Development of an IoT-based sensor for the detection of the moisture level of soil

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***Abstract*—Soil moisture plays a crucial role in determining irrigation requirements and has a direct impact on crop yield. Consequently, soil moisture sensors have become essential tools for accurately assessing soil water content. This review synthesises research conducted over the past two to three decades, highlighting the principles underlying commonly used soil moisture sensors and their diverse applications. The comparative analysis addresses the advantages, limitations, and influencing factors associated with various measurement techniques. Proposed improvements by scholars have established the major applications and performance benchmarks of soil moisture sensors, thereby shaping the directions for future development. The findings suggest that next-generation sensors should aim to achieve high precision, low cost, non-destructive measurement, automation, and advanced integration. Moreover, future research should focus on designing specialised sensors tailored to specific agricultural and environmental scenarios. This review intends to provide valuable reference material for practitioners and researchers engaged in the selection and application of soil moisture sensing technologies.**

***Index Terms*—Soil moisture sensor; Measurement principle; Influencing factors; Improvement methods; Development directions**

I. INTRODUCTION

Soil moisture is a fundamental parameter in agricultural science, as it directly affects plant growth, irrigation efficiency, and overall crop productivity (Dorigo, W. A., et al., 2017). Effective monitoring of soil water content is essential for sustainable farming practices, particularly in regions facing water scarcity. The advancement of sensor technologies has provided farmers and researchers with reliable tools to assess soil moisture in real time, thereby enabling precision irrigation and resource optimisation (H. R. Bogena et. al., 2007).

This section introduces the significance of soil moisture monitoring, outlines the role of sensors in modern agriculture, and establishes the rationale for reviewing existing research on soil moisture sensing technologies (Evett, S. R. et. al., 2012).

II. LITERATURE REVIEW

Over the past two to three decades, extensive research has been conducted on soil moisture sensors, leading to the development of diverse measurement principles and applications. Dielectric-based methods, such as capacitance and time-domain reflectometry, have gained prominence due to their accuracy and adaptability (Kim, Y. et. al., 2008). Resistive sensors, though cost-effective, often face limitations related to soil salinity and temperature variations. Gravimetric and neutron scattering techniques, although highly precise, are generally limited to laboratory or specialised field applications due to their complexity and cost.

1. Scholars have evaluated the pros and cons of these methods, emphasising factors such as soil texture, bulk density, and organic matter content that affect measurement accuracy (Jones, S.B. et al., 2002). Advances in sensor design, including miniaturisation, automation, and integration with wireless systems, have broadened their use in precision agriculture. The literature consistently highlights the need for high-precision, low-cost,

and non-destructive sensors that can be customised to specific agricultural and environmental contexts (Muñoz-Carpena, R., 2004).

III. APPLICATIONS OF SOIL MOISTURE SENSORS

Soil moisture sensors have become indispensable in modern agriculture and environmental monitoring due to their ability to provide accurate, real-time data (Robinson, D. A. et. al., 2008). Their applications extend across several domains:

- Precision Irrigation Management

Sensors are widely employed to determine the optimal timing and quantity of irrigation. By integrating sensor data into automated irrigation systems, farmers can significantly reduce water wastage and improve crop yield.

- Smart Farming and IoT Integration

With the rise of digital agriculture, soil moisture sensors are increasingly connected to wireless networks and Internet of Things (IoT) platforms. This integration enables remote monitoring, data analytics, and predictive modelling for improved farm management.

- Environmental and Climate Studies

Beyond agriculture, sensors are used to monitor soil water dynamics in ecological research, hydrological modelling, and climate change studies. They provide valuable insights into soil–plant–atmosphere interactions.

- Greenhouse and Controlled Environments

In greenhouse cultivation, sensors help maintain optimal soil moisture levels for high-value crops, ensuring consistent quality and productivity.

- Water Resource Management

Soil moisture data support regional water management policies by informing decisions on irrigation scheduling, drought assessment, and groundwater recharge strategies.

IV. ADVANTAGES AND LIMITATIONS OF SOIL MOISTURE SENSORS

Advantages

- Real-Time Monitoring: Sensors provide continuous and immediate data on soil water content, enabling timely irrigation decisions.
- Resource Efficiency: By optimising irrigation schedules, sensors help conserve water and reduce energy consumption.
- Automation Potential: Integration with smart irrigation systems allows for automated control, minimising human error.
- Enhanced Crop Productivity: Accurate soil moisture data support improved plant growth and yield outcomes.
- Scalability: Sensors can be deployed across diverse agricultural settings, from small farms to large-scale operations.

Limitations

- Soil Dependency: Sensor accuracy is often influenced by soil texture, bulk density, salinity, and organic matter.
- Environmental Sensitivity: Temperature fluctuations and external environmental conditions can affect readings.
- Calibration Requirements: Many sensors require frequent calibration to maintain accuracy, which can be labour-intensive.
- Cost Constraints: Advanced sensors, such as neutron probes or TDR devices, are expensive and may not be accessible to small-scale farmers.
- Durability Issues: Long-term stability and performance can be compromised by soil corrosion, mechanical wear, or sensor drift.

V. COMPARATIVE ANALYSIS OF SENSOR TECHNOLOGIES:

Sensor type	Principle	Accuracy	Cost	Limitation	Best use case
Capacitance	Measures the dielectric constant of soil	Moderate–High	Low–Medium	Affected by soil salinity and temperature	Field monitoring, affordable precision Agri
TDR	Measures the travel time of the EM pulse in soil	High	High	Expensive, requires expertise	Research, high-precision agriculture
Resistive	Measures electrical resistance	Low–Moderate	Very Low	Strongly affected by salinity and temperature	Low-budget, small farms
Gravimetric	Direct measurement by drying soil samples	Very High (lab)	Low	Destructive, time-consuming, not real-time	Laboratory calibration, reference standard
Neutron Probe	Measures hydrogen content via neutron scattering	Very High	Very High	Safety concerns, costly, requires a license	Specialised research, hydrology

VI. FUTURE DEVELOPMENT DIRECTIONS:

Recent studies suggest that soil moisture sensing technologies are moving toward smarter, more accessible solutions, which can be implemented commercially for the benefit of mankind (Soulis, K. X., & Elmaloglou, S., 2016)
Integration with AI and IoT: Sensors are increasingly linked to wireless platforms and machine learning models for predictive irrigation and climate modelling.

- Low-Cost, High-Precision Designs: Researchers emphasise reducing costs while maintaining accuracy, making sensors accessible to small farmers.
- Non-Destructive and Portable Methods: Development of handheld or in-situ probes that avoid destructive sampling, enabling real-time monitoring.
- Specialised Sensors: Tailored designs for specific soil textures, salinity levels, and climatic conditions to improve reliability.
- Automation and Smart Systems: Coupling sensors with automated irrigation systems to reduce human error and optimise water use.

VII. CHALLENGES AND RESEARCH GAPS

Despite significant progress in soil moisture sensing technologies, several challenges remain:

- Calibration Complexity: Sensor accuracy varies with soil texture, salinity, and organic matter, requiring frequent calibration.
- Durability Issues: Long-term stability is affected by corrosion, mechanical wear, and sensor drift in harsh environments.
- Environmental Sensitivity: Temperature fluctuations and external conditions can distort readings, especially in resistive sensors.
- Data Integration: Difficulty in linking sensor outputs with farm management systems and predictive models.
- Accessibility: High-precision sensors (e.g., TDR, neutron probes) remain costly and inaccessible for small-scale farmers.
- Research Gaps: Limited studies on sensor performance in diverse agroclimatic zones, and insufficient exploration of AI-driven calibration methods

VIII. CONCLUSION:

Soil moisture sensors have emerged as indispensable tools in modern agriculture and environmental monitoring. Over the past decades, research has advanced from basic resistive methods to sophisticated dielectric and neutron techniques, each offering unique strengths and limitations.
Their applications span precision irrigation, smart farming, climate studies, and water resource management, demonstrating their critical role in sustainable practices.
Comparative analysis shows that while high-precision sensors like TDR and neutron probes deliver excellent accuracy, cost and accessibility remain barriers for widespread adoption. Future development must

therefore focus on low-cost, portable, and non-destructive designs, integrated with AI and IoT platforms for predictive analytics. Addressing challenges such as calibration complexity, durability, and data integration will be essential to ensure reliability across diverse soils and climates.

In conclusion, soil moisture sensors are not just measurement devices but enablers of precision agriculture and environmental stewardship. Continued innovation will make them more accessible, accurate, and impactful, ultimately supporting global efforts in food security and sustainable resource management.

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