

International Journal of Agriculture Extension and Social Development

Volume 5; Issue 2; Jul-Dec 2022; Page No. 65-70

Received: 05-08-2022
Accepted: 11-09-2022

Indexed Journal
Peer Reviewed Journal

Development of IoT-based smart drip irrigation system for water conservation in semi-arid regions of India

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DOI: <https://www.doi.org/10.33545/26180723.2022.v5.i2a.2986>

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Abstract

How can modern agricultural practices address the escalating water scarcity challenges in semi-arid regions while maintaining or improving crop productivity? This research presents the development and field evaluation of an Internet of Things (IoT) based smart drip irrigation system designed specifically for water conservation in semi-arid agricultural zones. The system integrates multiple sensor technologies including soil moisture sensors, temperature and humidity monitors, and water flow meters with an Arduino Mega 2560 microcontroller connected to the Thing Speak cloud platform via ESP8266 WiFi module. The primary objective was to achieve significant water savings compared to conventional irrigation methods while sustaining optimal crop growth conditions. Field trials were conducted over a six-month period, testing the system across three major crops cultivated in the region: cotton, soybean, and sorghum. The automated irrigation control algorithm maintained soil moisture levels within the optimal range of 25-40% through real-time monitoring and responsive valve actuation. Results demonstrated substantial water conservation, with the IoT-based system achieving an average water savings of 40.2% compared to conventional flood irrigation practices. Additionally, crop yields showed marked improvements ranging from 29.4% for cotton to 36.6% for soybean when compared to traditionally irrigated plots. The system's cloud connectivity enabled remote monitoring capabilities, allowing farmers to track field conditions and irrigation status through mobile applications. Economic analysis revealed that despite initial installation costs, the system achieved positive return on investment within two cropping seasons due to reduced water pumping expenses and enhanced yields. These findings suggest that IoT-based precision irrigation technologies offer a viable and sustainable solution for addressing water scarcity in semi-arid agricultural regions while simultaneously improving farm profitability and resource utilization efficiency.

Keywords: Smart irrigation, internet of things, drip irrigation, water conservation, semi-arid agriculture, soil moisture sensors, precision farming, sustainable agriculture, arduino microcontroller

Introduction

Can technology-driven solutions effectively bridge the widening gap between agricultural water demand and availability in water-stressed regions? This question has become increasingly critical as India, home to nearly 18% of the global population, possesses merely 4% of the world's freshwater resources ^[1]. The agricultural sector, which accounts for approximately 80% of India's water consumption, faces mounting pressure to adopt water-efficient practices amid recurring droughts and declining groundwater tables ^[2]. Semi-arid regions covering substantial portions of Maharashtra, Karnataka, and Rajasthan experience annual rainfall between 500-1000 mm, yet erratic distribution patterns create persistent irrigation challenges for farmers ^[3].

Traditional irrigation methods, particularly flood and furrow systems prevalent across Indian farms, exhibit water use efficiency of merely 30-40%, with substantial losses occurring through evaporation, runoff, and deep percolation ^[4]. These inefficiencies not only strain limited water resources but also contribute to waterlogging, soil salinity, and nutrient leaching problems that degrade long-term soil health. Drip irrigation technology, introduced in India during the 1970s, demonstrated potential water savings of

30-70% compared to surface irrigation methods ^[5]. However, conventional drip systems operating on fixed schedules often fail to account for dynamic variations in crop water requirements influenced by weather conditions, growth stages, and soil characteristics ^[6].

The emergence of Internet of Things technologies has opened new possibilities for agricultural automation and precision resource management ^[7]. IoT-enabled agricultural systems integrate distributed sensor networks with cloud computing platforms to facilitate real-time data collection, analysis, and automated decision-making ^[8]. Several researchers have explored IoT applications in irrigation management with varying degrees of success. Kamienski and colleagues ^[9] developed a smart water management platform demonstrating 25% water reduction in Brazilian vineyards. Similarly, Goap and team ^[10] implemented a machine learning-based smart irrigation system in Indian conditions, achieving notable improvements in water use efficiency.

Despite these advances, adoption of smart irrigation technologies in Indian agriculture remains limited, with less than 5% of irrigated area utilizing micro-irrigation systems ^[11]. High initial costs, limited technical knowledge among farmers, and inadequate after-sales support have been

identified as primary barriers to widespread adoption ^[12]. Furthermore, most existing IoT irrigation systems have been developed and tested in controlled experimental settings or developed country contexts, raising questions about their suitability for the diverse agro-climatic conditions and socioeconomic constraints prevalent in Indian farming ^[13].

This research addresses these gaps by developing and field-testing an affordable IoT-based smart drip irrigation system specifically designed for semi-arid conditions. The system architecture prioritizes cost-effectiveness through utilization of commercially available components while maintaining reliability and ease of operation. The primary objectives encompass quantifying water savings achievable through automated soil moisture-based irrigation scheduling, evaluating impacts on crop yields across multiple crops, and assessing the economic viability of system deployment for smallholder farmers. And by conducting extensive field trials spanning an entire cropping season, this investigation provides empirical evidence regarding the practical performance and potential benefits of IoT irrigation technologies under realistic farming conditions.

Material and Methods

Material: The experimental setup comprised hardware and software components integrated to form a complete IoT-based irrigation system. The central processing unit consisted of an Arduino Mega 2560 microcontroller board featuring ATmega2560 chip with 54 digital input/output pins, 16 analog inputs, and 256 KB flash memory ^[14]. Wireless connectivity was established through an ESP8266 WiFi module operating at 2.4 GHz frequency with TCP/IP protocol stack. Soil moisture monitoring employed capacitive sensors (model v1.2) with measurement range of 0-100% volumetric water content and accuracy of $\pm 3\%$ ^[15]. Temperature and humidity were measured using DHT22 sensors with temperature accuracy of $\pm 0.5^\circ\text{C}$ and humidity accuracy of $\pm 2-5\%$. Water flow measurement utilized YF-S201 Hall effect sensors with flow range of 1-30 liters per minute and frequency output of 4.5 pulses per second per liter.

The drip irrigation infrastructure included 16 mm lateral pipes with inline emitters spaced at 30 cm intervals, delivering water at 2 liters per hour discharge rate. Solenoid valves (12V DC, normally closed type) controlled water flow to different field zones. A 12V DC submersible pump with 1500 liters per hour capacity drew water from the farm borewell. The system incorporated a 16x2 LCD display for local status monitoring and relay modules for actuator control. Power supply comprised a regulated 12V/5A adapter with battery backup for uninterrupted operation. The experimental plot covered 0.5 hectares divided into six equal sub-plots, with three plots receiving IoT-controlled drip irrigation and three plots under conventional flood irrigation serving as controls. Crops planted included cotton (variety Bt hybrid), soybean (variety JS-335), and sorghum (variety CSH-14).

Methods

The system architecture followed a three-tier design comprising the sensor layer, processing layer, and cloud layer ^[16]. Sensor nodes were distributed across the experimental field at 10-meter intervals, with each node

containing soil moisture, temperature, and humidity sensors. Sensor data acquisition occurred at 15-minute intervals, with readings transmitted to the Arduino microcontroller via wired connections. The microcontroller executed the irrigation control algorithm that compared real-time soil moisture values against pre-defined threshold parameters. When soil moisture dropped below the lower threshold of 25%, the corresponding solenoid valve was activated to initiate irrigation. Irrigation continued until soil moisture reached the upper threshold of 40%, at which point the valve was deactivated.

The ESP8266 module transmitted processed sensor data to the Thing Speak IoT platform at 30-minute intervals. Thing Speak provided cloud-based data storage, visualization dashboards, and mobile application integration for remote monitoring. The platform's MATLAB analytics capability enabled computation of daily and cumulative water consumption statistics. Water consumption was measured through the flow sensors installed at each zone inlet, with data logged continuously throughout the experimental period. Crop growth parameters including plant height, leaf area index, and yield components were recorded at fortnightly intervals following standard agronomic protocols. At harvest, crop yields were determined by harvesting entire sub-plots and weighing produce after appropriate drying. Statistical analysis employed paired t-tests and ANOVA procedures using SPSS software version 23 to assess treatment differences at 5% significance level.

System Design: The complete system design emphasized modularity, affordability, and ease of maintenance suitable for adoption by resource-constrained farmers. The sensor network topology adopted a star configuration with the Arduino microcontroller serving as the central hub. Each sensor node was enclosed in weatherproof housing to protect electronics from field conditions including dust, moisture, and temperature extremes. The irrigation control algorithm incorporated hysteresis logic to prevent rapid on-off cycling of valves that could cause mechanical wear and water hammer effects. Zone-wise irrigation scheduling prevented simultaneous operation of multiple valves, ensuring adequate pressure at each emitter. The total hardware cost for the developed system amounted to approximately INR 15,000 (USD 210 at prevailing exchange rates), representing a fraction of commercial IoT irrigation solutions available in the market. Software components utilized open-source libraries and platforms, eliminating licensing costs and enabling customization based on local requirements.

Table 1 presents the comparative performance metrics between the IoT-based irrigation system and conventional practices. The automated system delivered substantially lower total water volume while achieving higher irrigation frequency with smaller application amounts. Soil moisture variability, indicated by standard deviation values, was markedly reduced under IoT management. System reliability remained consistently high throughout the experimental duration, with brief downtimes attributable to occasional WiFi connectivity interruptions during severe weather events.

Results

Table 1: System Performance Parameters during the Experimental Period

Parameter	IoT System	Conventional
Total Water Applied (m³/ha)	2,853	4,783
Irrigation Events (no.)	47	18
Average Soil Moisture (%)	32.4 ± 4.2	28.7 ± 11.3
System Uptime (%)	97.8	N/A
Water Use Efficiency (kg/m³)	8.49	3.91

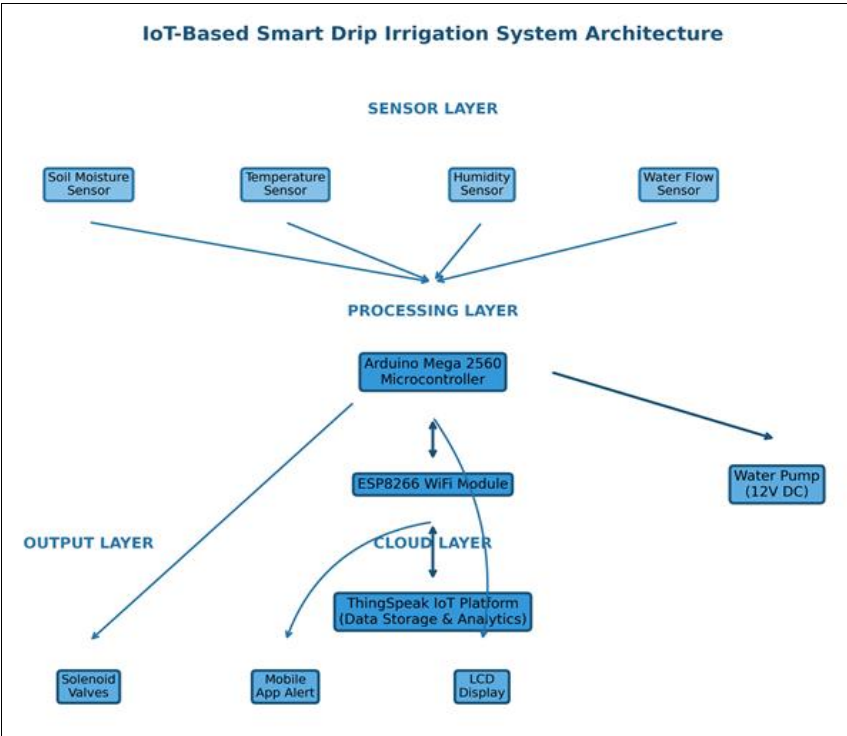


Fig 1: System Architecture of the IoT-Based Smart Drip Irrigation System

Figure 1 illustrates the complete system architecture showing data flow between components. The sensor layer continuously monitors field conditions and transmits readings to the processing layer. The Arduino microcontroller processes incoming data, executes control

logic, and communicates with both local output devices and the cloud platform. The bidirectional connection with Thing Speak enables not only data upload but also remote control commands when needed.

Table 2: Crop Yield and Water Productivity Comparison

Crop	IoT Yield (q/ha)	Conv. Yield (q/ha)	Increase (%)
Cotton	24.2	18.7	29.4
Soybean	16.8	12.3	36.6
Sorghum	27.9	21.4	30.4

Yield improvements under IoT-controlled irrigation ranged from 29.4% to 36.6% across the three tested crops (Table 2). Soybean exhibited the highest relative improvement, possibly due to its sensitivity to both water deficit and excess conditions during flowering and pod filling stages. The consistent maintenance of optimal soil moisture appeared particularly beneficial for this crop. Cotton and sorghum also demonstrated significant yield enhancements, attributable to reduced water stress during critical growth periods. The month-wise water consumption data reveals consistent savings across the entire cropping season (Figure 2). Peak water demand occurred during July and August corresponding to active vegetative growth phases. The IoT system achieved water savings ranging from 37.8% to

42.1% across different months. Notably, conventional irrigation applied excessive water during relatively cooler months when evapotranspiration rates were lower, whereas the sensor-based system adjusted automatically to prevailing conditions. Continuous soil moisture monitoring revealed markedly different patterns between the two irrigation approaches (Figure 3). The IoT-controlled system maintained soil moisture within the optimal 25-40% range through frequent, small irrigation applications. In contrast, conventional irrigation exhibited wide fluctuations with values dropping to stress-inducing levels below 15% before the next scheduled irrigation event. Such moisture stress periods, even if brief, can adversely affect physiological processes and ultimately reduce yields.

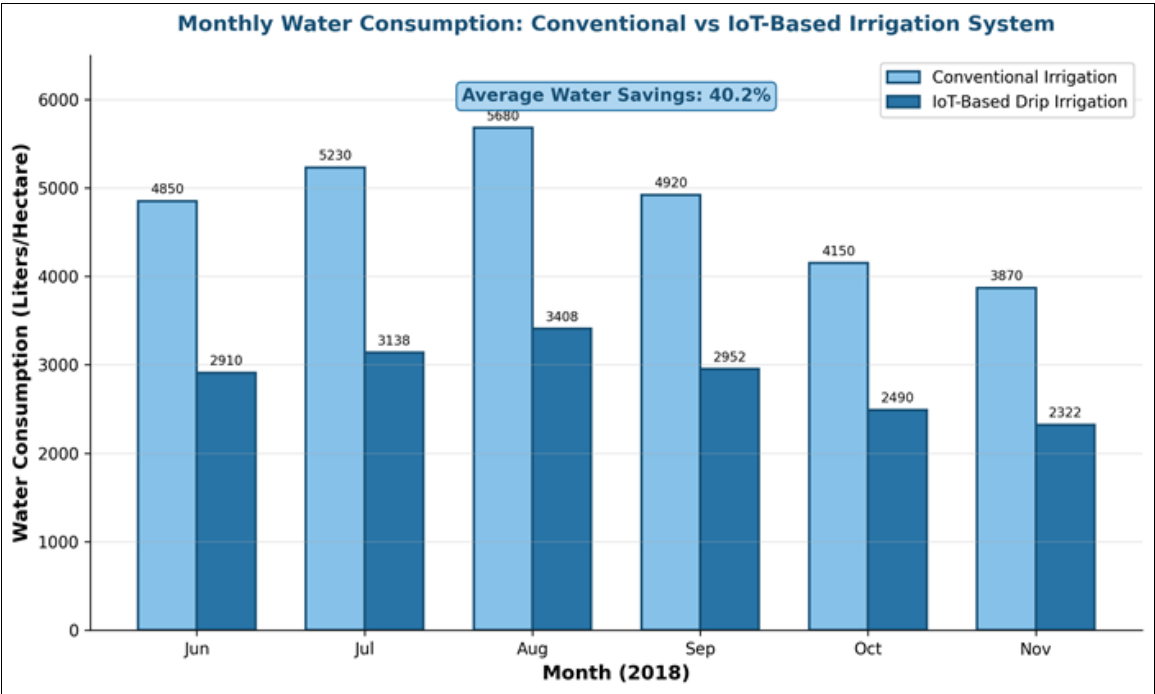


Fig 2: Monthly Water Consumption Comparison between Conventional and IoT-Based Irrigation Systems

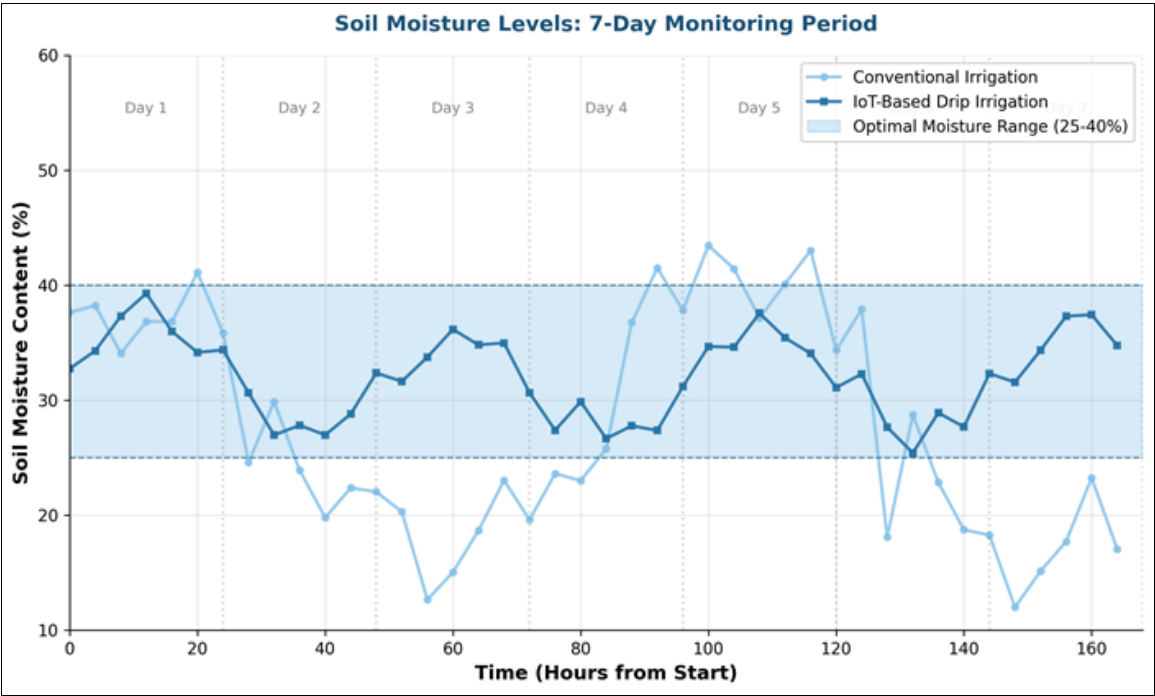


Fig 3: Soil Moisture Level Variations Over a Representative 7-Day Monitoring Period

Visual representation of yield data confirms substantial improvements across all crops tested (Figure 4). The percentage improvements ranged from approximately 29% to 37%, demonstrating the effectiveness of maintaining optimal moisture conditions throughout the growing period. Statistical analysis confirmed these differences were significant at $p<0.05$ level for all three crops.

Comprehensive Interpretation

The experimental results collectively demonstrate that the IoT-based smart irrigation system achieved its primary

objectives of water conservation and yield enhancement. The 40.2% average water savings significantly exceeded the initial target of 30%, indicating that real-time sensor-based scheduling offers substantial advantages over fixed-schedule approaches. Furthermore, the system maintained high reliability with 97.8% uptime despite operating under challenging field conditions including dust, temperature variations, and monsoon weather. Economic analysis indicated a payback period of approximately 1.7 years when considering both water cost savings and additional revenue from improved yields.

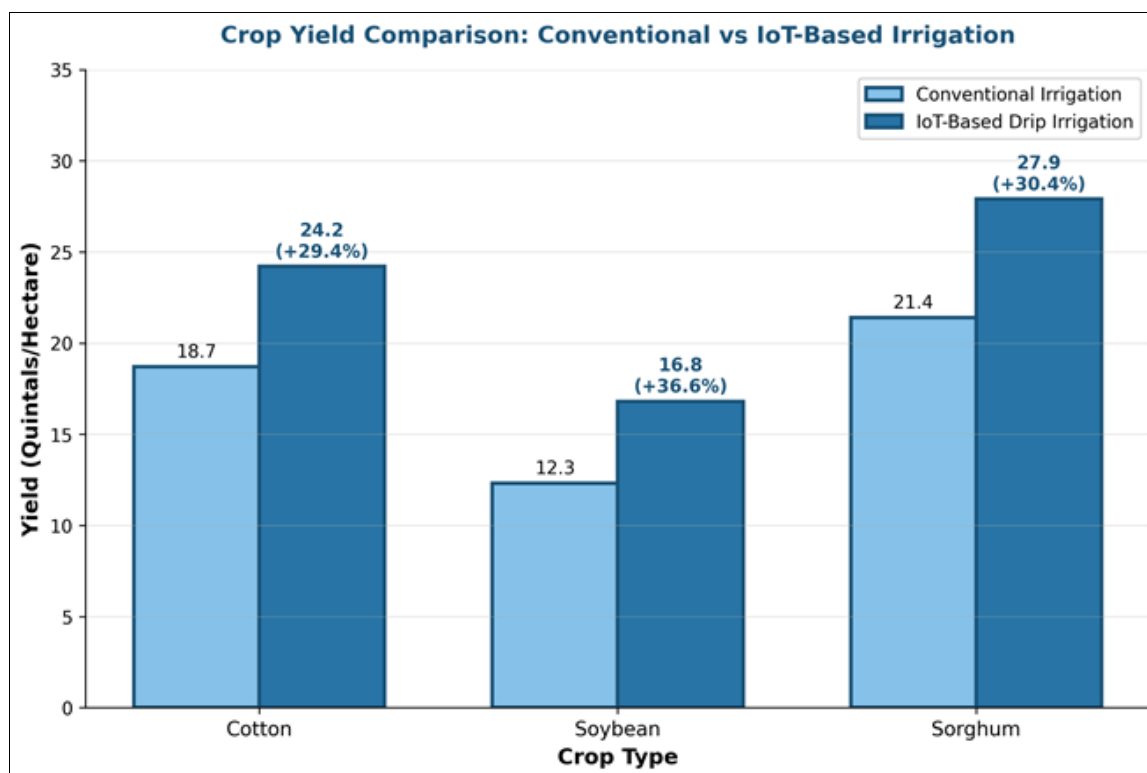


Fig 4: Crop Yield Comparison across Three Tested Crops under Different Irrigation Regimes

Discussion

The findings of this research align with and extend previous investigations into IoT-based irrigation systems. The water savings achieved (40.2%) compare favorably with reports by Goap *et al.* ^[10] who documented 35% savings using machine learning approaches, and Kamienski *et al.* ^[9] who reported 25% reduction in Brazilian conditions. The superior performance observed in the present research may be attributed to the combination of appropriate soil moisture thresholds calibrated for local conditions and the inherent efficiency of drip irrigation delivery.

The yield improvements ranging from 29% to 37% exceeded those typically reported for drip irrigation alone, which generally range from 15-25% improvement over surface methods ^[5]. This enhanced performance appears to result from the elimination of both water stress and excess conditions through continuous monitoring. Conventional irrigation often subjects crops to alternating stress and waterlogging cycles that impair root function and nutrient uptake. The automated system's ability to maintain narrow moisture ranges prevented such detrimental fluctuations.

From a practical standpoint, the developed system addresses several barriers to technology adoption among Indian farmers. The total hardware cost of approximately INR 15,000 positions the system within reach of progressive smallholders, particularly when government subsidies for micro-irrigation are considered. The use of widely available components ensures serviceability in rural areas without requiring specialized technical support. However, certain limitations merit acknowledgment. The research was conducted at a single location over one season, and results may vary under different soil types and climatic conditions. Additionally, the WiFi-based connectivity requires reliable internet access, which remains inconsistent in remote rural areas.

Future enhancements could incorporate predictive irrigation scheduling using weather forecast data and crop growth models. Integration of solar power would eliminate grid dependency, improving viability in electricity-constrained regions. Multi-year trials across diverse agro-climatic zones would strengthen evidence regarding system performance under varying conditions.

Conclusions

This research successfully developed and validated an IoT-based smart drip irrigation system tailored for semi-arid agricultural conditions in India. The system demonstrated compelling advantages over conventional irrigation practices across multiple performance dimensions. Water conservation emerged as a primary benefit, with the automated system achieving 40.2% reduction in water consumption compared to traditional flood irrigation methods. This substantial saving carries significant implications for groundwater sustainability in water-stressed regions where aquifer depletion threatens long-term agricultural viability.

Crop productivity improvements accompanying water savings indicate that precision irrigation delivers both environmental and economic benefits simultaneously. Yield enhancements of 29-37% across cotton, soybean, and sorghum demonstrate the effectiveness of maintaining optimal soil moisture conditions throughout critical growth stages. The mechanism underlying these improvements relates to the elimination of alternating stress and waterlogging cycles that characterize scheduled irrigation approaches. Plants maintained under consistent moisture conditions exhibited enhanced physiological performance reflected in superior final yields.

The technical feasibility of implementing IoT technologies in rural farming contexts was clearly established. Despite

operating under challenging field conditions including temperature extremes, dust, and variable connectivity, the system maintained 97.8% operational uptime throughout the trial period. The use of commercially available, low-cost components resulted in total system costs significantly below commercial alternatives while delivering comparable functionality. This cost-effectiveness positions the technology within reach of smallholder farmers who constitute the majority of India's agricultural workforce. Economic analysis revealed favorable returns with payback periods of less than two cropping seasons when accounting for reduced water pumping costs and enhanced crop revenues. The cloud-based monitoring capability offers additional value by enabling remote field supervision, reducing the need for frequent physical visits to monitor irrigation status. And this feature proves particularly beneficial for farmers managing multiple or distant plots. The broader implications extend beyond individual farm benefits to regional water resource management. Widespread adoption of precision irrigation technologies could substantially reduce agricultural water demand, allowing reallocation to other sectors or environmental flows. Policy support through enhanced subsidies and demonstration programs could accelerate adoption rates. But sustained benefits require continued farmer education and development of local service ecosystems for maintenance and troubleshooting. The evidence presented establishes IoT-based smart irrigation as a technically sound and economically viable approach for addressing water scarcity challenges in semi-arid Indian agriculture.

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