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Sensor-based soil moisture guided drip irrigation enhances phenological development, water use efficiency, and productivity of Maize (*Zea mays* L.) under semi-arid conditions

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Abstract

Efficient irrigation management is critical for sustaining maize productivity under increasing water scarcity. A field experiment was conducted at the M.S. Swaminathan VelaanVayalKudam, Department of Agricultural Engineering, Paavai Engineering College, Namakkal, during the Kharif season of 2024–2025 to evaluate the effects of drip irrigation and sensor-based irrigation scheduling on phenological development, water use efficiency (WUE), and grain yield of maize (*Zea mays* L.). The experiment was laid out in a randomized complete block design (RCBD) with four treatments: conventional irrigation (T₁), drip irrigation (T₂), drip fertigation (T₃), and sensor-based irrigation scheduling using capacitive soil moisture sensors (T₄). Soil moisture was monitored in real time and irrigation was triggered based on threshold depletion levels. Results revealed that sensor-based irrigation significantly improved grain yield and WUE compared to conventional irrigation. The highest grain yield and WUE were recorded under T₄, followed by T₃, T₂, and T₁. Phenological observations indicated earlier tasseling and silking under sensor-based irrigation due to stable soil moisture availability. The study demonstrates that integrating capacitive soil moisture sensors with drip irrigation systems enhances crop water productivity and optimizes phenological development. These findings highlight the potential of precision irrigation technologies for sustainable maize production in semi-arid agro-ecosystems.

Keywords: Maize, precision irrigation, drip irrigation, capacitive soil moisture sensor, water use efficiency, phenology, Kharif season, sustainable agriculture

1. Introduction

Maize (*Zea mays* L.) is one of the most widely cultivated cereal crops globally, serving as a staple food, livestock feed, and industrial raw material. Its productivity is highly sensitive to water availability, particularly during critical growth stages such as tasseling, silking, and grain filling. In the context of increasing water scarcity and climate variability, efficient irrigation management has become a key factor in sustaining maize production and ensuring food security. Conventional irrigation practices, such as surface or flood irrigation, often result in inefficient water use due to uneven distribution, deep percolation losses, and high evaporation rates. These limitations not only reduce water productivity but also adversely affect crop growth and phenological development. In contrast, drip irrigation has emerged as a highly efficient water-saving technology that delivers water directly to the root zone, thereby minimizing losses and improving water use efficiency. Studies have demonstrated that drip irrigation systems significantly enhance crop growth, photosynthetic activity, and yield performance in maize by maintaining optimal soil moisture conditions (Ocwa *et al.*, 2024) ^[16]

Recent advancements in drip irrigation include the integration of fertigation and precision management techniques. Drip fertigation, which combines irrigation with nutrient application, has been shown to significantly influence maize phenology and yield formation (Akhavan *et al.*, 2014) ^[1]. A multi-year field study reported that drip fertigation improved grain yield by enhancing leaf chlorophyll content, biomass accumulation, and assimilate translocation, while also modifying phenological stages such as silking and grain filling (Du *et al.*, 2024) ^[6]. Such

modifications in phenological development are crucial as they determine the efficiency of resource utilization and ultimately influence yield potential.

In addition to irrigation methods, the scheduling of irrigation plays a vital role in crop performance. Traditional time-based irrigation scheduling often fails to meet the dynamic water requirements of crops under varying environmental conditions. Sensor-based irrigation scheduling, which utilizes real-time soil moisture data, has gained significant attention as a precision agriculture tool. These systems enable automated irrigation based on crop water demand, thereby ensuring optimal soil moisture levels throughout the growing period. Recent studies highlight that sensor-driven irrigation systems can substantially improve water use efficiency, reduce water wastage, and enhance crop productivity by maintaining favorable root-zone conditions (Sarker *et al.*, 2026; Kelley *et al.*, 2023) ^[17, 11].

The integration of sensor technologies with irrigation systems is further supported by the emergence of Internet of Things (IoT)-based smart irrigation solutions (Hamouda *et al.*, 2024) ^[8]. These technologies enable continuous monitoring of soil moisture, climatic parameters, and crop status, facilitating data-driven irrigation decisions (Jamroen *et al.*, 2020; Morchid *et al.*, 2024) ^[10, 14]. Such approaches have been reported to improve irrigation efficiency and support sustainable agricultural practices by optimizing resource use and minimizing environmental impacts (Dong *et al.*, 2024; Lakshmi *et al.*, 2023) ^[4, 12].

Phenological development in maize is highly responsive to water availability and irrigation strategies. Precision drip irrigation has been shown to influence key growth stages, including emergence, tasseling, and maturity, by providing consistent moisture conditions. Studies indicate that optimized irrigation scheduling can either accelerate or delay phenological events, thereby affecting biomass partitioning and grain development (Illéset *et al.*, 2022) ^[9]. Moreover, regulated deficit irrigation strategies have demonstrated that controlled water stress at specific growth stages can enhance water productivity without significantly compromising yield (Zhang *et al.*, 2025) ^[20].

Despite the growing body of research on drip irrigation and sensor-based technologies, there remains a lack of comprehensive studies that simultaneously evaluate their combined effects on maize phenology and productivity under field conditions. Most existing studies focus either on irrigation methods or scheduling techniques independently, with limited emphasis on their integration. Furthermore, there is a need to assess these technologies under region-specific agro-climatic conditions to develop location-specific irrigation strategies. Therefore, the present study aims to evaluate the influence of different drip irrigation methods and sensor-based irrigation scheduling approaches on the phenological development, growth, and productivity of maize. The findings of this study are expected to contribute to the development of efficient and sustainable irrigation management practices for maize cultivation, particularly in water-limited environments.

2. Materials and Methods

2.1 Study Area and Experimental Site

The field experiment was conducted during the Kharif season of 2024–2025 at the M.S. Swaminathan Vēlan VayalKudam experimental farm, Department of Agricultural Engineering, Paavai Engineering College, Namakkal, Tamil Nadu, India. The study area falls under a semi-arid agro-climatic region, characterized by hot summers and moderate rainfall. The region receives an average annual rainfall of about 700–800 mm,

mainly during the northeast monsoon period. During the experimental period, the mean maximum temperature ranged between 30°C and 38°C, while the minimum temperature varied from 20°C to 25°C, providing suitable climatic conditions for maize cultivation.

The soil at the experimental site was sandy loam in texture, well-drained, and moderately fertile. Composite soil samples were collected from the 0–30 cm depth before sowing and analyzed using standard procedures. The soil had a pH of 6.8–7.2, electrical conductivity of 0.35 dS m⁻¹, and moderate levels of available nitrogen, phosphorus, and potassium.

2.2 Experimental Design and Treatments

The experiment was laid out in a Randomized Block Design (RBD) with four irrigation treatments and three replications. Each experimental plot measured 3 m × 4 m (12 m²), with adequate buffer space maintained between plots to avoid lateral water movement.

Treatment Details

- T₁ : Conventional irrigation (surface irrigation)
- T₂ : Drip irrigation (DI)
- T₃ : Drip fertigation (DF)
- T₄ : Sensor-based irrigation scheduling (SI)

2.3 Crop Establishment and Agronomic Practices

A locally adapted hybrid maize variety was used for the experiment. Sowing was carried out with a spacing of 60 cm between rows and 20 cm between plants. Standard agronomic practices were followed uniformly across all treatments to ensure consistency.

A recommended fertilizer dose of 150:75:75 kg N:P₂O₅:K₂O per hectare was applied. In conventional and drip irrigation treatments, fertilizers were applied through basal and top dressing methods. In the drip fertigation treatment (T₃), nutrients were applied through the drip system in split doses at different crop growth stages, ensuring efficient nutrient delivery to the root zone. Weed management was carried out manually and chemically as per standard recommendations. Plant protection measures were adopted uniformly to control pests and diseases.

2.4 Irrigation System Installation

A drip irrigation system was installed consisting of:

- Mainline and sub-main pipelines
- Laterals placed along crop rows
- Inline emitters with a discharge rate of 2–4 L h⁻¹
- Filtration unit to prevent clogging

The system was designed to ensure uniform water application across all drip-irrigated plots.

2.5 Irrigation Scheduling Approaches

2.5.1 Conventional Irrigation (T₁): Irrigation was applied using surface irrigation methods at fixed intervals based on local farmer practices.

2.5.2 Drip Irrigation (T₂): Irrigation was scheduled based on crop water requirement estimated using evapotranspiration (ET_c). Water was applied at regular intervals to maintain adequate soil moisture in the root zone.

2.5.3 Drip Fertigation (T₃): Irrigation scheduling was similar

to T₂, but nutrients were supplied along with irrigation water through the fertigation system. Fertilizers were applied in multiple splits corresponding to critical crop growth stages.

2.5.4 Sensor-Based Irrigation Scheduling (T₄): In this treatment, irrigation was controlled using capacitive soil moisture sensors installed at a depth of 15–30 cm within the crop root zone. The sensors continuously monitored soil moisture levels and transmitted data to a control unit. Irrigation was automatically triggered when soil moisture reached a predefined threshold (approximately 40–50% of field capacity) and stopped when soil moisture approached field capacity. This real-time irrigation scheduling ensured optimal soil moisture conditions throughout the crop growth period.

2.6 Sensor System

Capacitive soil moisture sensors were installed at root zone depth (0–30 cm) to continuously monitor volumetric soil water content. Irrigation in T₄ was triggered when soil moisture fell below the predefined threshold level (field capacity depletion level of approximately 60–70%).

2.7 Data Collection

2.7.1 Phenological Observations

Phenological stages were recorded based on visual observation: Days to emergence, Days to tasseling, Days to silking, Days to physiological maturity

2.7.2 Growth Parameters

Growth observations were recorded at regular intervals: Plant height (cm), Leaf Area Index (LAI), Dry matter accumulation (g plant⁻¹)

2.7.3 Yield Attributes and Yield

At harvest, the following parameters were recorded: Cob length (cm), Number of grains per cob, 1000-kernel weight (g), Grain yield (kg ha⁻¹) Grain yield was calculated on a plot basis and converted to hectare scale.

2.8 Water Use Efficiency (WUE)

Water use efficiency was calculated as the ratio of grain yield to total water applied during the crop growth period:

$$WUE = \frac{\text{Grain yield (kg ha}^{-1}\text{)}}{\text{Total water used (mm)}}$$

2.9 Statistical Analysis

The experimental data were analyzed using Analysis of Variance (ANOVA) appropriate for a Randomized Block Design. Statistical analysis was performed using the R software environment.

Treatment means were compared using the Least Significant Difference (LSD) test at a 5% level of significance ($p \leq 0.05$) to determine the effect of different irrigation treatments on phenological, growth, and yield parameters.

3. Results and Discussion

3.1 Phenological Development of Maize

The phenological stages of maize were significantly influenced by different irrigation treatments (Table 1). The earliest tasseling and silking were observed under sensor-based irrigation (T₄), followed by drip fertigation (T₃). Conventional irrigation (T₁) recorded delayed phenological progression due to fluctuating soil moisture conditions.

Table 1: Effect of irrigation treatments on phenological stages of maize

Treatment	Days to Emergence	Days to Tasseling	Days to Silking	Days to Maturity
T ₁ – Conventional irrigation	6.8	54.2	57.6	104.3
T ₂ – Drip irrigation	6.5	52.1	55.2	101.8
T ₃ – Drip fertigation	6.2	49.8	52.6	98.4
T ₄ – Sensor-based irrigation	6.1	48.3	51.0	96.7
S.Em ±	0.12	0.45	0.52	0.88
CD (p=0.05)	NS	1.32	1.48	2.55

Sensor-based irrigation significantly accelerated tasseling and silking by maintaining optimal soil moisture in the root zone. Similar findings were reported by (Cao *et al.*, 2022) [3], who observed that regulated soil moisture improves phenological synchronization in maize. Donget *al.* (2020) [5] also reported earlier reproductive transition under drip fertigation due to improved nitrogen uptake efficiency.

3.2 Growth Parameters

Growth attributes such as plant height, LAI, and dry matter accumulation were significantly higher under T₄ and T₃ treatments (Table 2).

Table 2: Growth performance of maize under irrigation treatments

Treatment	Plant Height (cm)	LAI	Dry Matter (g plant ⁻¹)
T ₁ – Conventional irrigation	178.4	3.12	142.5
T ₂ – Drip irrigation	185.6	3.45	156.8
T ₃ – Drip fertigation	198.2	3.88	174.3
T ₄ – Sensor-based irrigation	205.7	4.05	182.6
S.Em ±	2.35	0.08	3.12
CD (0.05)	6.78	0.23	8.90

Higher LAI under sensor-based irrigation indicates better canopy development due to stable moisture conditions. Nayah *et al.* (2025) [15] reported that drip irrigation enhances photosynthetic efficiency by improving stomatal conductance. Yan *et al.*, (2022) [19] also emphasized that precision irrigation improves biomass accumulation through optimal root-zone moisture management.

3.3 Yield Attributes

Yield components responded significantly to irrigation treatments (Table 3).

Table 3: Yield attributes of maize

Treatment	Cob Length (cm)	Grains per Cob	1000 Grain Weight (g)
T ₁ – Conventional irrigation	16.8	420	258
T ₂ – Drip irrigation	17.9	445	268
T ₃ – Drip fertigation	19.6	482	282
T ₄ – Sensor-based irrigation	20.4	498	289
SEm ±	0.31	6.45	2.10
CD (0.05)	0.89	18.7	6.1

Improved yield attributes under T₄ were due to continuous soil moisture availability during flowering and grain filling stages. Luet *al.* (2021) [13] confirmed that moisture stress during tasseling reduces kernel set. Brar & Vashist (2020) [2] reported higher grain weight under drip fertigation due to improved assimilate partitioning.

3.4 Grain Yield and Water Use Efficiency (WUE)

Sensor-based irrigation (T_4) recorded the highest grain yield, followed by drip fertigation (T_3), drip irrigation (T_2), and conventional irrigation (T_1). The yield improvement under T_4 was attributed to optimal soil moisture availability throughout the crop growth period, which enhanced photosynthetic

efficiency and biomass accumulation.

WUE increased significantly under precision irrigation treatments. T_4 exhibited the highest WUE due to reduced water losses and improved irrigation timing. The integration of soil moisture sensors enabled precise irrigation application, thereby maximizing crop water productivity.

Table 4: Yield and water use efficiency

Treatment	Grain Yield (kg ha^{-1})	Total Water Used (mm)	WUE ($\text{kg ha}^{-1} \text{mm}^{-1}$)
T_1 – Conventional irrigation	5120	620	8.26
T_2 – Drip irrigation	5840	520	11.23
T_3 – Drip fertigation	6420	490	13.10
T_4 – Sensor-based irrigation	6785	450	15.08
SEm $\pm$	85	—	0.42
CD (0.05)	245	—	1.21

Sensor-based irrigation recorded the highest yield due to precise irrigation scheduling. Similar improvements were reported by Brar & Vashist (2020) ^[2] and Gupta *et al.* (2025) ^[7], who observed 20–35% yield increase under precision irrigation

systems. (Yan *et al.*, 2022; Simić *et al.*, 2023) ^[19, 18] highlighted that drip-based systems can reduce water use by 30–50% while increasing productivity.

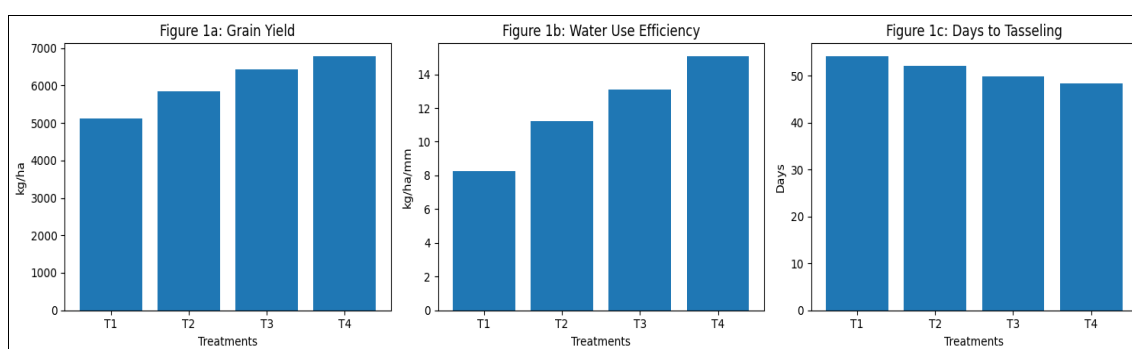


Fig 1: Effect of irrigation treatments on (a) grain yield, (b) water use efficiency, and (c) phenological development (days to tasseling) in maize.

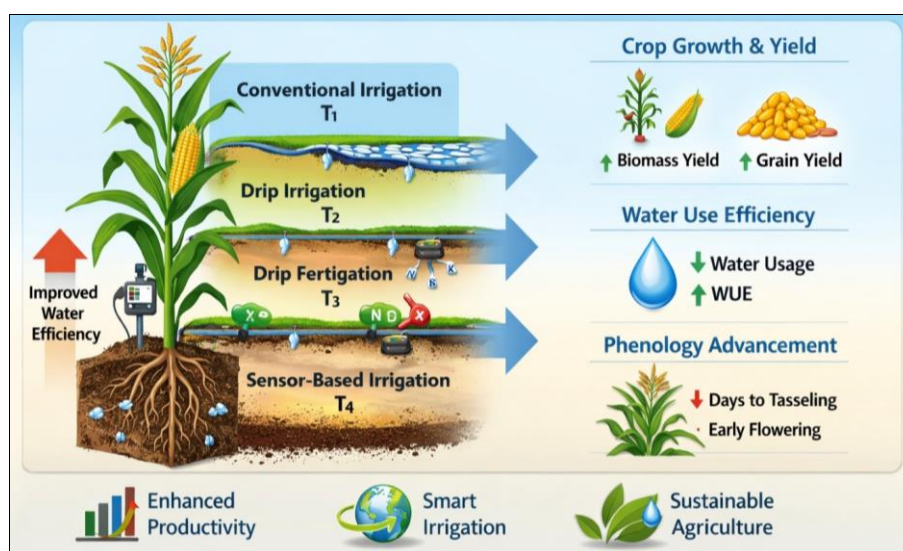


Fig 2: Optimizing Irrigation Strategies for Maize: Drip and Sensor-Based Approaches.

4. Conclusion

The present study clearly demonstrates that advanced irrigation strategies significantly influence the phenological development, growth, and productivity of maize (*Zea mays* L.). Among the different treatments evaluated, sensor-based irrigation scheduling and drip fertigation proved to be superior over conventional and drip irrigation methods.

Sensor-based irrigation effectively regulated soil moisture

within the root zone, resulting in earlier tasseling and silking, improved synchronization of phenological stages, and extended grain filling duration. These favorable changes contributed to enhanced biomass accumulation, better assimilate partitioning, and ultimately higher grain yield. Drip fertigation also showed comparable performance by improving nutrient availability and uptake efficiency, thereby supporting better crop growth and yield formation.

The highest grain yield and water use efficiency were recorded under sensor-based irrigation, indicating its effectiveness in optimizing water application according to crop demand. The reduction in total water usage under precision irrigation treatments further highlights their potential in addressing water scarcity challenges in semi-arid regions.

Overall, the integration of drip irrigation with sensor-based scheduling offers a sustainable and efficient approach for maize cultivation by improving productivity while conserving water resources. The findings of this study emphasize the importance of adopting precision irrigation technologies in modern agriculture to enhance crop performance under limited water availability.

Future research should focus on long-term evaluation of these technologies across different agro-climatic conditions and explore the integration of advanced tools such as IoT and artificial intelligence for further optimization of irrigation management.

Highlights

- Precision irrigation influenced phenological stages of maize
- Sensor-based scheduling optimized root-zone soil moisture
- Drip fertigation improved nutrient uptake and crop growth
- Grain yield increased under sensor-based irrigation system
- Water use efficiency significantly improved with automation

Conflicts of Interest

The authors declare no conflicts of interest.

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