC	Black mulch	200.16 ± 0.46^{c}	24.78 ± 0.80^{ab}
	Silver mulch	184.5 ± 0.52^{f}	25.17 ± 0.19^{ab}
	Bare soil	180.23 ± 0.45^{h}	24.59 ± 0.97^{b}
ET_C—100%	Black mulch	202.63 ± 0.94^{b}	26.07 ± 0.27^{ab}
	Silver mulch	186.23 ± 0.45^{d}	25.65 ± 0.16^{ab}
	Bare soil	182.26 ± 0.60^{g}	24.47 ± 0.89^{b}

Values labelled with the same letter within each column are not significantly different at $p \leq 0.05$. Values within the same columns with other letters are significantly different at $p < 0.05$ (values are means of three replicates)

Table 3 Mean comparisons for yield and water productivity of field-grown sweet corn at harvest

Irrigation Scheduling type	Irrigation treatment	Grain yield t/ha	Stover yield t/ha	Grain WP Kg/m^3	Stover WP Kg/m^3
IoT—100% FC	Black mulch	7.62 ± 0.10^{a}	14.82 ± 0.88^{a}	2.06 ± 0.02^{a}	4.02 ± 0.23^{a}
	Silver mulch	7.41 ± 0.09^{a}	13.45 ± 0.36^{ab}	2.01 ± 0.02^{ab}	3.65 ± 0.09^{abc}
	Bare soil	7.07 ± 0.13^{b}	12.27 ± 0.28^{bc}	1.91 ± 0.03^{c}	$3.33 \pm 0.07b^{cd}$
IoT—80% FC	Black mulch	6.69 ± 0.11^{c}	12.73 ± 0.80^{abc}	2.00 ± 0.03^{abc}	3.81 ± 0.24^{ab}
	Silver mulch	6.50 ± 0.02^{cd}	12.13 ± 0.19^{bc}	1.94 ± 0.06^{bc}	3.63 ± 0.05^{abc}
	Bare soil	6.40 ± 0.13^{e}	11.01 ± 1.30^{c}	1.80 ± 0.03^{d}	3.29 ± 0.38^{bcd}
ET_C—100%	Black mulch	6.76 ± 0.11^{bc}	13.34 ± 0.71^{ab}	1.64 ± 0.02^{e}	3.24 ± 0.17^{bcd}
	Silver mulch	6.70 ± 0.09^{c}	12.70 ± 0.68^{abc}	1.62 ± 0.02^{e}	3.08 ± 0.16^{cd}
	Bare soil	6.22 ± 0.18^{de}	11.33 ± 1.01^{bc}	1.51 ± 0.04^{f}	2.75 ± 0.24^{d}

Values labelled with the same letter within each column are not significantly different at $p \leq 0.05$. Values within the same columns with other letters are significantly different at $p < 0.05$ (values are means of three replicates)

severity, significantly decreased sweet corn growth and yield parameters (Table 3). Corn, a highly sensitive crop, is highly susceptible to droughts.

Water productivity response

In the current analysis, water productivity of grain and stalk was found to decrease with increasing irrigation, as reported in related studies showing that WP of sweet corn increased with decreasing irrigation levels (Cid et al. 2018). This was the case for all treatments except the ETc 100% treatment, which had low WP due to low yield (Table 3). The IoT 100% FC treatment increased grain and culm water productivity, indicating that the plant used water more efficiently, although it had a higher yield than ETc 100% and IoT 80% FC. The highest grain and culm water productivity was also recorded in the black mulch plot for the coloured plastic mulches. As a result of interaction effects, the highest grain and stalk yield was observed in IoT with 100% FC black-coloured mulch, followed by silver-coloured mulch and the control treatment (bare soil). The lowest grain and stalk yield was observed with 100% ETc with bare soil.

Root biomass and grain weight

In ETc-based drip irrigation, corn root biomass grew with increasing irrigation, with ETc 100% showing the highest value. However, the mean values of root biomass in ETc 100% and IoT 100% treatments FC were not significantly different. In contrast, the values for IoT at 80% FC differed considerably from both ETC at 100% and IoT at 100% FC. The highest root biomass was found at ETc 100% with black mulch, silver mulch and bare soil. Table 4 shows that the same letter indicates no significant difference among the three treatment means, while another letter indicates a substantial difference among the three treatment means at $p < 0.05$.

Table 4 Mean comparisons for root biomass and grain weight of field-grown sweet corn at harvest

Irrigation Scheduling type	Irrigation treatment	Grain weight (g/plant)	Root biomass (t/ha)
IoT—100% FC	Black mulch	203.92^{a}	12.72^{ab}
	Silver mulch	202.38^{a}	12.33^{bc}
	Bare soil	201.13^{a}	11.26^{c}
IoT—80% FC	Black mulch	199.10^{ab}	10.21^{d}
	Silver mulch	199.33^{ab}	10.73^{d}
	Bare soil	191.69^{b}	10.46^{d}
ET_C—100%	Black mulch	200.47^{ab}	12.99^{a}
	Silver mulch	195.66^{ab}	12.73^{ab}
	Bare soil	195.30^{ab}	11.63^{c}

Values labelled with the same letter within each column are not significantly different at $p \leq 0.05$. Values within the same columns with other letters are significantly different at $p < 0.05$ (values are means of three replicates)

The drip irrigation treatment IoT with 100% FC recorded the highest grain weight per plant, followed by ETc with 100% and IoT with 80% FC. Grain weight was highest in black mulch with IoT 100% FC, followed by silver mulch and minimal in control (bare soil). Grain weight per plant with IoT 100% FC was not significantly different from that with ETc 100% or IoT 80% FC. Table 4 shows grain weight per plant where the same letter indicates no significant difference among the three treatment means, while another letter indicates a substantial difference among the three treatment means at $p < 0.05$.

Discussion

IoT based drip irrigation system is crucial for the development of irrigation agriculture in the future. In recent years, irrigation systems embedded with water-saving irrigation decision schemes have been further developed to improve Irrigation Water Use Efficiency (IWUE) (Kumar et al. 2020, 2023; Vinod et al. 2022). During the field demonstration, it was proven that the installation of IoT-based sensor technology improves irrigation water use efficiency by analyzing the farmer's ongoing irrigation methods while providing modifications if needed. The availability of real-time data from in-field soil moisture sensors facilitates daily irrigation management decisions, particularly in the event of uncertain precipitation patterns. In the end, the quantity of groundwater can be protected by minimizing over irrigation, which can lower the potential of nutrients leaching below the root zone (Kumar et al. 2020, 2023; Vinod et al. 2022). Further, on-farm demonstrations are conducted in future research to improve the implementation of technology. In addition, it is necessary to continue and expand communication efforts to encourage the use of scientific data in making decisions regarding irrigation management. Furthermore, to manage irrigation, this IoT sensor technology can also be used to assist with other management techniques, including monitoring nutrient levels, pesticide and insecticide usage, frost protection, and monitoring plant health in relation to heat and water stress. Hence, it is crucial to continuously investigate the utilization of Internet of Things (IoT) sensor technologies in agriculture to mitigate the impact of climate change. In addition, due to a lack of wireless moisture sensors developed specifically for analysis, soil moisture data was frequently collected using wired probes equipped with a datalogger (Krishnan et al. 2020). These wired probes require a lot of labor and time to install in the soil profile. Furthermore, the lack of connection between the sensors and controller will lead to irrigation that needs to be more timely and sufficient, thereby affecting the advancement of smart irrigation systems.

This study used wireless IoT- based moisture sensors to acquire real-time data on soil moisture. The data were utilized to calculate the dynamic water usage efficiency and microclimate of sweet corn. This data can serve as a reliable reference for determining the appropriate irrigation depth and monitoring the microclimate of sweet corn. In order to prevent under- or over-irrigation, a precise irrigation decision system was subsequently developed by providing water for real-time irrigation. The proposed decision system for drip irrigation, which utilizes IoT technology to conserve water, relies on upper and lower field capacity thresholds for every irrigating event. This system was developed based on the basis of the soil's available water content. In general, only the water present in the soil that can be efficiently used by crop roots contributes to crop production. Over-irrigation or under-irrigation water, on the other hand, will have a harmful effect on the water-use efficiency and yield (Kumar et al. 2020, 2023; Vinod et al. 2022).

The future development of irrigation agriculture will rely on smart irrigation systems. During this study, a smart irrigation system was developed and tested in a real field to irrigate sweet corn. The IoT-based smart drip irrigation system was used to monitor and control water applications in the field effectively. We have developed a wireless IoT-based drip irrigation system that eliminates the drawbacks of previous systems, such as cost, coverage range, self-powering, weatherproofing, and outdoor use. For decision-making, soil moisture content, temperature, relative humidity, and soil temperature can be obtained in real-time. Irrigation was started when the available water depleted approximately 50% of the field capacity to prevent crop damage due to water stress. This is important because it decides how much available soil water plants can take from the root zone before the next irrigation. In the present study, the level of irrigation, the colour of plastic mulch, and their interactions were found to affect crop yield significantly. In this study, a wireless IoT-based drip irrigation system to obtain real-time data on soil moisture and other micro environmental attributes. The irrigation treatments using IoT with 100% FC resulted in the highest grain and stalk yields. These yields were more than 12.05% and 14.97% greater than the yields obtained from irrigation treatments using ETc with 100% and IoT with 80% FC, respectively. During the growing season, limited water supply results in soil and plant water deficiencies and reduces corn growth (Shirazi et al. 2011). As a result of a water deficit, corn physiological processes, such as tasseling and silking, are delayed, and plant height and vegetation growth are reduced (Payero et al. 2009; Shirazi et al. 2011), which reduces grain yields. Approximately 28–32% of the plant height and leaf area development were reduced during the corn vegetative and tasselling stages as a result of water stress (Cakir (2004)). According to Kazemeini et al. (2014), corn plant height, leaf area index, rows of corn, grain weight, and harvest index were reduced by water stress. As a result of low irrigation volumes, plant water requirements remain inadequate. This affects nutrient transport and delays the development of stems and leaves, resulting in shorter plants, reduced leaf area, sugar and protein content, and dry matter accumulation (Andrade et al. 2005), which leads to the premature death of leaves due to food transfer from leaves (Imam and Saqat-al-Islam 2005). These results are consistent with other studies (Shylla and Sharma, 2010; Paul et al. 2013; Ertek and Kara, 2013).

Mulch films represent a significant advancement in modern agriculture, offering numerous benefits that enhance crop growth and yield (Scarascia-Mugnozza et al. 2004). One of the most notable advantages of mulch films is their ability to reduce evapotranspiration, resulting in a substantial decrease in irrigation consumption (Ramalan and Nwokeocha 2000). The colour of the plastic mulch plays a crucial role in the microclimate around the crops, affecting characteristics such as transmittance, absorptivity, and reflectivity. The surface temperature of the mulch and the temperature of the soil underneath it are both influenced by colour. Black plastic mulch, in particular, is known as a black body absorber and radiator. It absorbs the most visible and infrared wavelengths of solar radiation and reemits the energy as heat or long-wavelength infrared radiation. This process raises the temperature of the soil, which promotes better plant growth and development, especially in colder areas or during the initial stages of growth. Moreover, the use of black plastic mulch promotes soil moisture retention, reduces soil erosion, and inhibits weed growth (Ramalan and Nwokeocha 2000; Ramalan and Nwokeocha 2000; Shirazi et al. 2011). The absorption of solar energy by black plastic mulch leads to energy loss from the atmosphere, which is subsequently lost due to radiation and induced convection. In comparison to bare soil, temperatures under black plastic mulch are typically higher during the day by 28 °C (50°F) at a 5 cm layer and 17 °C (30°F) at a 10 cm depth (Scarascia-Mugnozza et al. 2004). These environmental benefits of mulch films, such as reduced soil erosion and weed growth, contribute to a more sustainable and efficient agricultural system, making the use of mulch films a vital step in this direction. Plants receive high light intensity when they are covered in silver plastic mulches, which alter the amount and quality of light reflected up into the plant canopy (Hutton and Handley 2007). Due to their high level of water vapour impermeability, plastic mulches reduce the amount of water that evaporates from the soil. Plastic mulch minimises soil moisture evaporation when used in conjunction with drip irrigation, which lowers the demand for irrigation (Kazemeini et al. 2014). According to the study, silver plastic mulch with 100% FC had the lowest soil temperature during seed germination, whereas black plastic mulch with 100% FC had the highest. Conversely, it was discovered that black plastic mulch had the highest percentage of soil moisture, followed by silver plastic mulch. Silver and black plastic mulch may have facilitated better light scattering and the availability of photosynthetically active radiation, resulting in higher growth attributes. Additionally, the black mulch may have caused the soil to heat up in colder seasons, which can increase plant growth attributes, resulting in a higher yield.

According to the results and previous studies, mulches lower soil temperature in summer and increase it in winter. The application of mulch changes the soil temperature, which affects the soil's thermal regime (Arora et al. 2011; Pramanik et al. 2015). Olasantan (1999) observed that soil temperatures under mulch were higher in cold weather and lower in warmer weather. Nevertheless, biodegradable sheet mulch provides lower temperatures than polyethene (Moreno & Moreno 2008). Mulches reduce maximum soil temperatures while increasing minimum temperatures (Begum et al. 2022) and significantly decreasing soil temperatures (Sanders 2001). A study by Zhang et al. (2009) showed that soil temperature dropped by 4 ^{O}C during the warmer period and increased by 2 ^{O}C at a depth of 10 cm during the cooler period. Black plastic mulch increases soil temperature (Ibarra-Jiménez et al. 2012), but silver plastic mulch decreases it (Lamont, 1993). With its high reflectivity and low absorptivity, and transmittance, silver-coloured plastic could be a good option for tropical climates (Angima, 2009; Sanders 2001).

Previous research showed that using a soil moisture sensor-based irrigation scheduling system resulted in water savings of up to 60% when compared to traditional irrigation systems (Muñoz-Carpena et al. 2005; Grabow et al. 2013; Millán et al. 2019). A study conducted by Boltana et al. (2023) found that adopting a soil moisture sensor-based technique resulted in a reduction of 18% in irrigation water usage compared to the ET-based method in tomato fields (Boltana et al. 2023). Furthermore, the use of sensor-based irrigation techniques resulted in a significant improvement in water use efficiency in soybean and potato fields, with an overall increase of 49% and 16%, respectively, as reported by Wood et al. (2020) and Dong et al. (2023). The Artificial Intelligent (AI)-driven irrigation scheduling method evaluates various input data, including soil moisture, soil temperature, air temperature, relative humidity, plant canopy temperature, crop type, crop growth stage, and yield data, in order to generate AI techniques. The algorithms are commonly developed using machine learning, deep learning, and reinforcement learning methods. These algorithms offer predictive analytics regarding the optimal amount, timing, and frequency of irrigation, as well as yield data. This data can be utilized for long-term water usage scheduling, taking into account weather forecasts and allowing proactive interventions through predictive techniques. Studies by Mohammad et al. (2013) and Zia et al. (2021) have demonstrated that this AI-driven irrigation scheduling can enhance irrigation water use efficiency by up to 50%. Additionally, Jamroen et al. (2020) found that it can reduce water usage by 59% compared to the conventional industry methods. The results of the current study and previous studies suggest that soil moisture sensors and recent advances in IoT and WSN technologies are reliable and valuable tools for predicting soil moisture content under changing field conditions as well as an effective method for irrigation scheduling (Goap et al. 2018). A similar result was reported by (Krishnan et al. 2020; Zhu et al. 2018). In Summary, the developed IoT-based drip irrigation system provides an achievable goal for resolving the issues of water scarcity and food security, as compared to previous irrigation decision systems. IoT-based drip irrigation with 100% FC and 80% FC used 12.7% and 24.5% less irrigation water, respectively, than ETC-based drip irrigation while keeping the same marketable yields and quality of sweet corn as the farmer's traditional irrigation management. Pumping less water not only saves energy but also lowers farm energy expenses. An autonomous irrigation system provides the key benefit of reducing the time and labor costs associated with operating the irrigation system on farmers.

Conclusions

Precise irrigation scheduling is essential for high crop yields and water productivity. This study investigated irrigation scheduling techniques under different mulch treatments over two years. Two approaches to irrigation scheduling were used: ETc-based drip irrigation calculations and IoT-based drip irrigation techniques (100% FC and 80% FC) using capacitive soil moisture sensors (v2.0). The IoT device consists of sensors and a microprocessor that successfully collects information about environmental parameters such as temperature, humidity, soil temperature, and soil moisture. Using IoT technology, the data collected by the sensors was wirelessly uploaded to the cloud server (ThingSpeak IoT platform) for retrieval through an internet-enabled device. A wireless smart IoT drip irrigation system developed in this study provides an improved monitoring range. At the same time, the rugged, weatherproof, solar-powered data collection unit is suitable for extended outdoor use. Both irrigation methods significantly impacted plant height, cob length, yield, water productivity, and root biomass. Sweet corn yields were high in the IoT-based drip irrigation treatments with 100% FC. This irrigation scheduling approach produced high yields with low to medium irrigation. Compared to ETC-based drip irrigation, IoT-based drip irrigation with 100% FC and 80% FC used 12.7% and 24.5% less irrigation water, respectively, and achieved a 12.8% higher marketable yield than ETc- and IoT-based drip irrigation with 80% FC. ETc-based drip irrigation at recommended Kc levels resulted in a huge 12.5% over-irrigation compared to the IoT treatment at 100% FC. Grain and stalk yields increased by more than 12.05% and 14.97% in the IoT irrigation treatment at 100% FC compared to the other irrigation treatments. Black plastic mulch consistently increased soil temperature more than other mulches, with the highest increase at 2.65 ^{O}C at 15 cm depth, followed by silver mulch at 2 ^{O}C, compared to no mulch treatment. This study concludes that the placement and accuracy of soil moisture sensors affect irrigation efficiency in IoT-based drip irrigation systems.

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Authors' contributions S. Vinod Kumar: conceptualization, performing the experiments, writing the manuscript, data maintenance, software, and original draft. C. D. Singh: advisory committee chair, conceptualization, methodology, peer review, and editing. K. V. R. Rao: extended field facilities, provided technical input on calibration, and reviewed and edited the manuscript. Mukesh Kumar reviewed and edited the manuscript. Yogesh Anand Rajwade and K. R. Asha: provided technical input on the assembly of various components and reviewed and edited the manuscript.

Data availability Arduino code (electronic circuit management), Fritzing Open Software (electronic circuit and PCB design), Response Surface Methodology (statistical analysis), and test data. Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work in this article.

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