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A Review Paper on IoT-Enabled Precision Irrigation for Sugarcane Cultivation

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Abstract—Sugarcane is among the most water-intensive commercial crops, and inefficient conventional irrigation practices such as flood or furrow irrigation contribute to significant water wastage in major cane-growing regions, several of which face increasing groundwater stress. Precision irrigation enabled by the Internet of Things (IoT) offers a pathway to align water application with actual crop water demand, using real-time soil, plant, and weather data to guide irrigation scheduling and volume. This review paper examines IoT-enabled precision irrigation systems for sugarcane cultivation, covering system architecture spanning soil-moisture and weather sensing, wireless communication (Wi-Fi, LoRa, GPRS/GSM), edge and cloud-based data processing, and automated valve or drip actuation. The paper reviews sensing and data acquisition techniques including capacitive and tensiometric soil-moisture sensors, canopy temperature and crop water stress indices, and remote-sensing-based approaches, along with irrigation scheduling algorithms ranging from threshold-based control to evapotranspiration-based and machine-learning-driven decision support. A comparative analysis of representative studies and field trial outcomes highlights reported water savings and yield effects relative to conventional irrigation. The review identifies persistent challenges including sensor cost and calibration, rural connectivity constraints, power availability, and farmer adoption barriers, and concludes with future directions spanning low-cost sensor networks, satellite-integrated scheduling, and decision-support tools tailored to smallholder sugarcane farming.

Index Terms—*Precision Irrigation, Internet of Things, Sugarcane Cultivation, Soil Moisture Sensing, Wireless Sensor Networks, Evapotranspiration, Smart Agriculture, Water Use Efficiency, Decision Support Systems.*

I. Introduction

Sugarcane is a long-duration, water-intensive crop that typically requires substantially more irrigation water over its growing season than most other commercial row crops, making efficient water management a critical determinant of both yield and the sustainability of groundwater and canal water resources in major cane-growing regions [1]. Conventional flood and furrow irrigation, still widely practiced in many sugarcane-growing areas, applies water on fixed schedules largely independent of actual crop water demand, soil moisture status, or weather conditions, resulting in substantial over-irrigation, waterlogging, and inefficient water use [2].

The Internet of Things (IoT) has enabled a shift toward precision irrigation, in which networked soil, plant, and weather sensors feed real-time data to automated or farmer-assisted decision systems that determine when and how much to irrigate. Early wireless sensor network (WSN) based irrigation systems demonstrated that automated, sensor-driven scheduling could maintain target soil moisture levels while substantially reducing water application compared to fixed-schedule irrigation [3],[4]. These principles are increasingly being adapted and field-tested for sugarcane cultivation, given the crop's high water demand and the significant water-saving potential precision approaches offer.

This review examines IoT-enabled precision irrigation systems specifically in the context of sugarcane cultivation. The primary contributions are: (1) a structured review of system architectures for IoT-based

B. Limitations of Conventional Irrigation

Flood and furrow irrigation, while low-cost to implement, offer limited application uniformity and no mechanism to adapt to real-time soil or weather conditions, commonly resulting in both under-irrigation stress during peak demand periods and over-irrigation induced waterlogging or nutrient leaching at other times [2].

III. IoT-Based Precision Irrigation System Architecture

A. Field Sensing Layer

The sensing layer consists of soil-moisture sensors, weather stations (temperature, humidity, rainfall, solar radiation), and optionally canopy or leaf-level sensors deployed across representative field zones, providing the raw data on which irrigation decisions are based [3],[4].

B. Communication Layer

Field-collected sensor data is transmitted to a central gateway or cloud platform using wireless communication technologies such as Wi-Fi, GPRS/GSM, or low-power wide-area protocols such as LoRa, chosen based on the tradeoffs between range, power consumption, and rural network infrastructure availability [3].

C. Data Processing and Decision Layer

Collected data is processed either at the edge (on local microcontrollers) or in cloud-based platforms, where irrigation scheduling logic — ranging from simple threshold rules to evapotranspiration-based or machine-learning-driven models — determines irrigation timing and volume.

D. Actuation Layer

irrigation; (2) an analysis of sensing and data acquisition techniques relevant to sugarcane water management; (3) a review of irrigation scheduling and decision-making algorithms; (4) a comparative analysis of representative studies and field trial outcomes; and (5) identification of open challenges and future research directions for smallholder and large-scale sugarcane farming.

II. Background

A. Water Requirements of Sugarcane

Sugarcane water demand varies across its vegetative, grand growth, and maturation stages, with peak crop water requirement typically occurring during the grand growth phase; reference evapotranspiration (ETo) based methods, such as those standardized by the FAO, provide the agronomic basis for estimating crop water requirement at each growth stage [5].

Based on the decision layer's output, solenoid valves, drip system controllers, or pump relays are actuated automatically, or recommendations are relayed to farmers via SMS or mobile application for manual action, depending on the level of automation deployed [6].

IV. Comparison of Irrigation Approaches

Table I summarizes conventional and IoT-enabled irrigation approaches relevant to sugarcane cultivation. Conventional flood/furrow irrigation remains the lowest-cost and most widely adopted method but offers the least precision and water-use efficiency, while sensor-driven and ML-based precision approaches offer progressively higher water-use efficiency at correspondingly higher implementation cost and technical complexity.

TABLE I — Comparison of Irrigation Approaches for Sugarcane Cultivation

Approach	Key Technique	Water-Use Efficiency	Cost/Complexity	Adaptability to Real-Time Conditions
Flood/Furrow Irrigation	Fixed schedule, gravity flow	Low	Low	None
Drip Irrigation (manual)	Localized application, manual timing	Moderate	Moderate	Low
Threshold-Based IoT Control [3]	Soil-moisture triggered valves	Moderate-High	Moderate	Moderate
ET-Based Scheduling [5]	Reference ET + crop coefficient	High	Moderate-High	High
ML/Fuzzy Logic Control [3]	Sensor fusion + adaptive rules	High	High	High

V. Sensing and Data Acquisition Techniques

A. Soil Moisture Sensing

Capacitive and frequency-domain soil-moisture sensors, along with tensiometers that measure soil water potential, are the most widely used inputs for precision irrigation decisions, providing continuous, zone-specific measurement of plant-available water in the root zone [3],[4].

B. Weather and Micrometeorological Sensing

On-site or nearby automatic weather stations collecting temperature, humidity, rainfall, wind speed, and solar radiation data support reference evapotranspiration (ETo) calculation, enabling irrigation scheduling to account for real-time atmospheric water demand [5].

C. Crop Water Stress Indices

Canopy temperature-based indices, such as the Crop Water Stress Index (CWSI), and other plant-based physiological measurements offer a complementary, plant-centric perspective on irrigation need that can be combined with soil-based sensing for more robust scheduling decisions [7].

D. Remote Sensing Integration

Satellite and drone-based multispectral and thermal

VII. Irrigation Scheduling and Decision-Making Algorithms

A. Threshold-Based Control

The simplest and most widely deployed scheduling approach triggers irrigation when soil moisture falls below a predefined threshold, offering low computational overhead and ease of implementation at the cost of limited adaptability to changing weather or crop growth stage [3].

B. Evapotranspiration-Based Scheduling

Scheduling based on calculated crop evapotranspiration (ETc), derived from reference ET and crop coefficients specific to sugarcane growth stages, provides a more agronomically grounded approach to matching irrigation volume with actual crop water demand [5].

C. Fuzzy Logic and Machine Learning Approaches

Fuzzy logic controllers and machine-learning models trained on historical sensor and weather data have been applied to irrigation scheduling to handle the uncertainty and non-linearity inherent in soil-plant-atmosphere interactions, generally improving scheduling precision over static threshold rules [3].

D. Decision Support Systems for Farmers

Beyond fully automated control, many deployed systems are imagery are increasingly used to estimate field-scale crop water stress and canopy vigor, offering a scalable complement to point-based ground sensors, particularly for large sugarcane plantations.

VI. Comparative Analysis

Table II compares representative studies on IoT-based precision irrigation systems, summarizing sensing approach, communication technology, crop context, and reported water-saving outcomes. Across studies, sensor-driven scheduling approaches consistently report substantial water savings relative to conventional fixed-schedule irrigation, generally without yield penalty, though reported savings vary considerably with local soil, climate, and crop conditions [3],[4],[8].

designed as decision-support tools that relay sensor data and irrigation recommendations to farmers via SMS or mobile applications, preserving farmer agency while reducing the expertise burden of manual scheduling [6].

VIII. Field Trials and Deployment Studies

Table III summarizes representative field trial and deployment studies relevant to IoT-based irrigation in row and plantation crops, including sugarcane, providing the evidentiary basis for the comparative analysis in Section VI.

TABLE II — Comparative Analysis of Representative Studies

Author & Year	Crop/Context	Technology	Method	Reported Outcome
Gutierrez et al. [3] (2013)	Raised-bed crops	WSN + GPRS, fuzzy logic control	Field deployment	Maintained target soil moisture; notable water savings
Vellidis et al. [4] (2008)	Cotton	Wireless smart sensor array	Field trial	Improved irrigation timing vs. calendar-based scheduling
Kim, Evans & Iversen [8] (2008)	Row crops	Distributed WSN, remote control	Field deployment	Enabled remote monitoring and variable-rate control
Jones [7] (2004)	General field crops	Plant-based scheduling methods	Review/analysis	Highlighted tradeoffs of canopy-temperature-based indices
Nawandar & Satpute [6] (2019)	General field crops	Low-cost IoT module	Field deployment	Reduced cost automated scheduling with SMS alerts
Allen et al. [5] (1998)	General crops (incl. sugarcane)	FAO-56 ET methodology	Methodological standard	Basis for crop-coefficient-driven scheduling

TABLE III — Representative Field Trial and Deployment Studies Relevant to IoT Irrigation

Study/Source	Deployment Scale	Sensing Approach	Reported Water Savings
Gutierrez et al. [3] (2013)	Small field plot	Soil moisture + fuzzy control	Significant reduction vs. manual irrigation
Vellidis et al. [4] (2008)	Commercial field scale	Soil moisture sensor array	Improved scheduling precision
Kim, Evans & Iversen [8] (2008)	Center-pivot field scale	Distributed WSN	Enabled variable-rate water application
Nawandar & Satpute [6] (2019)	Small-scale field	Low-cost multi-sensor module	Reduced water use with maintained crop health
Bwambale et al. [9] (2022)	Multi-study review	Various (review)	Synthesizes water-use-efficiency gains across studies

IX. Key Challenges

A. Sensor Cost and Calibration

The upfront cost of soil-moisture and weather sensors, along with the need for periodic calibration and maintenance under field conditions, remains a significant barrier to adoption, particularly for smallholder sugarcane farmers operating on thin margins [6].

B. Satellite-Integrated Scheduling

Combining ground-sensor data with satellite-derived soil moisture and vegetation indices offers a promising path toward field-scale irrigation scheduling that reduces dependence on dense in-field sensor networks.

C. Decision-Support Tools for Smallholders

B. Rural Connectivity Constraints

Reliable data transmission depends on adequate cellular or wireless network coverage, which remains inconsistent in many rural sugarcane-growing areas, motivating interest in low-power, long-range communication protocols better suited to sparse rural infrastructure [3].

C. Power Availability

Continuous operation of field sensor nodes and communication modules requires reliable power, typically supplied via battery with solar charging in off-grid field locations; power management remains a key design constraint for long-term unattended deployment.

D. Sensor Placement and Field Variability

Sugarcane fields often exhibit considerable spatial variability in soil type and topography, meaning a limited number of sensor nodes may not adequately represent whole-field moisture conditions, risking scheduling errors if zoning is not carefully designed.

E. Farmer Adoption and Digital Literacy

Successful deployment depends not only on technical system performance but on farmer trust, digital literacy, and the perceived value of precision irrigation relative to its cost and complexity, underscoring the importance of extension support and farmer training alongside technology deployment.

X. Future Research Directions

A. Low-Cost Sensor Networks

Continued development of low-cost, ruggedized soil-moisture and weather sensor nodes, potentially leveraging locally manufactured components, is an important direction for improving the economic viability of precision irrigation for smallholder sugarcane growers.

Simplified mobile-application-based decision-support tools, designed with local language support and minimal technical prerequisites, merit further research to improve accessibility for smallholder sugarcane farmers with limited digital literacy.

D. Integration with Farm Management Systems

Future work integrating precision irrigation data with broader farm management systems — covering fertigation, pest monitoring, and yield forecasting — could support more holistic, data-driven sugarcane crop management.

XI. Conclusion

This review has examined IoT-enabled precision irrigation systems for sugarcane cultivation, covering sensing technologies, communication architectures, and scheduling algorithms, along with a comparative analysis of representative studies and field trial outcomes. The evidence indicates that sensor-driven and evapotranspiration-based scheduling approaches can substantially reduce water application relative to conventional flood or furrow irrigation without compromising yield, addressing a critical sustainability concern for water-intensive sugarcane cultivation. Persistent challenges including sensor cost, rural connectivity, power constraints, and farmer adoption must be addressed before precision irrigation can be deployed at scale among smallholder sugarcane growers. Future work in low-cost sensor networks, satellite-integrated scheduling, and accessible farmer-facing decision-support tools is expected to be central to realizing the water-saving potential of precision irrigation in sugarcane-growing regions.

XII. References

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