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RESEARCH ARTICLE

Validation of soil moisture sensors in automated irrigation system and performance evaluation in maize

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Abstract

A research work was conducted at the Agricultural College & Research Institute, Coimbatore, during the summer and winter seasons of 2023. It comprised two experiments. The first experiment evaluated five soil moisture sensors-Tensiometer, Time Domain Reflectometry (TDR), Theta Probe, Capacitance Sensor and Watermark Sensor-against gravimetric soil moisture measurements. The TDR sensor demonstrated the highest accuracy, with soil moisture readings closely matching gravimetric values at depths of 15 cm, 30 cm and 45 cm. The second experiment assessed maize water requirements under seven treatments: Tensiometer (T_1), Soil Moisture Sensor (T_2), Gravimetric Method (T_3), Penman-Monteith Method (T_4), Thornthwaite Method (T_5), SEBAL Method (T_6) and Conventional Method (T_7). Results showed that sensor-based irrigation enhanced maize growth parameters, including plant height (214.8 cm and 217.8 cm), leaf number (16.4 and 16.2), dry matter production (17413 kg ha^{-1} and 17324 kg ha^{-1}) and reduced time for tasseling (53.9 days and 53.2 days) and silking (61.2 days and 61.4 days), compared to conventional irrigation over the two seasons. Soil moisture sensor-based irrigation in maize achieved the highest water productivity (1.4 kg m^{-3} in summer and winter) and water use efficiency (13.6 and 14.0 kg ha^{-1} mm^{-1}). The study concluded that sensor-based irrigation, particularly with TDR sensors, is effective for automating irrigation and improving water use efficiency. The accuracy of in-situ measurement using sensors and tensiometers surpassed the empirical Penman-Monteith and Thornthwaite Methods and satellite-derived SEBAL method, reinforcing the reliability of sensors in automated irrigation models resulting in water saving and increased productivity. These findings significantly contribute to global water resource management by promoting efficient water use, reducing wastage and addressing the challenges of water scarcity. Additionally, they advance precision agriculture by enabling site-specific irrigation practices, optimizing crop yield and enhancing resource sustainability.

Keywords

growth parameters; maize; sensors; tensiometer; time domain reflectometry

Introduction

In recent decades, groundwater depletion (GWD) has become a critical global issue, with extraction rates surpassing natural replenishment. From 2000 to 2010, GWD increased by 22 % (1). India, home to 18 % of the global population but only 4 % of global water resources, faces acute water scarcity. Groundwater, accounting for 40 % of India's water needs, is being rapidly depleted, with projections indicating that 60 % of the country's aquifers will be in critical condition within two decades (2). Agriculture, the largest consumer of water globally, contributes significantly to this crisis, using around 60 % of freshwater withdrawals and 90 % of total water usage. Irrigated land, though only 18 % of total farmland, produces nearly half of global food, highlighting the critical need for efficient water management in agriculture.

Traditional irrigation methods, such as surface and flood irrigation, are highly inefficient, with water losses exceeding 50 % due to evaporation, runoff and deep percolation (3). These methods contribute to water scarcity and soil salinization. Drip irrigation, a more efficient alternative, delivers water directly to the root zone, conserving water and improving soil moisture (4). Israel, a global leader in irrigation practices, has successfully implemented full adoption of this technology among farmers (5). Drip irrigation has been shown to maintain up to 80 % soil moisture in key crops like rice, wheat and maize (6). It also promotes better root and shoot development, resulting in higher yields compared to traditional flood irrigation (7). In addition to drip irrigation, sensor-based automated irrigation systems are becoming a key technology for improving water use efficiency. These systems use moisture sensors, weather data and soil analysis to automate irrigation, delivering water only when needed and in the exact amount required. Israel has also pioneered the use of sensor-based automation in irrigation, where sensors are integrated into drip systems to further reduce water waste (5).

Similarly, in the United States, sensor-based systems are being adopted across agricultural sectors to optimize water use, particularly in water-scarce regions like California. Farmers use soil moisture sensors connected to automated systems that adjust water delivery based on real-time data, ensuring minimal water wastage and improved crop yields.

In Australia, sensor-based irrigation is widely used in cotton farming, where real-time data helps in adjusting irrigation schedules to local weather patterns and soil moisture levels. This technology has significantly reduced water consumption, particularly in the drought-prone regions of the country. As the most efficient irrigation method, drip systems deliver water directly to the root zone, whereas excessive water under flooded irrigation can cause nutrient leaching. Therefore, a controlled irrigation system is essential to supplement natural rainfall and supply the exact amount of water needed for optimal plant growth.

The latest trend in water and energy conservation techniques in agriculture is moving from manual systems to automated operations in pressurized systems. These modern methods employ technologies such as remote sensing, machine learning and data analytics, providing farmers with real-time insights and decision-making tools. By integrating data-driven strategies, farmers can better respond to environmental shifts, enhance crop yields and improve sustainability. This transition toward precision agriculture holds significant promise for ensuring food security, fostering environmental responsibility and supporting the long-term sustainability of agriculture in the face of global challenges (8). Recent advancements have introduced automated irrigation systems, integrating Internet of Things (IoT) technologies and remote sensing. These systems employ sensors, actuators and controllers to monitor and manage irrigation based on real-time soil moisture, temperature and humidity data.

The validation of soil moisture sensors under diverse field conditions is a crucial step in advancing smart irrigation technologies. Soil conditions vary significantly across regions, affecting water retention and movement in the soil profile. Standardizing and calibrating sensors to accurately capture this spatial variability ensures that irrigation systems deliver precise water quantities tailored to the specific needs of crops and locations. Such efforts not only enhance the efficiency of irrigation systems but also build the foundation for scaling precision agriculture technologies to diverse agricultural conditions.

Remote sensing complements IoT by providing real-time insights into crop health, soil moisture and weather conditions through satellite and drone-based imagery. Together, these technologies enable precision farming, optimizing water use and enhancing sustainability. Automated systems deliver water efficiently, maintaining optimal soil moisture and minimizing overwatering or underwatering. Predictive models further refine irrigation scheduling, ensuring effective resource use and higher crop yields.

To address these challenges, research titled "Validation of Soil Moisture Sensors in Automated Irrigation System and Performance Evaluation in Maize" was conducted. The study aimed to develop a smart irrigation system to enhance water productivity and efficiency for various crops across diverse locations. Its objectives included standardizing soil moisture sensors to capture spatial variability and determining crop water requirements for precise irrigation scheduling. Such innovations hold significant promise for transforming traditional farming practices and addressing the global challenge of water scarcity in agriculture.

Materials and Methods

Basic studies were conducted to identify the most suitable soil moisture sensor for assessing water requirements by evaluating the accuracy and responsiveness of five sensors which were selected based on the availability: Tensiometer (Irrometer), TDR (SONO-M1), Theta Probe (ML3 ThetaProbe), Capacitance (Tr-Ts RS485) and Watermark sensors (WATERMARK 200SS) at soil depths of 15, 30 and 45 cm. Sensor precision was validated against gravimetric soil moisture content, calculated by oven-drying soil samples at 105 °C for 24 hr and using the formula:

$$\text{Soil moisture content} = \frac{W_1 - W_2}{W_2} \times 100$$

Where, W_1 : weight of wet soil with a moisture can, W_2 denotes the weight of dry soil with a moisture can.

The TDR sensor demonstrated the highest accuracy and was selected for further testing and integration into the automated irrigation model in subsequent experiments.

The field experiments were conducted at the Eastern Farm of the Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore (11.0086 °N, 76.09385 °E; 426.72 m MSL) during the summer and winter seasons of 2023 under a semi-arid tropical climate. Weather data were collected from the Automated Weather Station at this site including maximum and minimum temperature, relative humidity (RH_{min} and RH_{max}), solar radiation (R_s) and wind speed (u_2). During Season I, maximum and minimum temperatures recorded were 37.5 °C and 21.0 °C, respectively, with relative humidity ranging from a peak of 96 % to a low of 19 %. The rainfall received during this season was 247 mm. The average wind speed during this season was 5.1 km h^{-1}. In Season II, temperatures varied from a maximum of 35.2 °C to a minimum of 21.0 °C, while relative humidity fluctuated between 98 % and 37 %. The average wind speed for this season was 5.3 km h^{-1} and the maximum solar radiation reached 5.4 MJ m^{-2} day^{-1}. The rainfall received during this season was 36.9 mm. The soil at the experimental site in Coimbatore was identified as clay loam and taxonomically classified as Typic Ustropept from the Noyyal series. In terms of texture, the soil is categorized as clay loam, with a field capacity of 26.52 %, a permanent wilting point of 13.51 % and a bulk density of 1.34 g cc^{-1}. The pH level of the soil was 7.3, with an electrical conductivity (EC) of 0.73 dS m^{-1} and an organic carbon content of 0.27 %. During both the summer and winter cropping seasons of 2023-2024, nitrogen levels were low, phosphorus levels were medium and potassium levels were high. The experiment was laid out in Randomized Block Design (RBD), consisting of three replications and seven treatments. The treatments were Tensiometer (T_1), Soil Moisture Sensor (T_2), Gravimetric Method (T_3), Penman-Monteith Method (T_4), Thornthwaite Method (T_5), SEBAL Method (T_6) and Conventional Method (T_7). The field was ploughed and laterals were raised with a spacing of 60 cm under the drip system. For the conventional field, the ridges and furrows were laid 60 cm apart. The seeds of hybrid maize COH (M) 6 were used at the rate of 20 kg ha^{-1}. The growth parameters such as plant height, number of leaves, days to attain 50 % tasselling and silking, dry matter production, water productivity and water use efficiency were recorded. The data gathered during the study were analyzed statistically following an earlier methodology (9). Treatment differences were considered significant if the calculated critical difference at a 5 % probability level indicated so and the results were presented in tables.

Results and Discussion

Validation of soil moisture measurements using sensors

The standard gravimetric method resulted in a soil moisture content of 33.30 %, 34.13 % and 36.24 % at 15 cm, 30 cm and 45 cm of soil depth. Among the sensors, the highest value of soil moisture content was recorded by Time Domain Reflectometry (TDR) soil moisture sensor with values of 31.82 %, 32.78 % and 35.39 % at depths of 15 cm, 30 cm and 45 cm respectively followed by an irrometer with the values of 31.20, 30.57 and 34.50 % at the respective soil depths of 15, 30 and 45 cm. The next best sensor in order was the watermark soil sensor which recorded a soil moisture content of 30.12, 29.94 and 33.24 % at respective soil depths of 15, 30 and 45 cm respectively. Among the different sensors used for assessing soil moisture content the lowest values of 27.84, 28.41 and 30.24 % were recorded by the Theta probe soil moisture sensor at the depths of 15, 30 and 45 cm respectively. The highest agreement of 95.6 to 97.7 % was observed with TDR soil moisture probe followed by irrometer which resulted in an agreement of 93.7 %, 89.6 % and 95.2 % at the depth of 15, 30 and 45 cm respectively (Table 1 & Fig. 1). Watermark soil moisture sensor also resulted in an agreement of 90.5, 87.7 and 91.7 % at various depths of 15, 30 and 45 cm respectively. The other two sensors viz theta probe soil sensor and capacitance soil moisture sensor resulted in lower agreement and thereby precision with the values of 83.4 % to 87.4 % as compared to the gravimetric method of soil moisture measurement. The high accuracy of TDR sensors in measuring soil moisture was due to their ability to assess the dielectric properties of the soil without being significantly affected by temperature or salinity variations. TDR sensors outperform other soil moisture measurement methods due to their ability to assess the dielectric properties of the soil, which are directly related to water content. These sensors send an electromagnetic pulse through the soil and the pulse's reflection time is influenced by the dielectric constant, which is higher in water than in dry soil. Unlike gravimetric or neutron scattering methods, TDR sensors are minimally affected by temperature or salinity variations because they measure the dielectric properties of the soil, not the water's chemical or physical properties. This results in more

Table 1. Validation of soil moisture content observed from sensors using gravimetric measurements

Depth (cm)	Soil moisture content (%)		Agreement with gravimetric measurements (%)
15	Irrometer	31.20	93.7
	TDR soil moisture probe	31.82	95.6
	Theta probe soil moisture sensor	27.84	83.6
	Capacitance soil moisture sensor	29.12	87.4
	Watermark soil moisture sensor	30.12	90.5
	Gravimetric method	33.30	-
30	Irrometer	30.57	89.6
	TDR soil moisture probe	32.78	96.0
	Theta probe soil moisture sensor	28.41	83.2
	Capacitance soil moisture sensor	28.83	84.50
	Watermark soil moisture sensor	29.94	87.7
	Gravimetric method	34.13	-
45	Irrometer	34.50	95.2
	TDR soil moisture probe	35.39	97.7
	Theta probe soil moisture sensor	30.24	83.4
	Capacitance soil moisture sensor	31.10	85.8
	Watermark soil moisture sensor	33.24	91.7
	Gravimetric method	36.24	-

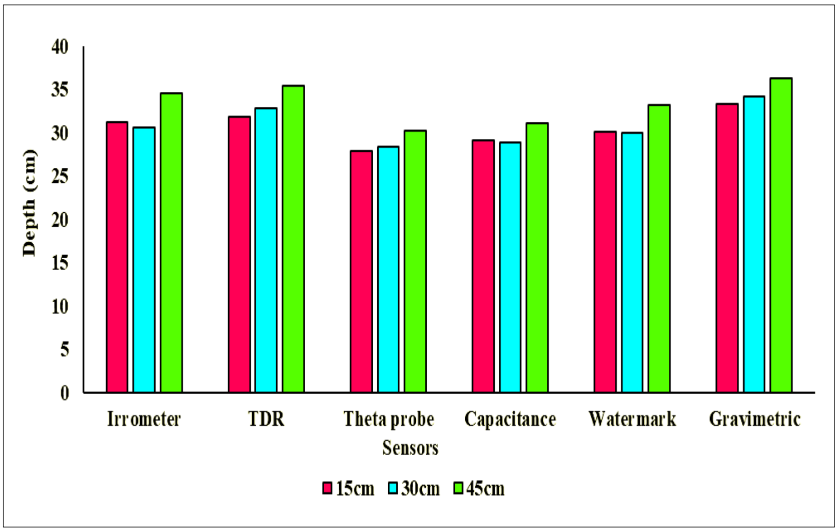

Fig. 1. Validation of soil moisture sensor data using gravimetric measurements at different depths.

accurate and consistent measurements under varying environmental conditions. TDR sensors also provide continuous, real-time data, making them ideal for precision agriculture. Similar findings of TDR sensors measuring soil moisture with higher accuracy than other methods (10). Similar findings of high accuracy of TDR sensors indicated that TDR sensors can achieve an accuracy of ± 1–2 % in moisture measurement under field conditions, while capacitance sensors and tensiometers may deviate by as much as 5 % (11). When comparing these results with studies conducted in different soil types or climates, TDR sensors consistently show robust performance. For example, in arid regions where salinity levels vary, TDR sensors maintain their accuracy, while capacitance sensors may experience greater errors due to the influence of soil salinity. Similarly, in clay-heavy soils where other methods may struggle with accurate moisture readings due to their inability to penetrate dense soil, TDR sensors continue to offer reliable measurements. These findings support the broader applicability and reliability of TDR sensors across diverse agricultural environments. TDR sensors maintain a relatively consistent response to soil moisture across various soil types, including sandy, loamy and clayey soils. This characteristic makes TDR particularly adaptable to different environmental conditions without necessitating significant adjustments. Based on the research findings TDR sensors can be seamlessly integrated into automated systems that continuously monitor soil moisture levels and adjust irrigation practices in real time. This feature of automated, instantaneous feedback provides substantial advantages over other methods, such as irrometers and watermark sensors, which depend on measurements of soil water tension that often require manual interpretation and calibration. The research highlighted that the real-time data provided by TDR sensors makes them an optimal choice for precision irrigation systems, ultimately leading to more efficient water usage and increased crop yields (12). Furthermore, access to real-time information enhances the management of soil moisture levels, thereby reducing the likelihood of over-irrigation or under-irrigation and it's important to consider some limitations. The initial costs of purchasing and installing these systems can be high, especially for large-scale agricultural operations. Additionally, maintaining these systems requires regular calibration and sensor checks to ensure accuracy, which can incur further costs and labor. Another challenge is the compatibility of sensor-based systems with existing irrigation infrastructure. Retrofitting older irrigation systems to work with automated sensors may require significant modifications or upgrades, which could be expensive and time-consuming. Despite these challenges, the long-term benefits of efficient water management often outweigh the initial investment.

Growth parameters of maize

Plant height

The various irrigation methods have significantly influenced the plant height and it is presented in Table 2. During summer, sensor-based irrigation recorded the tallest plants with a height of 53.1 cm, which was followed by tensiometer-based irrigation with 50.2 cm. In contrast, conventional irrigation

Table 2. Effect of automated irrigation models on plant height (cm) of hybrid maize

Treatments	Summer			Winter		
	30 DAS	60 DAS	Harvest	30 DAS	60 DAS	Harvest
T_1 – Tensiometer	50.2	166.2	208.9	51.0	165.9	205.1
T_2 - Soil moisture sensor	53.1	169.5	214.8	54.8	167.8	217.8
T_3 - Gravimetric method	49.3	153.1	199.6	50.3	151.8	200.7
T_4 - Penman monteith method	48.5	150.8	194.8	49.4	148.3	196.5
T_5 - Thornthwaite method	48.9	147.2	194.7	49.1	143.5	196.1
T_6 - SEBAL method	48.2	149.1	193.8	48.7	145.8	197.2
T_7 - Conventional method	46.9	137.7	183.5	47.2	140.8	185.1
S.Ed	1.6	9.2	5.5	1.9	4.5	6.4
CD (p=0.05)	3.5	11.3	11.9	4.0	9.6	13.7

resulted in shorter plants, measuring 46.9 cm at 30 days after sowing (DAS). The sensor-based irrigation continued to lead with the tallest plants at 169.5 cm and tensiometer-based irrigation was comparable with sensor-based irrigation with a value of 166.2 cm. The conventional irrigation method, however, recorded shorter plants, measuring 137.7 cm at 60 DAS. The sensor-based irrigation recorded a maximum height of 214.8 cm and it was followed by the tensiometer-based irrigation with 208.9 cm. Conventional irrigation showed a notable reduction in plant height, reaching 183.5 cm at the harvest stage.

At 30 DAS, during winter the sensor-based irrigation recorded the maximum height of 54.8 cm. The tensiometer-based irrigation recorded the plant height of 51.0 cm and the lowest plant height was observed in the conventional irrigation method with the value of 47.2 cm. A similar trend was followed in 60 DAS and at harvest with the values of 167.8 cm and 217.8 cm in sensor-based irrigation, 165.9 cm and 205.1 cm in tensiometer based irrigation, 140.8 cm and 185.1 cm in the conventional irrigation system. The result from this study revealed that the TDR soil moisture-based irrigation and the tensiometer based method had a more positive impact than the conventional irrigation method in maize (Fig. 2 & 3). This enhanced growth might be attributed to a more favourable soil-plant-water balance in drip irrigation, which promotes increased activity in meristematic cells and elongation of internodes. TDR sensors provide real-time, accurate measurements of soil moisture content, allowing for precise irrigation scheduling. This precision helps to ensure that plants receive the optimal amount of water at critical growth stages, which is essential for maximizing height and overall growth. In contrast, conventional methods often rely on generalized schedules that may not accurately reflect the actual moisture needs of the plants. This can lead to either over-irrigation or under-irrigation, both of which negatively impact plant health and height (13). Accurate monitoring of soil moisture enables farmers to optimize nutrient applications. When plants are adequately watered, nutrients are more accessible in the soil, promoting better absorption and utilization by the roots. Conventional irrigation methods may not provide sufficient insight into moisture levels, potentially leading to nutrient deficiencies that inhibit plant height. The water stress in maize reduced the plant height by 7 % as compared to non-stress conditions (14). Therefore, several researchers also reported an increase in plant height with increased frequency and amount of water application from

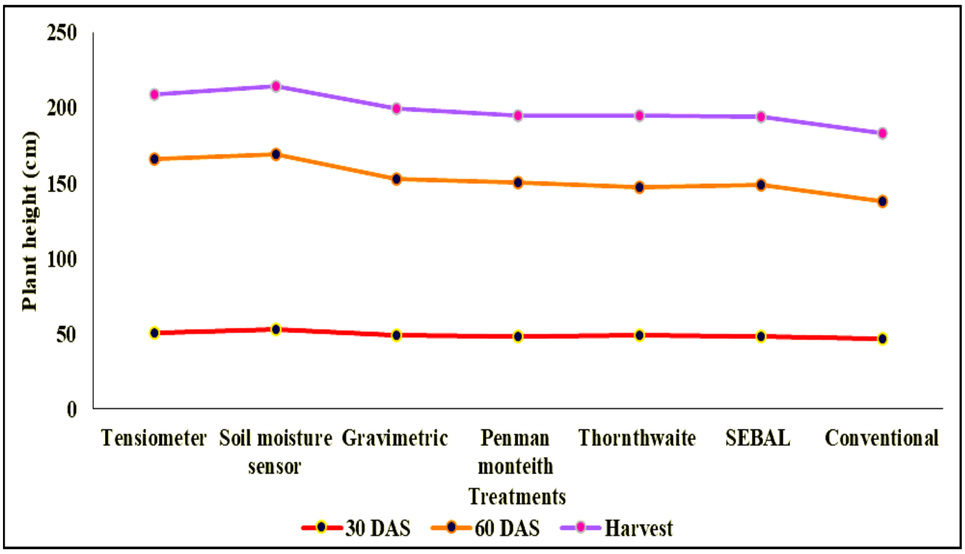

Fig. 2. Effect of automated irrigation on plant height (cm) of hybrid maize during summer 2023.

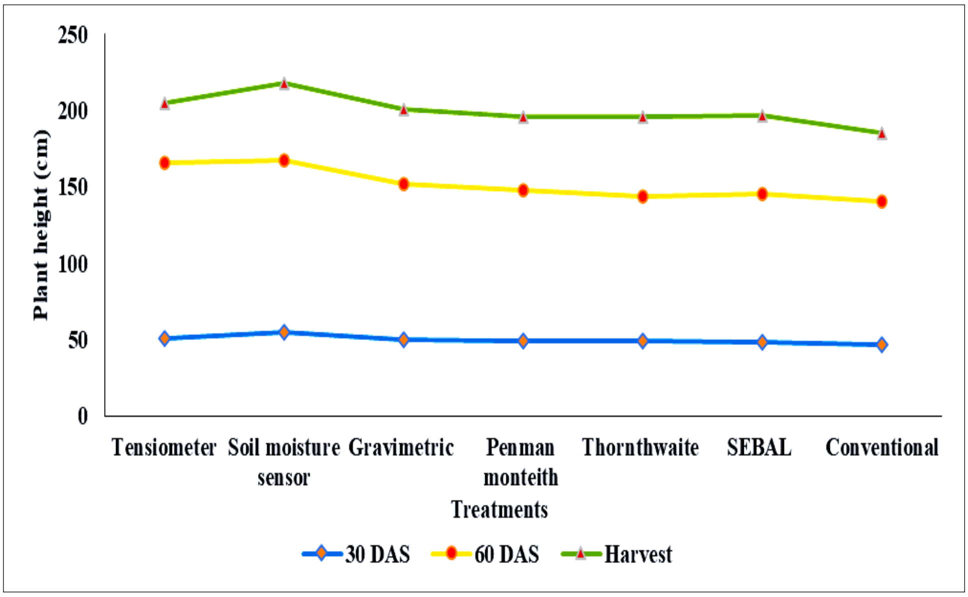

Fig. 3. Effect of automated irrigation on plant height (cm) of hybrid maize during winter 2023.

deficit levels to full irrigation (15, 16).

Number of leaves

The number of leaves doesn't show any significant variation among the treatments (Table 3). The maximum number of leaves of 6.5, 12.3 and 16.4 was observed in the sensor-based irrigation at 30, 60 and 90 DAS during summer. The conventional method of irrigation recorded the minimum leaf numbers compared to the sensor-based method with 5.5, 10.2 and 13.7 during 30, 60 and 90 DAS respectively. The same trend was obtained in the second season. The ability of TDR sensors to monitor soil moisture dynamics allows for timely irrigation interventions that can prevent periods of drought stress. Studies have shown that water deficit stress can significantly reduce leaf number and overall plant growth (17). By ensuring that maize receives adequate moisture through informed irrigation practices, TDR technology helps mitigate these stressors, promoting healthier plants with more leaves.

Dry matter production

The irrigation method had a significant influence on the dry matter production of maize was enlisted in Table 4. At 30 DAS, the maximum dry matter production was recorded in the sensor-based irrigation with 1779 kg ha^{-1}, followed by the tensiometer-based irrigation with the quantity of 1686 kg ha^{-1}. In contrast, the conventional irrigation method obtained the lowest dry matter production with 1272 kg ha^{-1}. At 60 DAS, sensor-based irrigation continuously recorded the maximum dry matter with 8592 kg ha^{-1}, while the tensiometer-based method was showed to be on par with the dry matter of 8127 kg ha^{-1} and the conventional method recorded the lowest dry matter production with the value of 6935 kg ha^{-1}. At harvest, sensor-based method recorded the maximum dry matter of 17413 kg ha^{-1}. However, the tensiometer-based method was found on par by obtaining the value of 16928 kg ha^{-1}. Conventional irrigation again recorded the lowest dry matter production of 14498 kg ha^{-1}. A similar trend was recorded in the winter season at all the growth stages of maize. The TDR-based irrigation method recorded more dry matter production than the conventional method. Water availability significantly affected stem elongation, which in turn influenced plant height, the final size and the number of individual leaves and ultimately led to a higher Leaf Area Index (LAI) and increased dry matter production (Fig. 4 & 5). Dry matter production was improved in sensor-based drip irrigation than the surface irrigation method. Dry matter production, indicative of overall plant growth, rises with greater plant height and LAI (18). This increase might be attributed to a larger number of sinks and an expanded photosynthetic capacity of the crop under frequent irrigation. As a result, this enhanced assimilated production directly influenced the dry matter generated per plant and per unit area. This coincided with the earlier studies (19, 20). Irrigation planning that utilizes soil sensors, such as soil moisture sensors and tensiometers, resulted in increased leaf area and higher levels of both fresh and dry biomass (21).

50 % tasseling and 50 % silking

The treatment doesn't show any significant difference with respect to 50 % tasseling and 50 % silking and it is given in Table 5. In the soil moisture sensor-based method the 50 % tasseling and 50 % silking occurred the earliest at 53.9 days, 53.2 days and 61.2 days, 61.4 days in the first and second seasons. This was followed by tensiometer, which took 54.2 and 53.9 days for 50 % tasselling and 62.4 and 62.5 days for 50 % silking in the two seasons. The conventional method took the longest time to reach 50 % tasselling and 50 % silking, by recording 56.4 and 56.7 days in the first season and 65.3 and 65.9 days in the second season. The days to 50 % tasseling and silking were also achieved earlier in the sensor-based method. The enhanced growth parameters observed with sensor-based irrigation might be attributed to improved nutrient and water uptake facilitated by the drip application of water. This method effectively increased nutrient absorption by the crop, leading to more vegetative growth. Similar findings regarding the positive impact of increased nutrient and water uptake on growth parameters have been documented by research (22,

Table 3. Effect of automated irrigation models on number of leaves of hybrid maize

Treatments	Summer			Winter		
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
T_1 – Tensiometer	6.3	11.5	15.2	6.4	11.3	15.4
T_2 - Soil moisture sensor	6.5	12.3	16.4	6.5	12.4	16.2
T_3 - Gravimetric method	6.1	11.3	14.9	6.2	11.4	15.0
T_4 - Penman monteith method	5.8	11.1	14.4	6.2	11.0	14.7
T_5 - Thornthwaite method	5.9	11.4	14.5	6.1	11.3	14.3
T_6 - SEBAL method	5.8	10.7	14.3	6.0	10.9	14.5
T_7 - Conventional method	5.5	10.2	13.7	5.6	10.1	13.6
S.Ed	0.3	0.6	0.8	0.3	0.6	0.8
CD (p=0.05)	NS	NS	NS	NS	NS	NS

Table 4. Effect of automated irrigation models on total dry matter production (kg ha^{-1}) of hybrid maize

Treatments	Summer			Winter		
	30 DAS	60 DAS	Harvest	30 DAS	60 DAS	Harvest
T_1 – Tensiometer	1686	8127	16928	1708	8295	16993
T_2 - Soil moisture sensor	1779	8592	17413	1892	8618	17324
T_3 - Gravimetric method	1603	8096	16752	1635	8139	16762
T_4 - Penman monteith method	1432	7478	15962	1515	7512	15831
T_5 - Thornthwaite method	1498	7522	15719	1505	7594	15793
T_6 - SEBAL method	1476	7425	15863	1521	7499	15784
T_7 - Conventional method	1272	6935	14498	1153	6793	14392
S.Ed	78.0	216.6	445.3	84.9	394.3	4425
CD (p=0.05)	167.8	465.8	957.3	182.7	847.8	951.5

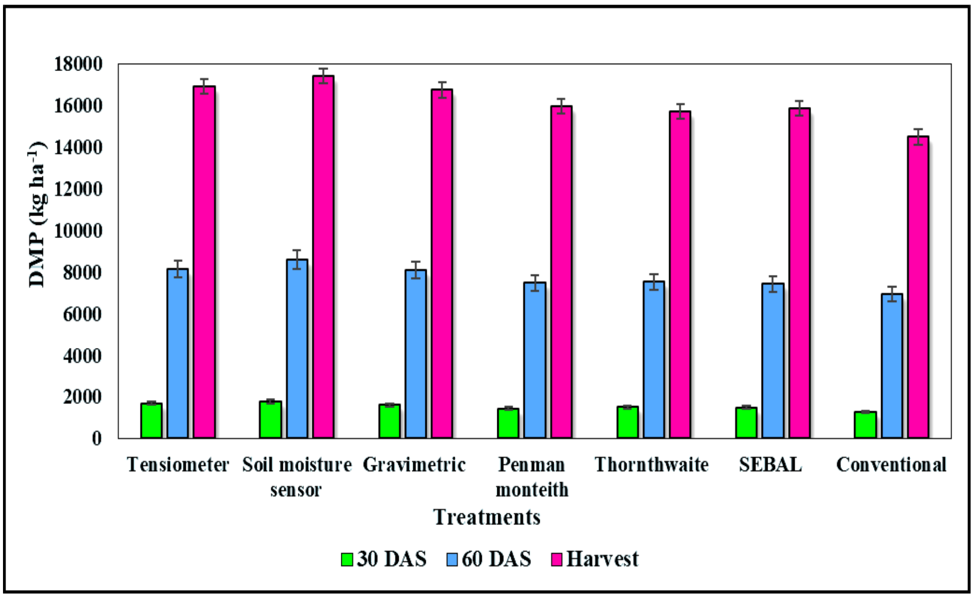

Fig. 4. Effect of automated irrigation on dry matter production (kg ha^{-1}) of hybrid maize during summer 2023.

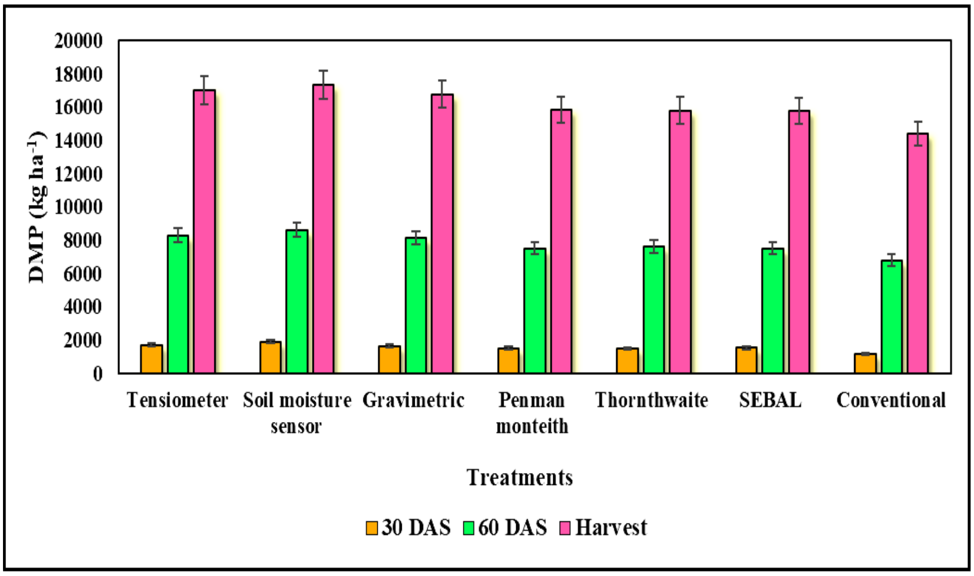

Fig. 5. Effect of automated irrigation on dry matter production (kg ha^{-1}) of hybrid maize during winter 2023.

Table 5. Effect of automated irrigation models on 50 % tasselling and silking of hybrid maize

Treatments	Summer		Winter	
	50 % tasselling	50 % silking	50 % tasselling	50 % silking
T_1 – Tensiometer	54.2	62.4	53.9	62.5
T_2 - Soil moisture sensor	53.9	61.2	53.2	61.4
T_3 - Gravimetric method	54.9	63.2	54.6	63.4
T_4 - Penman monteith method	55.8	64.5	55.4	64.9
T_5 - Thornthwaite method	55.4	64.7	55.7	64.2
T_6 - SEBAL method	55.2	64.2	55.3	64.3
T_7 - Conventional method	56.4	65.3	56.7	65.9
S.Ed	1.5	1.7	2.0	2.6
CD (p=0.05)	NS	NS	NS	NS

23).

Water parameters

Water productivity

The highest total water productivity for maize was recorded in the sensor-based method), reaching a value of 1.4 kg m^{-3} in both seasons (Table 6). Conversely, the conventional irrigation method recorded the lowest irrigation water productivity, with a value of 0.8 kg m^{-3}across the two seasons. The sensor network-based automated drip irrigation system consistently keeps the active root zone adequately moist in real-time, responding to the plant's needs. This approach leads to optimal total water productivity (CWP), contributing to significant savings in irrigation water usage. This observation is supported by previous research (24, 25). Sensor-based drip irrigation conserved water by applying it at low rates and frequent intervals that align with the actual water needs of the crop at various growth stages. Unlike surface irrigation, which wets the entire field, drip irrigation only moistens a portion of the soil surface surrounding the plants. This result confirms an finding in which it was reported that the drip irrigation method reduced water consumption by 30 % to 70 % compared to

Table 6. Effect of automated irrigation models on total water productivity (kg m^{-3}) and water use efficiency (kg ha^{-1} mm^{-1}) of hybrid maize

Treatments	Summer		Winter	
	Total water productivity (kg m^{-3})	Water use efficiency (kg ha^{-1} mm^{-1})	Total water productivity (kg m^{-3})	Water use efficiency (kg ha^{-1} mm^{-1})
T_1 - Tensiometer	1.2	11.7	1.1	11.5
T_2 - Soil moisture sensor	1.4	13.6	1.4	14.0
T_3 - Gravimetric method	1.1	11.0	1.1	11.1
T_4 - Penman monteith method	1.0	10.4	1.1	10.7
T_5 - Thornthwaite method	1.1	10.7	1.0	10.2
T_6 - SEBAL method	1.0	10.5	1.0	10.4
T_7 - Conventional method	0.8	7.6	0.8	7.6

surface irrigation, while productivity gains ranged from 20 % to 90 % across various crops (26).

Water use efficiency

The highest water use efficiency for maize was recorded in the sensor-based method, with values of 13.6 kg ha^{-1} mm^{-1} in the first season and 14.0 kg ha^{-1} mm^{-1} in the second season. The tensiometer method followed closely, with the recorded values of 11.7 kg ha^{-1} mm^{-1} and 11.5 kg ha^{-1} mm^{-1} across the two seasons. In contrast, the conventional method exhibited the lowest water use efficiency, with values of 7.6 kg ha^{-1} mm^{-1} in both seasons (Table 6). The improved water use efficiency observed with the drip irrigation system might be attributed to decreased water loss and more effective utilization of water by the plants, leading to increased yields. Additionally, the benefits of drip irrigation contributed to the maintenance of a consistent soil moisture potential (27). While higher irrigation levels do not necessarily lead to increased commercial crop yields, they can significantly diminish irrigation production efficiency (28). The reduced water use efficiency of surface irrigation was linked to greater evaporation losses of soil moisture, which occurred because the wet surface was more exposed during irrigation. Similar findings were reported previously (29-31).

Conclusion

From the research study, it is concluded that Time Domain Reflectometry (TDR) sensors and Irrometers can be effectively used for in-situ soil moisture measurements in automated irrigation systems. Sensor-based irrigation significantly enhanced maize growth parameters, including plant height, number of leaves and dry matter production, with the shortest duration for 50 % tasseling and silking across both seasons. The Tensiometer also showed comparable results with soil moisture sensors, while the conventional method exhibited the lowest growth attributes and the longest time for tasseling and silking. For large-scale adoption, farmers and policymakers can effectively integrate TDR sensors into irrigation systems by investing in automated drip irrigation systems that incorporate remote sensing and IoT technologies. Farmers should seek training on the installation and maintenance of these systems, ensuring they can take full advantage of the real-time soil moisture data. Policymakers can encourage adoption through subsidies or incentives that reduce initial installation costs and foster collaboration between technology providers and agricultural communities. However, additional factors should be explored, such as the durability of sensors under extreme weather conditions, like high heat or excessive rainfall, which may affect sensor performance. Research into materials and protective coatings for TDR sensors could help address these challenges. Furthermore, integrating machine learning algorithms for predictive irrigation could optimize water usage based on real-time data and forecasted weather patterns, leading to even more efficient irrigation practices. Therefore, the advanced automated drip irrigation system, integrated with IoT sensors and remote sensing, is recommended for large-scale adoption, offering potential for increased crop productivity, resource conservation and food security in the face of climate change.

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Authors' contributions

PS contributed to the conceptualization, supervision, funding acquisition and writing of the original draft. RM contributed to conceptualization, data curation, writing, review and editing. SAP participated in writing of the original draft, methodology and validation. PP handled software and formal analysis. VK contributed to resources and visualization. ASG contributed to methodology and writing. All authors read and approved the final manuscript

Compliance with ethical standards

Conflict of interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

1. Dalin C, Wada Y, Kastner T, Puma MJ. Groundwater depletion embedded in international food trade. Nature. 2017;543(7647):700–04. https://doi.org/10.1038/nature21403
2. World Bank. India: Groundwater critical but diminishing. 2012.
3. Darouich HM, Pedras CMG, Gonçalves JM, Pereira LS. Drip vs. surface irrigation: A comparison focusing on water saving and economic returns using multicriteria analysis applied to cotton. Biosyst Eng. 2014;122:74–90. https://doi.org/10.1016/j.biosystemseng.2014.03.010
4. Ayars JE, Fulton A, Taylor B. Subsurface drip irrigation in California-Here to stay? Agric Water Manag. 2015;157:39–47. https://doi.org/10.1016/j.agwat.2015.01.001
5. Megersa G, Abdulahi J. Irrigation system in Israel: A review. Int J Water Resour Environ Eng. 2015;7(3):29–37. https://doi.org/10.5897/IJWREE2014.0556
6. Jaidka M, Bathla S, Kaur R. Improved technologies for higher

maize production. In: IntechOpen, London, UK; 2019. https://doi.org/10.5772/intechopen.88997

7. Zhao W, Li J, Li Y, Yin J. Effects of drip system uniformity on yield and quality of Chinese cabbage heads. Agric Water Manag. 2012;110(1):118–28. https://doi.org/10.1016/j.agwat.2012.04.007

8. Getahun S, Kefale H, Gelaye Y. Application of precision agriculture technologies for sustainable crop production and environmental sustainability: A systematic review. Sci World J. 2024;2024(1):1–12. https://doi.org/10.1155/2024/2126734

9. Gomez KA, Gomez AA. Statistical procedures for agricultural research. New York: John Wiley and Sons; 1984.

10. Zhou L, Yu D, Wang Z, Wang X. Soil water content estimation using high-frequency ground penetrating radar. Water. 2019;11(5):1–16. https://doi.org/10.3390/w11051036

11. Jones HG, Tardieu F, Granier C. Precision irrigation: Advances in soil moisture monitoring and irrigation scheduling. Irrig Sci. 2005;23(3):175–91.

12. Evett SR, Heng LK, Moutonnet P, Nguyen ML. Field estimation of soil water content: A practical guide to methods, instrumentation and sensor technology. Vienna: International Atomic Energy Agency (IAEA); 2008. p. 131–41.

13. Zhang Y, Liu L, Sun J, Li C, Wan Y, Ji Y. Application of time domain reflectometry to triaxial shear tests on hydrate-bearing sediments. Measurement. 2024;238:1–31. https://doi.org/10.1016/j.measurement.2024.115369

14. Abioye EA, Zainal AMS, Mahmud MSA, Buyamin S, Ishak MHI, Abd Rahman MKI. A review on monitoring and advanced control strategies for precision irrigation. Comput Electron Agric. 2020;173:105441. https://doi.org/10.1016/j.compag.2020.105441

15. El-Habbasha SF, Okasha EM, Abdelraouf RE, Mohammed ASH. Effect of pressured irrigation systems, deficit irrigation and fertigation rates on yield, quality and water use efficiency of groundnut. Int J ChemTech Res. 2014;15(7):1–11.

16. Durga C, Ramulu V, Umadevi M, Suresh K. Evaluation of the effectiveness of nanosensor (IITB) based irrigation system on water productivity and yield of maize (*Zea mays*). Int J Curr Microbiol Appl Sci. 2020;9(8):2697–706. https://doi.org/10.20546/ijcmas.2020.908.306

17. Perez M, Lopez D, Gonzalez A. Impact of water deficit stress in maize: Phenology and yield components. Agric Water Manag. 2020;242(3):1–11.

18. Soulis KX, Elmaloglou S, Dercas N. Investigating the effects of soil moisture sensors positioning and accuracy on soil moisture-based drip irrigation scheduling systems. Agric Water Manag. 2015;148(2):258–68. https://doi.org/10.1016/j.agwat.2014.10.015

19. Garofalo P, Rinaldi M. Modelling phenotypical traits to adapt durum wheat to climate change in a Mediterranean environment. Ital J Agrometeorol. 2013;2(1):25–38.

20. Parthasarathi T, Vanitha K, Mohandass S, Vered E. Evaluation of drip irrigation system for water productivity and yield of rice. Agron J. 2018;110(6):2378–89. https://doi.org/10.2134/agronj2018.01.0002

21. Gordon DAR, Coenders-Gerrits M, Sellers BA, Sadeghi SM, Van Stan JT II. Rainfall interception and redistribution by a common North American understory and pasture forb, *Eupatorium capillifolium*. Hydrol Earth Syst Sci Discuss. 2019;24(1):4587–99. https://doi.org/10.5194/hess-2019-579

22. Hokam EM, El-Hendawy SE, Schmidhalter U. Drip irrigation frequency: The effects and their interaction with nitrogen fertilization on maize growth and nitrogen use efficiency under arid conditions. J Agron Crop Sci. 2011;197(3):186–201. https://doi.org/10.1111/j.1439-037X.2010.00460.x

23. Yadav PK, Choudhary S. Drip irrigation and mulches influence on performance of tomato (*Lycopersicon esculentum*) in arid Rajasthan. Prog Hortic. 2012;44(2):313–17.

24. Sidhu RK, Kumar R, Rana PS, Jat ML. Automation in drip irrigation for enhancing water use efficiency in cereal systems of South Asia: Status and prospects. Adv Agron. 2021;167(1):247–300. https://doi.org/10.1016/bs.agron.2021.01.002

25. Kumar S, Yadav A, Kumar A, Hasanain M, Shankar K, Karan S. Climate-smart irrigation practices for improving water productivity in India: A comprehensive review. Int J Environ Clim Change. 2023;13(12):333–48. https://doi.org/10.9734/ijecc/2023/v13i123689

26. Fanish SA, Muthukrishnan P. Effect of drip fertigation and intercropping on growth, yield and water use efficiency of maize (*Zea mays* L.). Madras Agric J. 2011;98(7–9):1–6. https://doi.org/10.29321/MAJ.10.100285

27. Biswal P, Faisal A, Tripathy S, Swain DK, Jha MK, Mohan G. Influence of drip irrigation and straw mulching on economic feasibility and soil fertility of rice-potato system in subtropical India. Irrig Sci. 2024;1–14. https://doi.org/10.1007/s00271-024-00951-5

28. Kumar JL, Imtiyaz M. Yield, irrigation production efficiency and economic returns of broccoli under variable drip irrigation and lateral spacing. J Sci Technol (Ghana). 2007;27(2):111–21. https://doi.org/10.4314/just.v27i2.33047

29. Mukherjee A, Kundu M, Sarkar S. Role of irrigation and mulch on yield, evapotranspiration rate and water use pattern of tomato (*Lycopersicon esculentum* L.). Agric Water Manag. 2010;98(1):182–89. https://doi.org/10.1016/j.agwat.2010.08.018

30. Sui R, Yan H. Field study of variable rate irrigation management in humid climates. Irrig Drain. 2017;66(3):327–39. https://doi.org/10.1002/ird.2111

31. Lathashree AV. Sensor-based irrigation management in rice (*Oryza sativa* L.) [M.Sc. thesis]. Bangalore: University of Agricultural Sciences GKVK; 2019.