

ELECTRICAL IMPEDANCE SPECTROSCOPY: NEW PERSPECTIVES FOR INTEGRATED SOIL WATER MONITORING

SPECTROSCOPIE D'IMPÉDANCE ÉLECTRIQUE: NOUVELLES PERSPECTIVES POUR UNE SURVEILLANCE INTÉGRÉE DE L'EAU DU SOL

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ABSTRACT

Effective soil and water management requires reliable estimation of soil moisture and related physical properties under dynamically evolving field conditions. However, most commercial dielectric moisture sensors rely on empirical calibration relationships that are strongly influenced by salinity, texture, and soil structure, resulting in limited robustness and temporal stability.

This work investigates broadband Electrical Impedance Spectroscopy (EIS) in the intermediate frequency range (1 kHz–10 MHz) as a physics-based approach for multiparametric soil characterization. Analytical dielectric modeling combined with effective medium approximations was used to evaluate the coupled influence of volumetric water content, pore-water salinity, and porosity on the complex dielectric permittivity spectrum. Simulated results predict that each parameter produces a distinct spectral signature: moisture and salinity induce characteristic polarization peak shifts, while porosity primarily modifies spectral amplitude with comparatively limited peak displacement.

To experimentally evaluate these predictions, a non-contact broadband impedance measurement platform was developed and tested on agricultural soils under controlled laboratory conditions. Preliminary measurements reproduced the principal spectral behaviors predicted by the analytical framework, demonstrating qualitative agreement between simulations and experiments despite remaining discrepancies associated with simplified effective medium assumptions.

These results support the feasibility of inverse spectral modeling for simultaneous estimation of multiple soil physical properties from a single broadband dielectric measurement. Ongoing work focuses on automated high-throughput validation experiments and the development of a mobile in-situ sensing platform for field-scale agricultural measurements.

Keywords: Soil and water management; Soil moisture; Controlled laboratory conditions; Dielectric measurement; Agricultural measurements.

RÉSUMÉ

La gestion efficace du sol et de l'eau exige une estimation fiable de l'humidité du sol et des propriétés physiques associées dans des conditions de terrain en évolution dynamique. Toutefois, la plupart des capteurs diélectriques commerciaux d'humidité reposent sur des relations d'étalonnage empiriques fortement influencées par la salinité, la texture et la structure du sol, ce qui limite leur robustesse et leur stabilité dans le temps.

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Ce travail étudie la spectroscopie d'impédance électrique (EIS) à large bande dans la gamme de fréquences intermédiaires (1 kHz–10 MHz) comme approche fondée sur la physique pour une caractérisation multiparamétrique du sol. Une modélisation diélectrique analytique, combinée à des approximations de milieu effectif, a servi à évaluer l'influence couplée de la teneur volumique en eau, de la salinité de l'eau interstitielle et de la porosité sur le spectre complexe de permittivité diélectrique. Les résultats simulés prédisent que chaque paramètre produit une signature spectrale distincte : l'humidité et la salinité induisent des déplacements caractéristiques des pics de polarisation, tandis que la porosité modifie principalement l'amplitude spectrale, avec un déplacement des pics comparativement limité.

Afin d'évaluer expérimentalement ces prédictions, une plateforme de mesure d'impédance à large bande sans contact a été mise au point et testée sur des sols agricoles dans des conditions contrôlées de laboratoire. Les mesures préliminaires ont reproduit les principaux comportements spectraux prédits par le cadre analytique, montrant un accord qualitatif entre les simulations et les expériences malgré les écarts persistants liés aux hypothèses simplifiées de milieu effectif.

Ces résultats confirment la faisabilité de la modélisation spectrale inverse pour estimer simultanément plusieurs propriétés physiques du sol à partir d'une seule mesure diélectrique à large bande. Les travaux en cours portent sur des expériences automatisées de validation à haut débit et sur le développement d'une plateforme mobile de détection in situ destinée aux mesures agricoles à l'échelle du terrain.

Mots-clés : Gestion efficace du sol et de l'eau; Humidité du sol; Conditions contrôlées de laboratoire Mesure diélectrique; Mesures agricoles.

1. INTRODUCTION

Irrigation remains the primary consumer of water globally, with agriculture accounting for 72% of all freshwater withdrawals worldwide (FAO 2025). Soil and water management is therefore essential to improve irrigation practices (scheduling, irrigation amount) to achieve global food security and climate-resilience under changing environmental regimes. In-situ sensors offer the opportunity to monitor real-time variations of soil's physical properties, providing valuable insights to support decision-making at the plot and farm scales. However, soil variables such as soil moisture are generally not measured directly, instead they are inferred from bulk electrical sensor responses. In agricultural soils, variables including water content, salinity, texture and pore structure jointly control the bulk electromagnetic behavior of the medium (Friedman 2005, Corwin and Lesch, 2005). Accounting for this coupled influence is therefore essential for the reliable interpretation of sensor data in agricultural water management.

Most commercial soil moisture probes operate on single frequency electromagnetic or dielectric principles (such as Time Domain Reflectometry TDR or Frequency Domain Reflectometry FDR operating on the order of 100 MHz) and use empirical conversion relationships to translate measured relative permittivity (ϵ_a) into soil moisture. Consequently, appropriate soil-specific calibration that take into account soil texture, temperature and salinity is required for accurate and reliable field measurements (Mane et al. 2024). While targeted calibrations can drastically minimize absolute measurement errors, they demand a considerable investment of time and their long-term temporal stability has yet to be established.

In active agricultural environments, regular anthropogenic interventions such as tillage and machinery compaction, paired with natural wetting-drying cycles and biological root activity, continuously alter the soil's structural porosity (ϕ) and pore geometry (Pagliai et al. 2004). Fertilisation and irrigation practices, as well as the evaporation process, also affect the dynamics of salt concentration in the soils. Consequently, static calibration curves suffer from temporal drift, demanding labor-intensive periodic reassessment that hinders widespread sensor deployment. This article argues that evaluating soil moisture, salinity, texture, and structural porosity simultaneously rather than as isolated, independent variables could provide a pathway towards a multiparametric soil health sensor.

Broadband Electrical Impedance Spectroscopy (EIS) in the intermediate frequency domain, extending approximately from 1 kHz to 10 MHz, offers a powerful physics-based alternative to conventional empirical methods. By mapping the frequency-dependent complex impedance spectrum of the soil matrix, this method exploits the specific frequency windows where interfacial polarization and surface conduction mechanisms are relevant and sensitive to the above-mentioned soil physical parameters.

2. METHODS

2.1 Theoretical Foundations of Broadband Electrical Impedance Spectroscopy

2.1.1 Complex Impedance and Non-Contact Capacitive Sensing

To evaluate the electrical behavior of the soil matrix, a complex impedance measurement is conducted using insulated planar electrodes. Instead of injecting a direct physical current via invasive, corrosion-prone pins, the non-contact sensor establishes a localized alternating (AC) electric field that penetrates the soil medium across an insulating layer. Under this configuration, the sensor-soil coupling is modeled as a lossy, or “leaky” capacitor. The fundamental physical response of this system to an applied angular frequency (ω) is quantified by its complex impedance, $Z^*(\omega)$, formulated as:

$$Z^*(\omega) = \frac{1}{j\omega C^*(\omega)} \quad (1)$$

Where j is the imaginary unit satisfying $j^2 = -1$, $\omega = 2\pi f$ is the angular frequency, and $C^*(\omega)$ is the complex capacitance of the coupled system. The complex capacitance directly mirrors the spatial and physical configuration of the target medium, yielding:

$$C^*(\omega) = \varepsilon^*(\omega)C_0 \quad (2)$$

Where C_0 is the geometric capacitance of the sensor in vacuum, and $\varepsilon^*(\omega)$ is the complex relative dielectric permittivity of the soil. Combining these expressions gives:

$$Z^*(\omega) = \frac{1}{j\omega \varepsilon^*(\omega)C_0} \quad (3)$$

In practice, additional de-embedding procedures are required to compensate for parasitic contributions and the capacitance of the insulating layer, particularly for planar electrode configurations.

2.1.2 The Intermediate Frequency Spectrum and Maxwell-Wagner Polarization

The complex dielectric permittivity can be decomposed into its real and imaginary components:

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) \quad (4)$$

In the intermediate frequency range utilized by this methodology (1 kHz to 10 MHz), the dielectric response of soils is strongly governed by Maxwell-Wagner (MW) interfacial polarization and surface conduction mechanisms (Revil, 2014). It is known in the hydro-geophysics as β -polarization. These phenomena arise at interfaces between phases with contrasting electrical properties, particularly between mineral grains, air voids, and conductive pore water.

Under an alternating electric field, ions accumulate at these interfaces, producing frequency-dependent dielectric and conductive responses observable in both ε' and ε'' . The magnitude and characteristic frequency of these relaxation mechanisms are influenced by soil moisture, pore-water salinity, texture, and pore geometry. Consequently, the intermediate frequency dielectric spectrum contains physically meaningful information related to the structural and hydraulic state of the soil matrix.

2.1.3 Contextual Placement: EIS vs. Prevalent Agricultural Geophysics

The multi-parametric sensitivity of intermediate-frequency dielectric spectroscopy can be contextualized relative to the three most prevalent geophysical methods deployed in agricultural settings across peer-reviewed literature, patents, and the US university extension literature (Becker et al. 2025): Electrical Resistivity (ER), Electromagnetic Induction (EMI), and Visible and Near-Infrared (Vis-NIR) spectroscopy.

Conventional ER and EMI methods are frequently used to estimate bulk electrical conductivity or apparent dielectric properties of soils. However, these measurements are often performed over limited frequency ranges, making it difficult to fully distinguish the coupled influences of moisture, salinity, texture, and soil structure from a single aggregated response variable. Similarly, optical Vis-NIR techniques provide valuable information regarding surface soil composition and moisture conditions but remain primarily sensitive to near-surface measurements.

In contrast, broadband EIS exploits the frequency-dependent dielectric response of soils across the intermediate frequency range (1 kHz–10 MHz). By jointly analyzing the real and imaginary components of the complex dielectric permittivity, EIS provides access to polarization and conductive mechanisms linked to pore-water salinity, volumetric water content, and soil structural properties. Consequently, broadband dielectric spectra may provide a pathway toward simultaneous multiparametric characterization of agricultural soils using a single sensing platform.

To interpret these coupled spectral responses, a physics-based analytical framework is required to relate the measured dielectric signatures to physically meaningful soil parameters.

2.2 Analytical Soil Modeling

Analytical dielectric modeling was used to interpret the coupled influence of soil moisture, salinity, texture, and porosity on the measured impedance spectra. Rather than relying on empirical calibration relationships, the proposed framework uses effective medium approximations (EMA) to relate complex dielectric permittivity to physically meaningful soil parameters. The modeling approach consists of three sequential steps progressing from individual phase properties to the effective response of the complete soil matrix.

2.2.1 Step 1: Dielectric Properties of Individual Phases

The first step defines the intrinsic dielectric permittivity behavior of the four principal phases composing an unsaturated agricultural soil: mineral grains, air, free pore water, and bound interfacial water. Mineral particles and air are treated as weakly conductive phases with approximately frequency-independent dielectric properties.

In contrast, the free-water and bound-water phases exhibit frequency-dependent complex permittivity responses. The free-water phase is primarily governed by pore-water ionic conductivity, providing a proxy for soil salinity. The bound-water phase represents water molecules adsorbed near mineral surfaces and clay platelets. Due to restricted molecular mobility and interfacial effects, bound water exhibits reduced permittivity and modified conductivity relative to free water, making it sensitive to soil texture and clay mineralogy.

2.2.2 Step 2: Dielectric Signature of Coated Soil Particle Inclusions

The second step incorporates interfacial soil structure by modeling soil grains as coated spherical inclusions consisting of a mineral core surrounded by a thin shell of bound water. The thickness of this interfacial layer is linked to soil texture and clay content.

The equivalent permittivity of these coated inclusions was calculated using Sihvola's analytical coated-sphere formulation (Sihvola, 1999). This approach combines the dielectric properties of the mineral core and bound-water shell into a single equivalent inclusion permittivity, enabling representation of interfacial polarization effects within the soil matrix.

2.2.3 Step 3: Modeling the Complete Soil Matrix Using Symmetric Bruggeman Mixing

In the final step, coated soil particles and air inclusions are embedded within a continuous free-water background medium using a symmetric Bruggeman effective medium approximation. The Bruggeman formulation accounts for interactions between the different phases and their volumetric distributions within the heterogeneous soil matrix.

Within this framework, porosity is represented through the relative volumetric fractions of the air and liquid phases, while volumetric water content is determined from the total liquid-phase fraction. The resulting effective complex permittivity therefore emerges directly from the physical composition and structure of the soil.

Although the full mathematical derivation detailing the exact emergence of these structural parameters from the effective medium approximation is beyond the scope of this paper, this three-step framework establishes a physically grounded basis for future inverse modeling and multiparametric soil sensing.

2.3 Experimental Methodology

To evaluate the validity of the analytical framework under controlled conditions, a validation set of experiments were conducted. The experimental methodology consisted of the development of a non-contact sample holder, and the independent variation of key soil parameters including volumetric water content, pore water salinity, and porosity.

2.3.1 Electronic Sensing Hardware and Sample Holder Design

The sensing platform consists of a custom cylindrical sample holder incorporating a circular interdigitated planar electrode geometry integrated into the base of the measurement cell (**Figure 1.**). The cell has an internal radius of 144 mm and is made of polymethyl methacrylate (PMMA) to provide mechanical rigidity and electrical insulation while minimizing conductive boundary effects. A 500 μm borosilicate glass disc was positioned above the electrode plane to electrically isolate the soil from direct electrode contact, thereby reducing electrochemical corrosion effects during repeated measurements. The planar electrode topology additionally preserves unobstructed access to the soil surface for controlled fluid dispensing supporting future integration into an automated test bench.

Complex impedance spectra were acquired using a Keithley 4200-SCS Parameter Analyzer operating across the intermediate-frequency range. To minimize parasitic impedance contributions, measurements were performed using a four-terminal pair configuration. The high-potential and high-current terminals were connected to one side of the electrode structure, while the low-potential and low-current terminals were connected to the opposing side.



Figure 1. 3D rendering of the soil sample holder

This configuration minimizes the influence of cable resistance, contact impedance, and lead parasitics, ensuring that the measured impedance response primarily reflects variations in the complex dielectric permittivity of the soil sample. (Figure 2.).

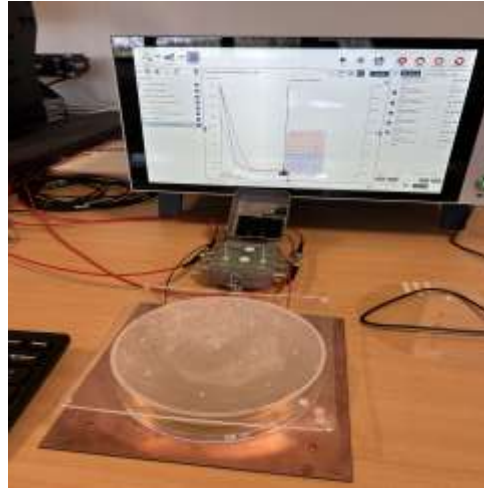


Figure 2. Sample holder measurement setup

2.3.2 Soil Samples

Two soil types collected from agricultural fields in southern France were used for experimental validation. Soil textures are reported according to GEPPA triangle classification (Mathieu et al., 1998). All experiments were conducted using 400 g soil samples.

The moisture sensitivity experiments were conducted using a sandy sand (Ss) soil collected from the Bourrian plot (4.5% clay, 10.9% silt, 84.6% sand) with a dry bulk density of 1.3 g/cm³.

The salinity and porosity experiments were conducted using sandy (S) soil (5.9% clay, 10.4% silt, 83% sand) with a bulk density of 1.2 g/cm³ collected from the Ferme des Lices site. The initial pore-water electrical conductivity of the soil was approximately 0.4 mS/cm.

2.3.3 Moisture Sensitivity Validation

To validate sensitivity to volumetric water content (VWC), incremental hydraulic loading experiments were performed on soil samples dried in the oven until complete dehydration. Water was added in 2.5% gravimetric increments corresponding to 10 g additions per 400 g dry soil sample. Mass measurements were performed using a precision balance with 0.01 g resolution.

Following each hydraulic increment, samples were allowed to equilibrate prior to measurement to promote uniform capillary redistribution within the soil matrix. Gravimetric water content values were subsequently converted to volumetric water content using the measured dry bulk density ($\theta = \omega_g \rho_g$ where θ is the volumetric water content, ω_g is gravimetric water content, and ρ_g is dry bulk density).

2.3.4 Preliminary Salinity Sensitivity Assessment

A preliminary evaluation of salinity sensitivity was conducted using two soil samples maintained at identical volumetric water content (10% VWC). One sample was prepared using distilled water, while the second was prepared using a saline solution with an electrical conductivity of 40 mS/cm obtained by dissolving sea salt in distilled water.

The resulting impedance spectra were compared to assess the sensitivity of the sensing platform to pore-water conductivity variations independent of bulk moisture content. The distilled-water sample additionally served as the electrical baseline reference for the measurements.

2.3.5 Preliminary Porosity Sensitivity Assessment

To investigate sensitivity to structural soil variations independently of fluid-content changes, two soil states with distinct porosities were prepared through controlled mechanical loosening and mixing.

The soil was mechanically agitated within a fixed-volume sample holder to increase the void fraction and reduce bulk density. Following mixing, the volumetric expansion of the soil caused excess material to rise above the fixed boundary of the sample ring.

This excess material was removed level with the container boundary and weighed, allowing the updated dry bulk density and corresponding porosity to be determined. The resulting samples exhibited approximate porosities of 43% and 51%, respectively and had a VWC of 10%. Impedance spectra acquired from both structural states were subsequently compared to evaluate the sensitivity of the dielectric response to porosity variations.

3. RESULTS & DISCUSSIONS

3.1 Analytical Modeling Spectral Predictions

To evaluate the distinct influence of the three parameters tested on the complex dielectric permittivity, the analytical model was simulated across the frequency range 10^3 to 10^7 Hz. The simulations indicate that each parameter produces a distinct modification of the complex permittivity spectrum rather than a uniform scaling response, suggesting that the parameters could be spectrally decoupled.

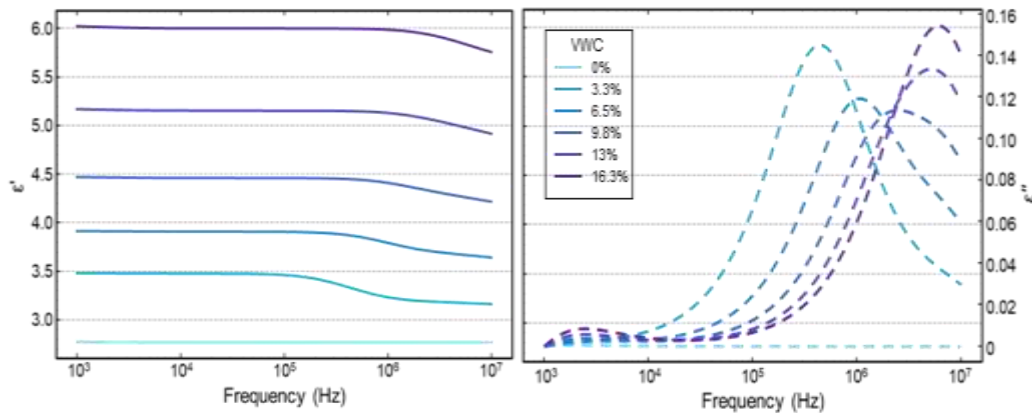


Figure 3. Simulated frequency response of complex dielectric permittivity at various soil moistures

Figure 3. presents the simulated dielectric response for volumetric water contents ranging from 0% to 16.3%. Increasing moisture content produces an increase in the real permittivity (ϵ') across the full frequency range. In the imaginary part (ϵ''), a dominant polarization peak is observed together with a secondary feature near 10^7 Hz. As moisture increases, the principal polarization peak progressively shifts toward higher frequencies, forming a characteristic spectral signature associated with water content variations.

The impact of varying soil salinity (0.04 mS/cm and 0.4 mS/cm) is presented in **Figure 4**. In contrast to moisture variations, salinity produces relatively limited changes in the low-frequency plateau of ϵ' . However, increasing salinity similarly shifts the dominant polarization peak of ϵ'' toward higher

frequencies. The combination of a comparatively stable low-frequency ε' response and a frequency-shifted ε'' peak constitutes the characteristic salinity signature predicted by the model.

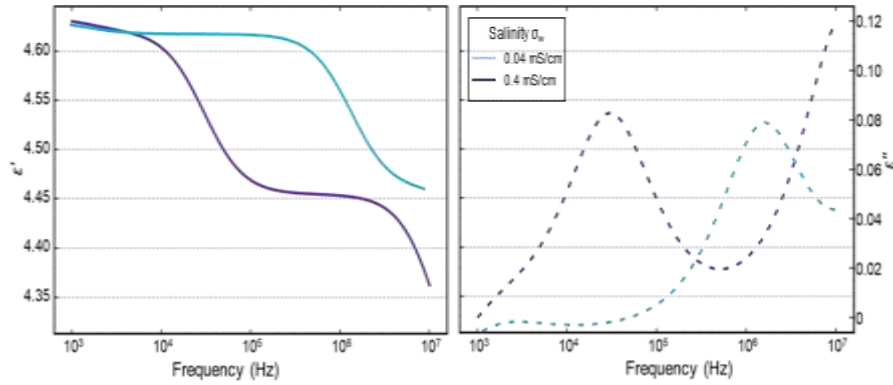


Figure 4. Simulated frequency response of complex dielectric permittivity at various salinities

Figure 5. Figure 5 illustrates the simulated response to porosity variations between 43% and 51%. Unlike moisture and salinity, porosity variations primarily affect the magnitude of both ε' and ε'' while producing minimal displacement of the polarization peak frequency. The absence of a significant peak-frequency shift distinguishes porosity from the two other investigated parameters.

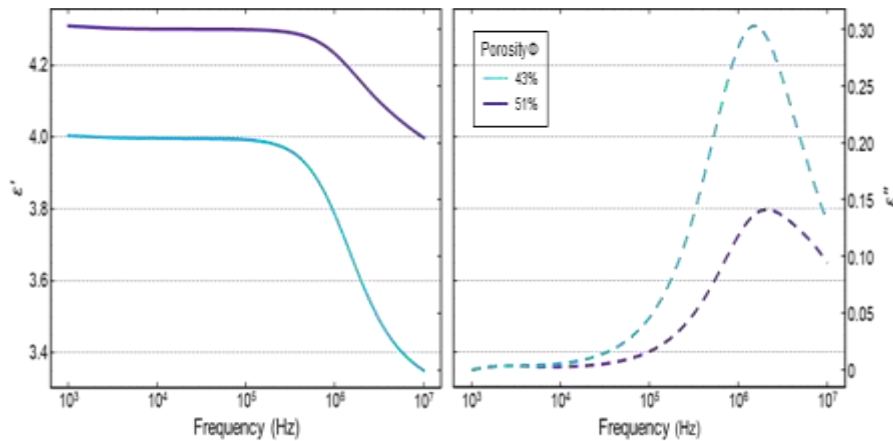


Figure 5. Simulated frequency response of complex dielectric permittivity at various porosities

Overall, the analytical model predicts that moisture, salinity, and porosity generate distinct spectral signatures within the complex permittivity response. Moisture simultaneously modifies the magnitude of ε' and shifts the polarization peak frequency. Salinity primarily alters the polarization peak position while maintaining a comparatively stable low-frequency ε' response. In contrast, porosity predominantly modifies spectral amplitude without significantly shifting the polarization peak frequency. These predicted spectral behaviors are subsequently compared against the experimental measurements.

3.2 Experimental Validation

3.2.1 Salinity Validation

Figure 6. compares the experimentally measured dielectric spectra with the analytical predictions for two pore-water salinity conditions (0.04 mS/cm and 0.4 mS/cm). Overall, strong qualitative agreement is observed between the modeled and measured responses. In particular, both datasets exhibit a

relatively stable low-frequency ϵ' response together with a salinity-dependent shift of the dominant ϵ'' polarization peak toward higher frequencies.

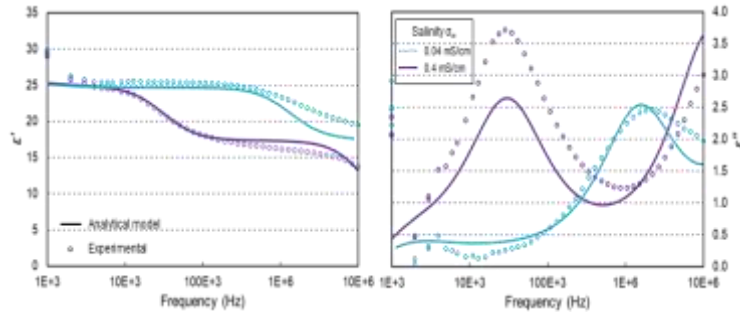


Figure 6. Simulated vs experimental frequency response of complex dielectric permittivity at various salinities

To facilitate comparison of the spectral behavior, the analytical permittivity amplitudes were normalized to the experimental range. Prior to normalization, the modeled real permittivity values remained within approximately 3–5, indicating that the present comparison primarily evaluates agreement in spectral quantitative shape and relaxation behavior rather than absolute permittivity magnitude.

Residual electrode polarization effects are additionally observable in the experimental low-frequency region, particularly below (2.10^3) Hz. These parasitic interfacial effects partially obscure the low-frequency plateau predicted by the analytical model. Ongoing correction and compensation of the electrode polarization contribution are expected to further improve agreement in the low-frequency domain. Despite these limitations, the experimental measurements reproduce the principal spectral trends predicted by the analytical framework, supporting the hypothesis that salinity variations produce a distinct and identifiable dielectric signature.

3.2.2 Soil Moisture Validation

Figure 7. compares the experimentally measured imaginary dielectric response with the analytical predictions for varying volumetric water contents. Consistent with the analytical model, increasing moisture content produces a progressive displacement of the dominant ϵ'' polarization peak toward higher frequencies.

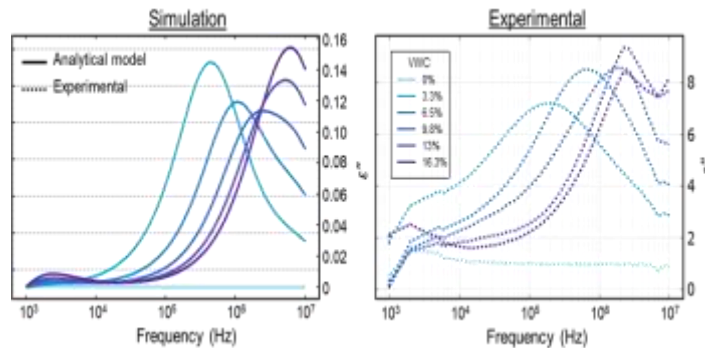


Figure 7. Simulated (left) vs experimental (right) frequency response of imaginary part of dielectric permittivity at various soil moistures

Although the experimental spectra exhibit broader peak distributions compared with the simulations, the overall spectral evolution remains consistent with the predicted behavior. In particular, the monotonic frequency shift of the relaxation peak with increasing volumetric water content is preserved

experimentally, supporting the hypothesis that moisture variations generate a distinct dielectric spectral signature. The secondary polarization feature at around 10^7 Hz is also visible in the experimental results.

3.2.3 Porosity Validation

Figure 8. presents the comparison between the simulated and experimental dielectric responses for two soil porosity conditions. In agreement with the analytical predictions, porosity variations primarily modify the amplitude of the dielectric response while producing comparatively limited displacement of the dominant polarization peak frequency.

The experimental measurements reproduce the predicted increase in ϵ'' magnitude associated with higher porosity, despite a small mismatch in the absolute frequency of the polarization. This behavior is consistent with the spectral signature predicted by the analytical model and contrasts with the peak-frequency shifts observed for salinity and moisture variations. For ϵ' , the experimental measurements reproduce the general spectral shape predicted by the model; however, a discrepancy is observed in the relative ordering of the two porosity states. Experimentally, the lower-porosity sample exhibits a larger ϵ' response, whereas the analytical model predicts the inverse trend. This inversion may indicate limitations of the current effective medium approximation (EMA), particularly near the percolation transition where the connectivity of the pore and solid phases strongly influences the effective dielectric response. Residual low frequency electrode polarization effects are also observable.

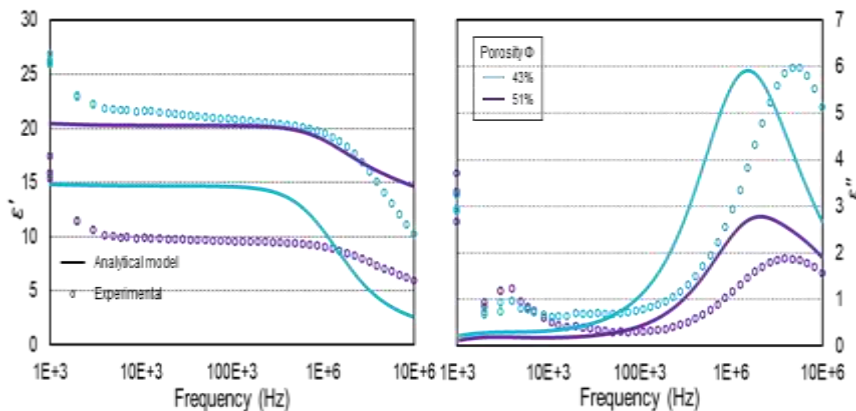


Figure 8. Simulated vs experimental frequency response of complex dielectric permittivity at various porosities

Given the preliminary nature of the porosity experiments and the limited number of structural states investigated, these results should primarily be interpreted as an initial validation of the predicted porosity-dependent spectral behavior.

CONCLUSION

In this preliminary study, an analytical broadband dielectric model was developed and experimentally evaluated for the coupled characterization of soil moisture, salinity, and porosity using non-contact Electrical Impedance Spectroscopy (EIS). Both the simulations and the laboratory measurements demonstrate that these parameters produce distinct modifications of the complex dielectric spectrum in the intermediate frequency range. In particular, moisture and salinity were shown to induce characteristic polarization peak shifts, while porosity primarily modified the spectral amplitude with comparatively limited peak displacement. Despite remaining discrepancies in absolute permittivity scaling and low-frequency parasitic effects, the experimental results reproduced the principal qualitative spectral behaviors predicted by the analytical framework, supporting the feasibility of spectral decoupling of multiple soil properties from a single broadband measurement.

The present work should however be regarded as an initial proof-of-concept validation rather than a complete quantitative characterization. The salinity and porosity experiments were limited to representative comparison states, and the current measurements remain affected by residual electrode polarization and experimental variability associated with manual sample preparation. Ongoing work is therefore focused on the development of an automated experimental test bench capable of performing repeatable experiments under controlled conditions. Such a platform will enable the acquisition of statistically robust datasets necessary to validate the analytical model not only qualitatively through spectral trend identification, as presented in this study, but also quantitatively through calibrated permittivity reconstruction and parameter estimation.

In parallel, a portable field-deployable version of the sensing platform is under development to investigate EIS measurements directly under real agricultural field conditions. Extending the methodology from controlled laboratory experiments to in-situ environments represents an important step toward practical multiparametric soil monitoring for irrigation and soil health management.

Ultimately, the proposed inverse modeling framework opens the possibility of developing a new type of broadband multiparametric soil sensors capable of simultaneously estimating moisture, salinity, and structural/textural soil properties from a single dielectric spectrum. Such an approach could contribute toward the development of new multiparametric soil health sensors to support ongoing agro-ecological transitions.

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