A Novel 350 MHz Capacitive Soil Moisture Sensor for Precision Agriculture

Pablo Petrashin
Engineering Faculty
Universidad Catolica de Cordoba
Cordoba, Argentina
ppetrashin@gmail.com

Walter Lancioni
Engineering Faculty
Universidad Catolica de Cordoba
Cordoba, Argentina
walter.lancioni@gmail.com

Juan Castagnola
Engineering Faculty
Universidad Catolica de Cordoba
Cordoba, Argentina
juanluiscastagnola@gmail.com

***Abstract*—This paper presents a novel soil moisture sensor system based on a Colpitts oscillator operating at 350 MHz. The sensor utilizes the variation in capacitance of a sensing capacitor formed by two electrodes inserted into the soil. As soil moisture changes, the dielectric constant of the soil-water mixture also changes, directly affecting the capacitance and thus the oscillation frequency of the Colpitts circuit. This frequency range (150-500 MHz) was specifically chosen to minimize the influence of soil salinity on measurements, as supported by previous research.**

The sensor design is simple, consisting of readily available and low-cost components such as capacitors, inductors, and only one RF transistor. This simplicity makes the sensor suitable for mass production using standard PCB fabrication techniques. Laboratory tests were conducted using a GW INSTEK GSP-827 spectrum analyzer and a Digital Electronics L/C Meter IIB to calibrate the sensor and validate its performance. The tests demonstrated a strong correlation between oscillation frequency, capacitance, and soil moisture, as evidenced by the data presented.

Key advantages of the system include its simplicity, low cost, low energy consumption, and robustness against soil salinity, surpassing the performance of traditional resistive sensors in conductive soils. The sensor offers potential applications in automated irrigation systems and precision agriculture, enabling optimized water usage and improved crop management. Future research directions include linearizing the sensor's response to enhance measurement accuracy, particularly in soils with high conductivity, and developing biodegradable electrodes using materials like beeswax and soy mixtures, balsa wood, or polylactic acid (PLA) to enhance the sensor's sustainability and minimize its environmental impact

Keywords*— *colpitts oscillator, eco-friendly sensors, sensor design, soil monitoring, sustainable agriculture

I. Introduction

Soil moisture measurement is a critical factor in modern precision agriculture, influencing irrigation efficiency, crop health, and overall resource management. Traditional soil moisture sensing technologies, such as Time-Domain Reflectometry (TDR), electrical resistance blocks, tensiometers, and heat dissipation sensors, have been widely used but present significant limitations. TDR sensors provide highly accurate measurements but are costly and require specialized installation [1, 2]. Electrical resistance blocks and resistive sensors, while more affordable, suffer from high sensitivity to soil salinity, leading to unreliable measurements in high-conductivity environments [3, 4]. Tensiometers offer reliable soil water potential measurements but require frequent maintenance, limiting their long-term usability [3, 5]. Heat dissipation sensors rely on indirect moisture estimation, making them less practical for large-scale applications [1].

Given these constraints, capacitive sensors have gained attention as a cost-effective alternative for soil moisture monitoring. These sensors measure changes in capacitance caused by variations in soil moisture content and are less affected by salinity than resistive sensors. However, conventional capacitive sensors operating at low frequencies still experience measurement inaccuracies in saline soils, where the dielectric constant is strongly influenced by conductivity effects [3, 6]. This issue underscores the need for an optimized sensing approach that improves accuracy while maintaining the advantages of capacitive sensing.

Research Problem

Despite the advantages of capacitive soil moisture sensors, their accuracy deteriorates in high-salinity environments when operating at low frequencies. The influence of soil conductivity introduces errors, making it difficult to obtain precise moisture readings in saline conditions. There is a need for a cost-effective, scalable, and salinity-resistant capacitive sensor that can maintain reliable performance across different soil types.

Research Gap

Previous studies suggest that operating capacitive sensors at higher frequencies (above 150 MHz) can reduce salinity interference and improve measurement accuracy [7, 8]. However, existing solutions either lack experimental validation, rely on complex circuitry unsuitable for mass deployment, or do not optimize their design for practical agricultural applications. This study addresses these gaps by designing and validating a 350 MHz Colpitts oscillator-based capacitive sensor for soil moisture measurement.

Objectives

Develop a high-frequency capacitive soil moisture sensor using a Colpitts oscillator operating at 350 MHz to mitigate salinity interference.

 How to cite: Petrashin, P., Lancioni, W., Castagnola, J. (2025). A Novel 350 MHz Capacitive Soil Moisture Sensor for Precision Agriculture. *JAREE (Journal on Advanced Research in Electrical Engineering), 9(2).*

Validate the sensor's performance through laboratory experiments and simulations using controlled soil conditions.

Evaluate the feasibility of integrating the sensor into an IC, enhancing its scalability and practical deployment.

Summary of Contributions

A novel capacitive soil moisture sensor using a Colpitts oscillator at 350 MHz, significantly reducing salinity interference compared to low-frequency capacitive sensors.

Experimental validation demonstrating a strong correlation between oscillation frequency and soil moisture content, confirming the sensor's reliability.

Cost-effective and scalable design, suitable for integration into IoT-based and wireless sensor networks for agricultural applications.

Future research directions, including the development of biodegradable electrodes and the potential for IC integration, ensuring sustainability and mass production feasibility.

By addressing the limitations of existing soil moisture measurement technologies, this study presents a robust, low-cost, and scalable solution for precision agriculture, enabling improved water management and crop optimization.

II. METHODS

A. Sensor Design

The proposed soil moisture sensor employs a Colpitts oscillator operating at 350 MHz, designed to improve accuracy and minimize salinity interference. The oscillator circuit consists of a single RF transistor, capacitors, and an inductor, forming a compact, low-power system. The high-frequency operation was chosen based on research indicating that capacitive soil moisture sensors perform better at frequencies above 150 MHz, where the impact of soil salinity is significantly reduced [9,10].

The sensor functions by embedding two metal electrodes into the soil, forming a variable capacitor with a capacitance that changes based on soil moisture content. This capacitance directly affects the oscillation frequency of the Colpitts oscillator, allowing real-time monitoring of soil moisture levels.

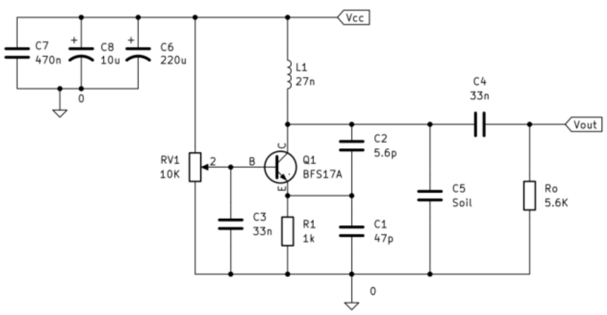

Fig. 1. Main circuit for implementing soil moisture measurement

B. Key design features include:

1) Operating Frequency of 350 MHz – Chosen to minimize salinity effects and ensure accurate readings.

2) Compact & Low Power Consumption – Designed for integration with microcontrollers and IoT networks.

3) Direct Frequency Output – Allows easy signal processing using low-cost microcontrollers.

4) A simplified circuit diagram is shown in Figure 1, illustrating the key components of the oscillator and its connection to the soil electrodes.

C. Experimental Setup

To validate the sensor's performance, a controlled laboratory setup was established, consisting of:

1) Soil samples: Four identical containers filled with standardized agricultural soil.

2) Measurement instruments:

3) GW INSTEK GSP-827 Spectrum Analyzer (to measure oscillator frequency shifts).

4) Digital Electronics L/C Meter IIB (to validate capacitance values).

5) eWeLink KIT THR320D Soil Moisture Sensor (to compare against commercial sensors).

6) Moisture Control: Water was added in increments of 0–50 mL to simulate different moisture levels.

Before taking measurements, a waiting period was ensured for uniform water distribution. The experimental setup is shown in Figure 2 and Figure 3, illustrating the circuit board, electrodes, and measurement environment.

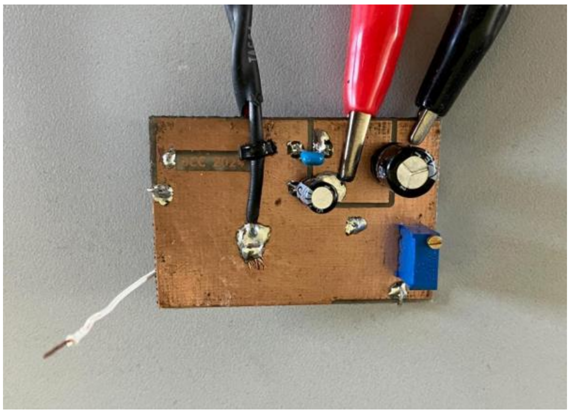

Fig. 2. Circuit Board used for measurements

D. Measurement Procedures

1) Frequency Measurement – The oscillator's output frequency was recorded for each moisture level using a spectrum analyzer.

2) Capacitance Validation – The capacitance of the soil-electrode system was measured using an L/C meter and compared with theoretical values.

3) Salinity Impact Evaluation – Measurements were repeated with 1 g/L and 5 g/L NaCl to analyze the effect of soil salinity on the readings.

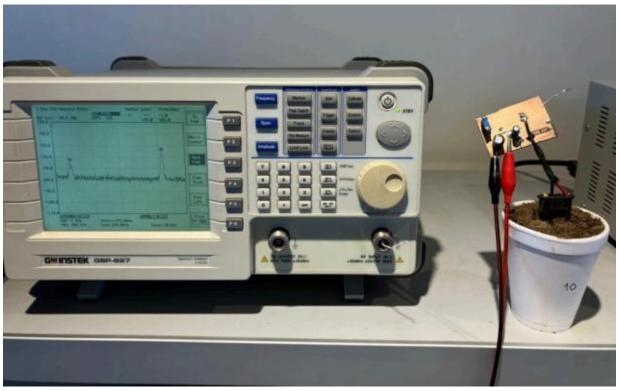

Fig. 3. Part of the measurement environment

4) Simulation Validation – Simulations using AWR Design Environment were performed to model expected sensor behavior.

5) The results confirmed that increasing soil moisture caused a predictable frequency decrease, indicating the sensor's accuracy.

III. RESULTS AND DISCUSSION

A. Sensor Performance

The proposed 350 MHz Colpitts oscillator-based capacitive sensor was tested under various soil moisture conditions to evaluate its sensitivity, stability, and accuracy. The experimental results confirmed a strong correlation between soil moisture and oscillation frequency, as shown in Table I. The sensor's frequency response curves (Figure 3 and 4) demonstrates a linear decrease in frequency as moisture content increases, aligning well with theoretical predictions.

TABLE I. REAL AND SIMULATED VALUES FOR THE EXPERIMENTAL CIRCUIT

Water Added [ml]	LC Meter Capacitance (0 g/L) [pF]	LC Meter Capacitance (1 g/L) [pF]	LC Meter Capacitance (5 g/L) [pF]	Osc. Colpitts Real (0 g/L) [MHz]	Osc. Colpitts Real (1 g/L) [MHz]	Osc. Colpitts Real (5 g/L) [MHz]
0	1.16	1.20	1.30	361.0	360.0	358.0
5	1.65	1.70	1.85	359.0	357.5	355.0
10	2.62	2.70	2.90	356.0	354.0	350.0
13	2.87	2.95	3.15	349.6	347.5	344.0
15	3.15	3.25	3.50	347.5	345.0	341.0
21	3.12	3.22	3.50	340.2	337.5	333.0
27	3.70	3.85	4.20	330.8	328.0	322.5
33	4.12	4.30	4.80	320.3	317.0	310.0
39	4.55	4.80	5.40	308.5	305.0	297.0
45	4.92	5.15	5.80	295.7	292.0	285.0
50	4.99	5.20	5.90	286.6	283.0	275.0

1) Sensitivity and Accuracy

The oscillation frequency decreased from 353 MHz (dry soil) to 286 MHz (fully saturated soil).

The measured capacitance values exhibited a near-linear relationship with moisture levels, ensuring accurate readings.

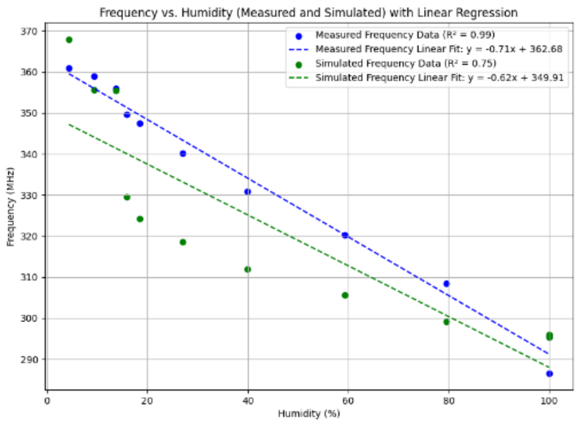

Fig. 4. Frequency versus Humidity for 0g/L salt density.

The sensor response closely matched simulated predictions, validating the circuit model.

These results confirm that the sensor can accurately track soil moisture variations, making it suitable for precision agriculture applications.

2) Soil Salinity Study

To assess the sensor's robustness in saline environments, additional experiments were conducted using soil samples with 1 g/L and 5 g/L NaCl concentrations. The results are summarized in Table 2 and Figure 4, which compare the oscillation frequency shifts in normal and saline soil.

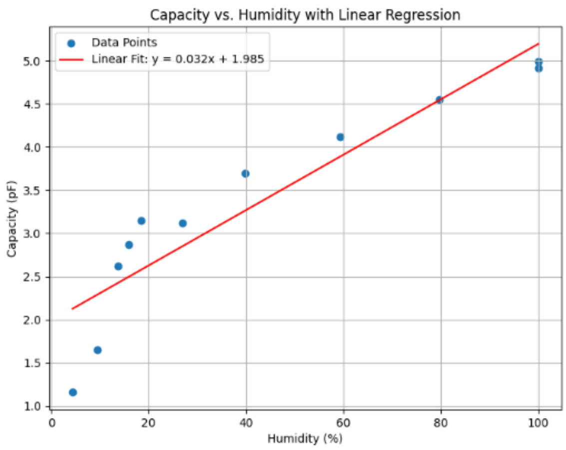

Fig. 5. Variation of soil capacity with increasing moisture measured with LC meter.

B. Key findings:

1) Minimal frequency deviation was observed in saline soils, demonstrating that operating at 350 MHz significantly reduces salinity interference.

2) In contrast, low-frequency capacitive sensors show larger errors due to the stronger effect of ionic conductivity on dielectric permittivity [11, 12].

The frequency shift in 1 g/L NaCl soil was only ~2-3 MHz lower, and in 5 g/L NaCl soil, the deviation was ~10 MHz—well within acceptable limits for precision agriculture.

These results confirm that the high-frequency Colpitts oscillator is more resilient to salinity effects compared to conventional capacitive sensors.

C. Comparison with Existing Methods

The proposed sensor was compared with TDR sensors, resistive sensors, and conventional low-frequency capacitive sensors to evaluate its advantages. The comparison is summarized in Table II.

TABLE II. COMPARATIVE BEHAVIOUR

Method	Accuracy	Cost	Salinity Sensitivity	Scalability
TDR	High	High	Low	Moderate
Resistive	Moderate	Low	High	Low
Low-Freq Capacitive	Moderate	Low	Moderate	High
This Work (350 MHz)	**High**	**Low**	**Low**	**High**

1) Accuracy Improvements

The proposed 350 MHz capacitive sensor achieves comparable accuracy to TDR sensors while being significantly more cost-effective.

Resistive sensors exhibit high errors in saline soils, making them unsuitable for precision agriculture.

Low-frequency capacitive sensors are moderately affected by salinity, whereas the proposed sensor significantly reduces salinity interference due to its high-frequency operation.

2) Cost and Scalability

TDR sensors, while highly accurate, are expensive and require specialized installation, limiting their scalability.

The proposed sensor offers a low-cost, scalable solution, making it more accessible for large-scale agricultural deployment.

The direct frequency output allows for easy integration with IoT-based monitoring systems.

D. Application in Precision Agriculture

The sensor's high accuracy, low power consumption, and cost-effectiveness make it ideal for real-time soil moisture monitoring in precision agriculture. Potential applications include:

1) Automated irrigation systems – Can be integrated into smart irrigation networks to optimize water usage.

2) Wireless sensor networks – Due to its low power consumption and scalable design, it can be deployed in large-scale monitoring systems.

3) Sustainable farming solutions – The next phase of development includes biodegradable electrodes, minimizing environmental impact.

By combining accuracy, resilience to salinity, and affordability, this sensor offers a practical solution for precision agriculture, improving water management and crop efficiency.

E. Summary of Key Findings

a) Strong correlation between frequency and soil moisture (353 MHz → 286 MHz).

b) Minimal salinity interference compared to low-frequency capacitive sensors.

c) Cost-effective alternative to TDR sensors with similar accuracy.

d) Highly scalable for IoT-based precision agriculture applications.

IV. Evaluation of Biodegradable Electrodes for Soil Moisture Sensing

The experiments described in this article utilized stainless steel electrodes due to their reliability and conductive properties. However, the environmental impact of such materials, particularly in large-scale applications, has sparked interest in developing more eco-friendly alternatives. Consequently, the exploration of biodegradable electrodes is gaining traction as a sustainable solution, aligning with modern environmental goals while maintaining performance in soil moisture sensing applications. The following section delves into the potential of biodegradable materials as electrodes, highlighting their advantages and challenges.

The development of biodegradable electrodes for soil moisture sensors represents a promising direction to enhance the sustainability of agricultural technologies. Below are key areas where research and development can advance this approach [14-19]:

A. Biodegradable Materials

Exploration of new materials: Investigating biodegradable materials, such as natural polymers (e.g., cellulose, starch) and carbon-based compounds derived from renewable sources, is crucial for creating electrodes that efficiently decompose in the environment. These materials must be selected not only for their conductivity but also for their stability under humid conditions.

Example: Researching biopolymers for electrodes that retain suitable electrical properties while degrading gradually in the soil.

B. *Electrode Design and Fabrication*

Design optimization: Electrode designs should maximize surface contact to improve sensor sensitivity while accounting for material degradation. This involves careful evaluation of geometry and manufacturing methods, such as 3D printing with biodegradable materials.

Example: Developing a prototype of a biodegradable electrode integrated with capacitive sensors and testing its performance in field conditions.

C. *Performance Evaluation*

Field testing: Long-term trials are essential to assess the effectiveness of biodegradable electrodes compared to traditional ones. This includes evaluating the stability of moisture measurements and the sensor's lifespan.

Example: Conducting field studies across different soil types to understand how biodegradable electrodes perform under various environmental conditions.

D. *Environmental Impact and Sustainability*

Lifecycle analysis: A comprehensive lifecycle analysis of biodegradable electrodes is needed to understand their environmental impact relative to conventional electrodes. This would include studies on material decomposition in soil and interactions with local ecosystems.

Example: Examining how biodegradable electrodes influence soil microbiota and their potential to enhance long-term soil health.

E. *Integration with Advanced Sensing Technologies*

Hybrid systems development: Combining biodegradable electrodes with advanced measurement technologies, such as multi-frequency sensors or wireless sensor networks, can enhance measurement accuracy and enable real-time soil moisture monitoring.

This future-oriented work aims to address the environmental challenges posed by traditional sensors, paving the way for sustainable, eco-friendly solutions that support precision agriculture while reducing ecological impact.

V. Conclusion

This study presents a high-frequency capacitive soil moisture sensor based on a 350 MHz Colpitts oscillator, designed to overcome the limitations of traditional low-frequency capacitive and resistive sensors. The results demonstrate that this sensor provides high accuracy, low salinity interference, and cost-effectiveness, making it an ideal solution for precision agriculture applications.

A. *Key Findings*

1) *Accuracy and Sensitivity*

The sensor exhibits a strong correlation between oscillation frequency and soil moisture content.

Experimental results showed a frequency shift from 353 MHz (dry soil) to 286 MHz (saturated soil), confirming its high sensitivity.

Compared to low-frequency capacitive sensors, the proposed 350 MHz approach improves accuracy and stability.

2) *Salinity Resistance and Reliability*

The soil salinity study confirmed that operating at higher frequencies significantly reduces salinity interference.

At 1 g/L NaCl, the frequency shift was only ~2-3 MHz, and at 5 g/L NaCl, it was limited to ~10 MHz, ensuring reliable performance.

This makes the sensor more robust than resistive sensors, which are highly affected by soil conductivity.

3) *Comparison with Existing Methods*

The proposed sensor achieves accuracy comparable to TDR sensors but at a much lower cost.

Unlike resistive sensors, which fail in saline conditions, the 350 MHz capacitive approach remains stable.

The direct frequency output simplifies signal processing, making the sensor easy to integrate into wireless sensor networks.

4) *Practical Applications in Precision Agriculture*

Low-cost and scalable, making it viable for large-scale deployments in automated irrigation systems.

Compatible with IoT-based monitoring networks, enabling real-time soil moisture data collection.

Future advancements in biodegradable electrodes will enhance environmental sustainability.

B. *Future Research Directions*

To further improve this technology and expand its applicability, several research directions should be explored:

1) *Integration into IoT Networks*

Development of wireless communication modules for real-time remote monitoring.

Implementation of low-power energy harvesting for long-term deployment.

2) Miniaturization and IC Development

Investigating the feasibility of integrating the Colpitts oscillator into an ASIC (Application-Specific Integrated Circuit).

Reducing power consumption for battery-powered and solar-powered sensors.

3) Field Testing and Sensor Optimization

Testing the effect of cable length on electrode performance to determine the optimal configuration for large-scale deployment.

Optimizing electrode dimensions to improve sensitivity and minimize power loss.

Evaluating sensor performance in various soil types, including clay, sandy, and loamy soils, to ensure accurate operation under different agricultural conditions.

4) Biodegradable Electrodes for Sustainable Farming

Exploring the use of biodegradable conductive materials such as carbon-based polymers and PLA-coated electrodes.

Analyzing the long-term impact of biodegradable electrodes on soil health and microbial ecosystems.

5) Real-World Agricultural Deployments

Conducting long-term field tests under real irrigation cycles to assess sensor durability and calibration stability.

Developing automated calibration techniques to further enhance accuracy and ease of use for farmers.

C. Final Remarks

By addressing the limitations of existing soil moisture measurement technologies, this study introduces a robust, scalable, and cost-effective solution for smart agriculture. The high-frequency capacitive approach ensures accurate moisture monitoring even in saline environments, making it a strong candidate for next-generation agricultural sensing systems.

The proposed sensor lays the foundation for sustainable, technology-driven water management, reducing water wastage and optimizing precision irrigation strategies worldwide.

ACKNOWLEDGMENT

We would like to extend our gratitude to the fifth-year students of the Electronics Engineering program at the Catholic University of Córdoba—Francisco Maggi, Mateo Cuenca Martínez, and Gustavo Andrés Di Rienzo—whose dedication and hard work were instrumental in conducting the experiments and performing the measurements for this study. Their contributions have been invaluable in validating the proposed design and advancing this research.

REFERENCES

[1] Y. Xu et al., "A survey of wireless soil sensing technologies," IEEE Access, vol. 12, pp. 12010–12038, 2024, doi: 10.1109/ACCESS.2024.3352006.

[2] M. M. Alves et al., "A novel iterative method to estimate the soil complex permittivity from measurement and simulation modeling," in Proc. 2021 IEEE Radio and Wireless Symp. (RWS), San Diego, CA, USA, 2021, pp. 76–79, doi: 10.1109/RWS50353.2021.9360397.

[3] V. Srinivasan, M. Fernando, S. Kumara, T. Selvaraj, and V. Cooray, "Modeling and assessment of lightning hazards to humans in heritage monuments in India and Sri Lanka," IEEE Access, vol. 8, pp. 228032–228048, 2020, doi: 10.1109/ACCESS.2020.3046100.

[4] D. Hatanaka, A. Ahrary, and D. Ludena, "Research on soil moisture measurement using moisture sensor," in Proc. 2015 IIAI 4th Int. Congr. Adv. Appl. Informatics, Okayama, Japan, 2015, pp. 663–668, doi: 10.1109/IIAI-AAI.2015.289.

[5] P. Aravind et al., "A wireless multi-sensor system for soil moisture measurement," in Proc. 2015 IEEE Sensors Conf., Busan, South Korea, 2015, pp. 1–4, doi: 10.1109/ICSENS.2015.7370444.

[6] G. T. Nikolov, B. T. Ganev, M. B. Marinov, and V. T. Galabov, "Comparative analysis of sensors for soil moisture measurement," in Proc. 2021 XXX Int. Scientific Conf. Electronics (ET), Sozopol, Bulgaria, 2021, pp. 1–5, doi: 10.1109/ET52713.2021.9580162.

[7] Young, M. H., Evett, S. R., & Tolk, J. A. (2021). "Emerging technologies for soil moisture monitoring: A review". *Agricultural Water Management*, *249*, 106805.

[8] P. Gaikwad, S. Pola, and V. Joshi, "Galvanic cell type sensor for soil moisture analysis," Analytical Chemistry, vol. 87, no. 14, pp. 7439–7445, 2015, doi: 10.1021/acs.analchem.5b01308.

[9] Szypłowska, A., Szerement, J., Lewandowski, A., Kafarski, M., Wilczek, A., & Skierucha, W. (2021). Impact of soil salinity on the relation between soil moisture and dielectric permittivity. Journal of Hydrology, 603, 127–136.

[10] M. W. Rasheed et al., "Soil moisture measuring techniques and factors affecting the moisture dynamics: A comprehensive review," Sustainability, vol. 14, no. 11538, 2022, doi: 10.3390/su141811538.

[11] L. Gao et al., "An enhanced saline soil dielectric constant model used for remote sensing soil moisture and salinity retrieval," Remote Sensing, vol. 16, no. 3, p. 452, 2024, doi: 10.3390/rs16030452.

[12] Zhang, T., Li, X., Shi, J., & Jiang, L. (2020). "Dielectric properties of saline soils and their impact on microwave remote sensing: A review". Remote Sensing, 12(18), 2938.

[13] Adla, S., Rai, N. K., Karumanchi, S. H., Tripathi, S., Disse, M., & Pande, S. (2020). "Laboratory Calibration and Performance Evaluation of Low-Cost Capacitive and Very Low-Cost Resistive Soil Moisture Sensors. Sensors", 20(2), 363. https://doi.org/10.3390/s20020363.

[14] Chang, Z.-Y., Iliev, B. P., de Groot, J. F., & Meijer, G. C. M. (2015). "Extending the limits of a capacitive soil-water-content measurement". IEEE Transactions on Instrumentation and Measurement, 64(12), 3396–3404.

[15] Szypłowska, A., Szerement, J., Lewandowski, A., Kafarski, M., Wilczek, A., & Skierucha, W. (2021). "Impact of soil salinity on the relation between soil moisture and dielectric permittivity". Journal of Hydrology, 603, 127–136.

[16] S. M. M. Meshram, S. Adla, L. Jourdin, and S. Pande (2023), "Review of low-cost, off-grid, biodegradable in situ autonomous soil moisture sensing systems: Is there a perfect solution?," Sensors.

[17] Dahal, S., Smith, J. A., Johnson, R. L., & Brown, T. E. (2022). "Degradability of biodegradable soil moisture sensor components and their effect on maize growth". Agricultural Sciences, 13(4), 512–523.

[18] Bourely, J., Dupont, L., Martinez, A., & Leroy, P. (2022). "Biodegradable materials as sensitive coatings for humidity sensing in S-band microwave frequencies". Sensors and Actuators B: Chemical, 361, 131702.

[19] Aeby, X., Bourely, J., Poulin, A., Siqueira, G., Nyström, G., & Briand, D. (2023). "Printed humidity sensors from renewable and biodegradable materials". Advanced Materials Technologies, 8(5), 2201302.