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Optimizing water use in agriculture: The role of sensor-based irrigation for sustainable crop production

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Abstract
Efficient water management is a critical component of sustainable agriculture, particularly as global water resources face increasing stress due to climate change and population growth. Traditional irrigation methods often lead to water wastage and inefficiencies. Sensor-based irrigation systems offer a promising solution by enabling real-time monitoring of soil moisture, crop water needs, and environmental factors. Sensor-based irrigation systems present a promising approach by enabling real-time monitoring of soil moisture, plant water status, and environmental conditions, thereby improving water-use efficiency and mitigating wastage.
This review explores various sensor technologies, including soil moisture sensors (tensiometers, granular matrix sensors, neutron moisture probes), crop sensors (sap flow sensors, dendrometers), and additional monitoring tools such as infrared canopy temperature sensors and flow sensors. These technologies facilitate precise irrigation scheduling, reducing water application while enhancing crop yields. Experimental studies have demonstrated significant improvements in water-use efficiency and economic benefits in cereal crops such as rice, wheat, and maize. For instance, sensor-based drip irrigation in rice resulted in water savings of up to 36.89%, while in wheat, irrigation efficiency improved from 69.2% to 88.0% compared to manual irrigation.
Despite their potential, widespread adoption of sensor-based irrigation faces barriers, including high initial costs, technical complexity, and connectivity limitations in rural areas. Addressing these challenges through policy support, subsidies, and farmer training programs is crucial for broader implementation. This study underscores the transformative role of sensor-based irrigation in ensuring sustainable water resource management in agriculture, particularly in water-stressed regions.

Keywords: Water management, sustainable agriculture, sensor-based irrigation

Introduction
Water, the cornerstone of agricultural productivity, but its availability is under pressure due to growing demand from increasing populations and changing consumption habits. Agriculture, as the dominant water consumer, accounts for approximately 70% of global water withdrawals, a figure that rises to a staggering 82% in India (Jury 2007) [10]. This disproportionate reliance on water resources, coupled with the increasing frequency and intensity of droughts, underscores the critical need for sustainable water management practices within the agricultural sector (Khan 2024) [11]. Inefficient irrigation methods, characterized by excessive water application and significant losses, exacerbate water scarcity and threaten food security. The imperative to optimize water utilization in agriculture has never been more pressing.
The challenge is further compounded by the declining per capita water availability. In India, water availability is expected to drop from 5177 cubic meters in 1951 to just 1640 cubic meters by 2050 (Agarwal 2021) [2]. Many regions in Africa, the Middle East, and Asia also face serious water shortages (Jury 2007) [10]. In India, 54% of the country experiences high to extreme water stress, especially in key farming areas like Punjab, Haryana, and Rajasthan (Sindhu 2024) [26]. To address this, we must move away from traditional irrigation methods and adopt advanced, data-driven systems that optimize water use.

(Source: - https://miro.medium.com/v2/resize:fit:720/format:webp/0*Awt81LQnhJmZ2w3M.jpg)

IoT-Powered Smart Irrigation System for Agriculture

Sensor-based irrigation systems offer a promising solution to address these critical challenges. By enabling real-time monitoring of soil moisture, temperature, and plant water status, these technologies empower farmers to make informed decisions regarding irrigation scheduling and water application. These systems, utilizing a diverse array of sensors—including tensiometers, granular matrix sensors, neutron moisture probes, and sap flow sensors—provide valuable insights into the dynamic interplay between soil, water, and plants (Clauser 2024) [4]. This data-driven approach allows for optimized irrigation, minimizing water wastage, maximizing crop yields, and mitigating the detrimental effects of over- or under-irrigation (Violino 2023) [30].

Water is essential for plant growth, helping plants maintain structure, transport nutrients, and perform photosynthesis (Navyashree 2023) [16]. Since monsoon rainfall can be unpredictable and uneven, farmers often need additional irrigation to ensure proper crop growth (Rao 2015) [21]. Sensor-based irrigation systems help by giving accurate and timely data about soil and plant water needs, allowing farmers to use water efficiently (Seyer and Ahamed 2024).

This study will examine the various types of sensors employed in precision irrigation, including

1. Soil moisture sensors (tensiometers, granular matrix sensors, neutron moisture probes, time domain reflectometry, capacitance sensors, and soil moisture indicators),
2. Crop sensors (sap flow sensors and dendrometers), and
3. Other relevant sensors such as infrared canopy temperature sensors, level sensors, EC-pH sensors, pressure sensors, and flow sensors.

Each sensor type offers unique advantages and limitations in terms of accuracy, cost, and applicability. We will critically evaluate the performance of these sensors in different agricultural settings, considering factors such as soil type, climate, and crop type.

Beyond the technical aspects of sensor technologies, this study will also address the challenges associated with their adoption, particularly in developing countries. These challenges include the initial cost of implementation, the need for data analysis expertise, and connectivity issues in rural areas. We will explore potential solutions to overcome these barriers, such as government subsidies, farmer training programs, and the development of affordable and user-friendly sensor systems.

1. Sensor based efficient water resource management in Cereal crops

Suma *et al*. (2022) [28] conducted a study at ZARS, Bengaluru, on red sandy loam soil to investigate the impact of sensor-based irrigation management on water use efficiency in rice cultivation. The results demonstrated a significant increase in both Irrigation Water Use Efficiency (IWUE) and Farm Water Use Efficiency (FWUE) with sensor-based irrigation compared to drip irrigation. Sensor-based automated drip irrigation at 25% depletion of available soil moisture resulted in an 18.58% water savings compared to drip irrigation, while sensor-based automated drip irrigation at 50% depletion achieved a notable 36.89% water savings.

Lathashree (2019) [12] conducted an experiment at GKVK, Bengaluru, on red sandy loam soil to evaluate the impact of sensor-based irrigation management on rice yield, straw yield, water use, and water use efficiency. The results showed that sensor-based irrigation significantly increased both grain and straw yields compared to puddled transplanted rice. Aerobic rice cultivation with sensor-based drip irrigation and fertigation achieved the highest grain yield of 8233 kg ha^{-1} and straw yield of 9032 kg ha^{-1}, along with the highest water use efficiency of 117.8 kg ha-cm^{-1}. The improvement in water and nutrient use efficiency was attributed to precise water application based on real-time soil moisture data, minimizing water losses due to over-irrigation. Economically, this treatment exhibited the highest benefit-cost ratio of 3.11, demonstrating the potential for significant economic gains with optimized sensor-based irrigation strategies.

Pramanik *et al*. (2022) [18] conducted an experiment at IARI, New Delhi, on alluvial soil to investigate the impact of sensor-based irrigation management on water application and irrigation performance indicators at different critical growth stages of wheat. The results showed that sensor-based irrigation significantly improved irrigation application efficiency (88.0%) compared to manual control irrigation (69.2%). This improvement was consistent across all growth stages, with sensor-based irrigation requiring less water while maintaining high water requirement efficiency. Sensor-based irrigation increased wheat yield to 57.7 q ha^{-1} compared to 54.5 q ha^{-1} in manual irrigation. It also demonstrated higher water use efficiency (1.94 kg m^{-3}) and water productivity (38.4 Rs. m^{-3}) compared to manual control irrigation (1.48 kg m^{-3} and 29.2 Rs. m^{-3}, respectively).

Ravneet *et al*., 2021 [22] evaluated four different irrigation management scenarios on rice-wheat system yield and irrigation water productivity in Patiala, Punjab, on silt clay soil. The study compared Continuous Flooding (CT-Flood), Zero-till Flood (ZT-Flood), Zero-till Subsurface Drip (ZT-SSD), and Zero-till Surface Drip (ZT-SD) irrigation methods. Results showed that ZT-SSD and ZT-SD significantly outperformed CT-Flood and ZT-Flood in terms of rice-wheat system yield, achieving yields around 14.8 t ha^{-1} yr^{-1} compared to 14.2 t ha^{-1} yr^{-1} and 14.5 t ha^{-1} yr^{-1}, respectively. Furthermore, ZT-SSD and ZT-SD demonstrated higher irrigation water productivity (around 2.5 kg m^{-3} yr^{-1}) compared to CT-Flood (around 1 kg m^{-3} yr^{-1}) and ZT-Flood (around 1.5 kg m^{-3} yr^{-1}) (Fig. 2). Significant benefits of zero-till practices combined with subsurface or surface drip irrigation in improving yield and water use efficiency in rice-wheat systems on silt clay soils.

Gurunath *et al*. (2022) [8] conducted a split-plot experiment at ZARS, Bengaluru, to assess the impact of sensor-based irrigation and nitrogen management on baby corn growth in red sandy loam soil. Among the irrigation treatments, IoT-based drip irrigation at 50% Daily Average Soil Moisture (DASM) resulted in the highest plant height (150.3 cm), leaf area (7951 cm^2), and cob weight (78.9 g cob^{-1}). In terms of nitrogen management, Site-Specific Nutrient Management (SSNM) with split application of NPK demonstrated the highest yield parameters, recording the highest husked (195.8 q ha^{-1}) and dehusked yield (199 q ha^{-1}), along with the highest number of cobs per plant (3). When comparing irrigation methods, IoT-based drip irrigation at 50% DASM exhibited the highest water use efficiency (41%), followed by Soil Moisture-Based Irrigation (SMI) drip irrigation (36%) and surface irrigation (23%). These findings emphasize the potential of precision irrigation techniques, particularly IoT-based drip irrigation, in enhancing water conservation and crop productivity in baby corn cultivation.

(Source: https://www.marketresearchintellect.com/images/blogs/harvesting-efficiency-agricultural-irrigation-sensor-market-booms-with-innovation.webp)

Integration drip irrigation with sensor

Chaithra *et al*. (2021) [3] investigated the impact of sensor-based irrigation on maize growth in red sandy loam soil at GKVK, Bengaluru. Drip irrigation at three-day intervals, green Soil Moisture Indicator (GSMI) based drip irrigation, yellow soil moisture indicator-based drip irrigation (YSMI) exhibited significantly higher plant height (194.1 cm, 200.0 cm, and 203.4 cm, respectively) compared to the control (184.6 cm). Similarly, these treatments had a greater number of leaves (12.0, 12.6, and 13.3 leaves per plant) and larger leaf area (8052 cm², 9013 cm², and 9083 cm² per plant, respectively) compared to the control (9.67 leaves per plant and 7390 cm² per plant). This enhanced vegetative growth resulted in higher dry matter production (416.0 g, 436.0 g, and 479.5 g per plant, respectively) compared to the control (350.3 g per plant). sensor-based drip irrigation initiated at 25% depletion of available soil moisture (DASM) recorded the highest kernel yield (106.76 q ha^{-1}) and stover yield (122.73 q ha^{-1}), with the highest water use efficiency (21.92 kg ha-mm^{-1}), generated the highest gross returns (200170 Rs. ha^{-1}) and net returns (144850 Rs. ha^{-1}), with a benefit-cost ratio of 3.62, indicating the most favourable economic returns.

Durga *et al*. (2020) [6] conducted an experiment at PJTSAU, Hyderabad, on red sandy loam soil during the rabi season of 2017-18, evaluating different irrigation methods and schedules on maize yield and water productivity. The study reported that Treatment S4, which employed an optimized irrigation method and schedule, resulted in the highest grain yield (70.5 q ha^{-1}), straw yield (129.5 q ha^{-1}), and harvest index (35.43%). This treatment also exhibited the highest water productivity (1.53 kg m^{-3}), highlighting its superior water utilization efficiency. The results emphasized that selecting an appropriate irrigation schedule can significantly enhance yield while conserving water.

Desai (2022) [5] evaluated next-generation technologies in maize cultivation at GKVK, Bengaluru, on red sandy loam soil. The study found that incorporating precision irrigation, optimized nutrient management, and advanced crop monitoring, resulted in the highest kernel yield (85.54 q ha^{-1}) and stover yield (91.44 q ha^{-1}). Additionally, this treatment demonstrated the highest irrigation water use efficiency (IWUE) of 20.79 kg ha-mm^{-1}, suggesting that integrating precision agricultural techniques can significantly improve water use efficiency and biomass production.

Singh *et al*. (2023) [27] conducted a field experiment in Nebraska on silt clay loam soil during the 2020 growing season to compare the yield and IWUE of maize and soybean under sensor-based irrigation, conventional irrigation, and rainfed conditions. For maize, sensor-based irrigation achieved a yield of 133.2 q ha^{-1} while using significantly less water (101.5 mm) compared to conventional irrigation, which required 213.4 mm of water for the same yield. As a result, sensor-based irrigation exhibited a much higher IWUE (17.35 kg ha-mm^{-1}) than conventional irrigation (8.29 kg ha-mm^{-1}). A similar trend was observed in soybean, where sensor-based irrigation used 91.4 mm of water and achieved a yield of 46.0 q ha^{-1}, compared to conventional irrigation, which required 152.4 mm of water for a slightly higher yield (47.2 q ha^{-1}). The IWUE for sensor-based irrigation in soybean was recorded at 3.93 kg ha-mm^{-1}, outperforming conventional irrigation (3.09 kg ha-mm^{-1}).

2. Sensor based efficient water resource management in Commercial crops

Vories *et al*. (2019) [31] conducted a study in Portageville, Missouri, on alluvial soil to assess the performance of ISSCADA (Irrigation Scheduling Supervisory Control and Data Acquisition), Arkansas Irrigation Scheduler (AIS), and rainfed conditions on seed cotton yield and irrigation WUE across two seasons. In the first season, ISSCADA achieved the highest seed cotton yield (31.62 q ha^{-1}) with superior IWUE (1.5 kg m^{-3}) compared to AIS (29.24 q ha^{-1} and 0.4 kg m^{-3}, respectively). Rainfed conditions resulted in the lowest yield (27.90 q ha^{-1}). In the second season, AIS recorded a slightly higher yield (28.65 q ha^{-1}) than ISSCADA (26.86 q ha^{-1}); however, ISSCADA exhibited better IWUE (1.1 kg m^{-3}) compared to AIS (0.5 kg m^{-3}), despite applying less water (374 mm vs. 421 mm). These findings underscore the role of ISSCADA in optimizing water use while maintaining competitive cotton yields.

Similarly, Ramesh *et al*. (2019) [20] evaluated the impact of sensor-based irrigation (SSD) and different fertigation levels on WUE in sugarcane cultivated on red soil in Tamil Nadu, India. The study revealed that SSD significantly enhanced WUE, with a mean WUE of 149.9 kg ha-mm^{-1} compared to the control (51.8 kg ha-mm^{-1}). Among fertigation treatments, 75% of the Recommended Daily Fertilizer (RDF) as water-soluble fertilizer (WSF) recorded the highest mean WUE (161.7 kg ha-mm^{-1}). A significant interaction between SSD and fertigation levels highlighted the importance of tailored fertigation strategies for maximizing water use efficiency and sugarcane productivity.

3. Sensor based efficient water resource management in Vegetable crops

Meundimath *et al.* (2018) [15] conducted an experiment at IWMRC, Belavatagi, on black soil, evaluating different drip irrigation levels and intercropping systems on chilli equivalent yield, economics, and water use efficiency. The combination of higher irrigation levels with intercropping resulted in the highest chilli equivalent yield of 1954 kg ha^{-1}, gross returns of Rs. 293100 ha^{-1}, net returns of Rs. 220364 ha^{-1}, and a benefit-cost ratio of 4.03. The highest water use efficiency (WUE) recorded was 2.88 kg ha-mm^{-1}.

Sharma *et al.* (2021) [24] conducted an experiment at MPUAT, Udaipur, on sandy loam soil, investigating the impact of different irrigation schedules on okra yield and water use efficiency. The highest crop yield (98 q ha^{-1}) and longest fruit length (16.2 cm) were achieved with a total irrigation water application of 428.5 mm. The highest water use efficiency (21.5 kg ha-mm^{-1}) was recorded under this treatment, demonstrating efficient water utilization. Increasing irrigation water beyond a threshold did not result in proportional yield increases and led to lower water use efficiency.

Palumbo *et al.* (2021) [17] conducted a pot experiment in Southern Italy, evaluating different irrigation levels on green bean plants. Sensor-based irrigation significantly reduced total water consumption and minimized leaching losses compared to a timer-based treatment. The SENSOR_0.35 and SENSOR_0.25 treatments resulted in comparable or higher yields (160 g pot^{-1} and 135 g pot^{-1}, respectively) and significantly higher water use efficiency (10.7 g L^{-1} and 10.9 g L^{-1}, respectively).

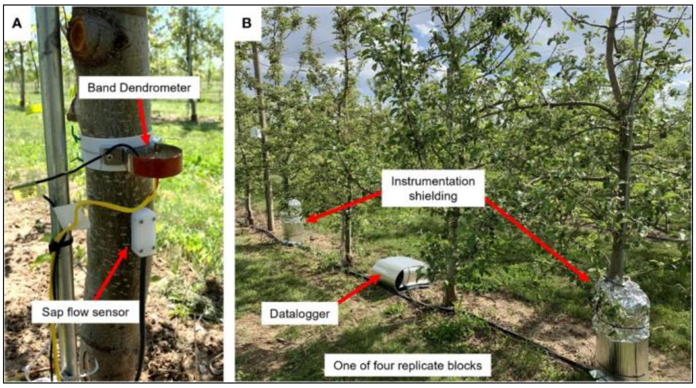
Vinutha *et al.* (2023) [29] conducted an experiment at GKVK, Bengaluru, on red sandy loam soil, evaluating sensor-based irrigation regimes (75%, 50%, and 25% of available soil moisture) compared to surface irrigation on capsicum yield and water use efficiency. The 75% ASM treatment exhibited the highest average fruit yield (485.9 q ha^{-1}) and the highest WUE (102.25 kg ha-mm^{-1}). Increasing irrigation levels beyond 75% ASM resulted in decreasing yield and WUE. Surface irrigation, while applying the most water (913.80 mm), resulted in the lowest yield and WUE.

4. Sensor based efficient water resource management in Millets

Abhishek (2021) [1] examined the impact of sensor-based irrigation management on finger millet grown in red sandy loam soil at GKVK, Bengaluru. The study demonstrated that Sensor-Based Irrigation at 80% Etc resulted in the highest grain yield (35.60 q ha^{-1}) and straw yield (44.96 q ha^{-1}), with the highest WUE (8.07 kg ha-mm^{-1}) and significant water savings (41.7%) compared to the control. Additionally, Sensor-Based Irrigation at 100% ETc + Mulching achieved the highest gross returns (Rs. 116465 ha^{-1}), net returns (Rs. 66045 ha^{-1}), and benefit-cost ratio (2.31), indicating superior economic profitability. These findings suggest that sensor-based irrigation management not only enhances water conservation and yield but also improves the economic viability of finger millet cultivation.

5. Sensor based efficient water resource management in Orchard plants

Phenological stages in orchard trees influence the relationship between maximum daily shrinkage (MDS) and stem water potential (ΨStem), with stronger correlations observed early in the season, declining as fruit development progresses (Egea *et al.*, 2009; Marsal *et al.*, 2015) [7, 14]. Liu *et al.* (2012) [13] identified two key growth phases in apple trees: an initial period of rapid trunk and leaf expansion followed by a plateau phase coinciding with fruit maturation.



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(A) A band dendrometer (above) and sap flow sensor (below)
(B) Dataloggers with insulation (center box) connected to two sensor instillations with thermal and protective shielding (left and right of center box).

Wheeler *et al.* (2023) [32] highlighted seasonal variations in trunk growth and sap flow in high-density orchards. Early-season MDS correlated strongly with ΨStem but declined as fruit development influenced water dynamics. Late-season reductions in MDS were linked to osmotic loading, fruit load, and soil water limitations. Sap flow remained closely tied to ETr, with canopy development affecting correlations. These findings emphasize the need to consider phenology when assessing tree water status and optimizing irrigation.

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