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# Influence of Exchangeable Sodium Percentage on Soil Dielectric Properties at C-Band Frequencies

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**Abstract**

Exchangeable Sodium Percentage (ESP) is a critical indicator of soil sodicity that strongly influences soil structure, chemical environment, and electromagnetic behavior, yet its role in controlling soil dielectric properties is rarely considered in microwave studies. This work investigates the effect of ESP on the complex dielectric permittivity of soils at C-band frequency (5.3 GHz) under controlled laboratory conditions. Soil samples spanning non-sodic to highly sodic classes were conditioned to a range of volumetric moisture contents, and the real (ε′) and imaginary (ε″) components of dielectric permittivity were measured using an open-ended coaxial probe technique. Results show that dielectric constant increases primarily with moisture content; however, at comparable moisture levels, soils with higher ESP consistently exhibit elevated ε′ values, particularly under wet conditions, due to sodium-induced structural changes and increased bound water contribution. More significantly, dielectric loss displays a strong and systematic dependence on ESP, increasing disproportionately with sodicity as a result of enhanced ionic conductivity and sodium mobility within the soil pore solution. The combined influence of moisture and ESP reveals threshold behavior, where sodicity-related conductive losses dominate dielectric response at moderate to high moisture levels. These findings demonstrate that sodicity-induced dielectric effects are independent of moisture alone and are not captured by conventional dielectric mixing models. The study highlights the need for ESP-aware dielectric parameterization to improve microwave modeling and soil characterization in salt-affected environments.

**Keywords:** Exchangeable Sodium Percentage, Dielectric Constant, Dielectric Loss, Sodic Soils, C-Band Microwave.

## 1. INTRODUCTION

Microwave interaction with soil is governed by the dielectric properties of the soil–water–air system, which control electromagnetic wave propagation, attenuation, and scattering in the near-surface layer. Soil dielectric behavior is described by its complex permittivity, consisting of a real component (ε′) that influences wave propagation and reflection, and an imaginary component (ε″) that represents dielectric loss due to energy dissipation. At microwave frequencies, small variations in dielectric permittivity lead to significant changes in electromagnetic response, making these parameters fundamental to microwave-based soil characterization.

At C-band frequencies (~5.3 GHz), widely used in soil studies, ε′ is strongly controlled by volumetric moisture content because of the high dielectric constant of water. As a result, ε′ is often treated as the primary parameter linking soil moisture to microwave response. However, ε″ also plays a critical role by regulating signal attenuation and penetration depth, particularly in chemically complex soils. Dielectric loss arises from dipolar relaxation of

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water molecules and conductive losses associated with ionic charge transport, and becomes increasingly important in soils affected by salinity or sodicity [1].

Soil sodicity, quantified by Exchangeable Sodium Percentage (ESP), causes significant structural and chemical changes in soils, including clay dispersion, aggregate breakdown, reduced pore connectivity, and increased ionic conductivity of the pore solution. These sodium-induced effects modify water distribution and enhance charge mobility, leading to dielectric responses that cannot be explained by moisture content alone. Nevertheless, conventional dielectric mixing models generally neglect ESP and assume chemically inert soil matrices.

This study addresses this limitation by experimentally investigating the influence of ESP on soil dielectric properties at C-band frequencies under controlled laboratory conditions. The effects of ESP on both $\varepsilon'$ and $\varepsilon''$ are quantified across a range of moisture contents, providing a dielectric-level understanding of sodicity-induced microwave behavior and supporting improved dielectric modeling of salt-affected soils.

## 2. MATERIALS AND METHODS

### 2.1 Soil Sampling and Classification

Soil samples were collected from agricultural fields exhibiting varying degrees of sodicity, representative of conditions commonly encountered in irrigated and semi-arid regions. Sampling was restricted to the surface layer, as this zone exerts the strongest control on microwave interaction and dielectric response at C-band frequencies. Surface soil samples were collected from a depth of 0–10 cm using a stainless-steel auger to minimize contamination and disturbance. At each sampling location, multiple subsamples were collected and composited to ensure spatial representativeness.

The collected soil samples were air-dried at ambient temperature and gently disaggregated to preserve intrinsic mineral characteristics while minimizing artificial alteration of soil structure. The dried samples were passed through a 2 mm sieve to remove coarse fragments, roots, and organic debris, thereby ensuring uniformity for laboratory dielectric measurements. This preparation protocol allowed consistent comparison of dielectric properties across samples while maintaining physicochemical characteristics relevant to sodicity-induced effects.

Standard laboratory analyses were performed to determine soil pH, electrical conductivity (EC), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), texture, and bulk density following established soil analysis procedures. Exchangeable sodium percentage was calculated as the ratio of exchangeable sodium to the soil cation exchange capacity and expressed as a percentage. Based on measured ESP values, the soils were classified into four sodicity categories: non-sodic, low sodic, moderately sodic, and highly sodic. This classification enabled systematic evaluation of the progressive influence of sodium dominance on soil dielectric behavior [2].

The physicochemical properties corresponding to each ESP class are summarized in **Table 1**. The table highlights the systematic increase in ESP, SAR, pH, and electrical conductivity across the soil classes, accompanied by textural and bulk density variations characteristic of sodic soil development. These properties provide the baseline framework for interpreting subsequent variations in dielectric constant and dielectric loss as a function of soil sodicity.

Table 1. Physicochemical Properties of Soil Samples across Different Exchangeable Sodium Percentage (ESP) Classes

| Soil Class | ESP (%) | SAR ($mmol^{1/2}$ $L^{-1/2}$) | pH (1:2.5) | EC (dS $m^{-1}$) | Texture | Bulk Density (g $cm^{-3}$) |
|---|---|---|---|---|---|---|

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| | | | | | | |
|---|---|---|---|---|---|---|
| Non-sodic | 3.8 ± 0.5 | 4.1 ± 0.6 | 7.4 ± 0.2 | 0.42 ± 0.05 | Sandy loam | 1.42 ± 0.03 |
| Low sodic | 8.6 ± 0.7 | 7.9 ± 0.8 | 7.9 ± 0.3 | 0.61 ± 0.07 | Loam | 1.39 ± 0.04 |
| Moderately sodic | 15.4 ± 1.1 | 13.6 ± 1.2 | 8.4 ± 0.3 | 0.88 ± 0.09 | Clay loam | 1.35 ± 0.05 |
| Highly sodic | 23.8 ± 1.6 | 21.9 ± 1.8 | 9.1 ± 0.4 | 1.21 ± 0.12 | Clay | 1.31 ± 0.06 |

### 2.2 Sample Preparation and Moisture Conditioning

Following collection and initial characterization, soil samples were air-dried at ambient laboratory temperature to remove residual moisture while preserving intrinsic mineral and chemical properties. The dried samples were gently crushed using a wooden mortar and pestle to break down large aggregates without altering particle size distribution. All samples were then passed through a 2 mm sieve to remove coarse fragments and organic residues, ensuring uniformity and reproducibility in subsequent dielectric measurements.

Prepared soil samples were conditioned to predefined volumetric moisture contents to examine the combined influence of moisture and Exchangeable Sodium Percentage on dielectric behavior. Distilled water was added gravimetrically to achieve target moisture levels ranging from 5% to 30%, with increments of 5%, consistent with the experimental conditions reported in the study. After water addition, the samples were thoroughly mixed to ensure homogeneous moisture distribution and sealed in airtight containers to prevent evaporation.

The moisture-conditioned samples were allowed to equilibrate for a minimum of 24 hours at controlled laboratory temperature (25 ± 1 °C). This equilibration period ensured uniform redistribution of water within the soil matrix and stabilization of physicochemical interactions prior to dielectric measurements [3]. The gravimetric method was used to verify moisture content before testing, thereby minimizing uncertainty associated with moisture heterogeneity. This standardized preparation and conditioning protocol enabled consistent comparison of dielectric properties across soils with different sodicity levels.

### 2.3 Dielectric Measurement Technique

Dielectric measurements were carried out under carefully controlled laboratory conditions using the open-ended coaxial probe technique coupled with a Vector Network Analyzer (VNA). This technique is widely recognized for accurately determining the complex dielectric permittivity of soils at microwave frequencies due to its non-destructive nature, rapid response, and suitability for heterogeneous materials. It enables simultaneous measurement of the real ($\varepsilon'$) and imaginary ($\varepsilon''$) components of dielectric permittivity, which are critical for understanding microwave propagation, scattering, and attenuation mechanisms in soils.

Prior to data acquisition, the measurement system was calibrated using standard open, short, and load calibration procedures to ensure accurate reflection coefficient estimation across the selected frequency range [4]. Calibration was performed before each measurement session to minimize systematic errors arising from cable losses, probe–sample contact variations, and environmental fluctuations. All measurements were conducted at a controlled temperature of 25 ± 1 °C to maintain consistency and repeatability in dielectric response.

Dielectric characterization was performed in the C-band microwave frequency range (4–8 GHz), with a central frequency of 5.3 GHz, closely matching the operational frequency of Sentinel-1 SAR systems. The selected frequency range ensures direct applicability to microwave remote sensing studies while retaining sensitivity to near-surface soil dielectric

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variations. A frequency resolution of 0.05 GHz was maintained to capture detailed spectral variations within the band.

As shown in Table 2, the volumetric moisture content of soil samples was varied systematically from 5% to 30% in increments of 5%, using the gravimetric water addition method to ensure precise moisture control. After water addition, samples were allowed to equilibrate to achieve uniform moisture distribution throughout the matrix. Soil samples were prepared by air-drying and sieving through a < 2 mm mesh to ensure homogeneity and eliminate large aggregates that could affect probe contact and measurement consistency. To ensure statistical robustness and minimize experimental uncertainty, each measurement at every moisture level was performed with a minimum of three replicates (≥ 3) [5].
Together, the parameters summarized in Table 2 establish a standardized and reproducible framework for evaluating soil dielectric behavior under controlled C-band microwave conditions.

Table 2. Experimental Conditions and Dielectric Measurement Parameters Used in the Study

| Parameter | Specification |
|---|---|
| Microwave frequency band | C-band (4–8 GHz) |
| Central frequency | 5.3 GHz |
| Dielectric measurement technique | Open-ended coaxial probe |
| Instrumentation | Vector Network Analyzer |
| Frequency resolution | 0.05 GHz |
| Volumetric moisture range | 5–30% |
| Moisture increment | 5% |
| Moisture equilibration method | Gravimetric water addition |
| Measurement temperature | 25 ± 1 °C |
| Sample preparation | Air-dried, sieved (< 2 mm) |
| Number of replicates | ≥ 3 |

**2.4 Data Quality Control and Replication**
To ensure reliability and reproducibility of dielectric measurements, all experiments were conducted with a minimum of three independent replicates for each combination of soil sample, moisture level, and Exchangeable Sodium Percentage class. Replicate measurements were performed by repositioning the open-ended coaxial probe on freshly prepared sample surfaces to minimize local heterogeneity effects and probe–soil contact variability. The reported dielectric parameters represent mean values derived from these replicate measurements.
All measurements were carried out under controlled laboratory conditions, with temperature maintained at 25 ± 1 °C throughout the experimental period. Temperature stability was ensured because dielectric permittivity, particularly the imaginary component, is sensitive to thermal variations that influence dipolar relaxation and ionic conductivity. Samples were allowed to equilibrate thermally prior to measurement to avoid transient temperature-induced fluctuations in dielectric response [6].
Measurement uncertainty was evaluated using standard statistical error estimation procedures. The variability associated with replicate measurements was quantified by calculating the standard deviation for both the real and imaginary components of dielectric permittivity. Instrumental uncertainty related to calibration and frequency resolution was minimized through repeated calibration and consistent measurement protocols. These quality control measures ensured that observed variations in dielectric properties could be

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confidently attributed to differences in moisture content and Exchangeable Sodium Percentage rather than experimental artifacts.

## 3. RESULTS AND DISCUSSION

### 3.1 Effect of ESP on Dielectric Constant (ε′)

The dielectric constant (ε′) of soil exhibited a strong dependence on volumetric moisture content across all Exchangeable Sodium Percentage (ESP) classes [7]. As moisture increased from dry to wet conditions, ε′ increased systematically, reflecting the dominant contribution of liquid water to microwave propagation at C-band frequencies. This trend was consistent for non-sodic, low sodic, moderately sodic, and highly sodic soils, confirming that soil moisture remains the primary driver of ε′ variations.

However, at comparable moisture levels, soils with higher ESP consistently exhibited higher dielectric constant values than non-sodic soils. This divergence became increasingly pronounced at moderate to high moisture contents. Under relatively dry conditions, differences in ε′ among ESP classes were small, whereas under wetter conditions the separation between curves corresponding to different ESP levels increased significantly [8]. These results indicate that sodicity modifies the effective dielectric response of soil beyond the influence of moisture alone, particularly when sufficient water is present to interact with the altered soil matrix.

The enhanced dielectric constant observed in high-ESP soils can be attributed to sodium-induced changes in soil microstructure and water distribution. Elevated ESP promotes clay dispersion and breakdown of soil aggregates, leading to increased specific surface area and reduced macroporosity. These structural changes enhance the proportion of bound water relative to free water within the soil. Bound water exhibits restricted molecular mobility and altered dielectric relaxation behavior compared to free water, contributing to higher apparent dielectric constants at microwave frequencies. Additionally, dispersed clay particles increase the interfacial polarization effects within the soil–water system, further elevating ε′ values in sodic soils.

The combined influence of moisture and ESP on dielectric constant demonstrates that sodicity acts as a secondary but significant modifier of soil dielectric behavior at C-band frequencies [9]. These findings suggest that conventional dielectric mixing models, which primarily link ε′ to volumetric moisture content, may not fully capture the dielectric response of sodic soils, particularly under wet conditions where sodium-induced structural effects are most pronounced.

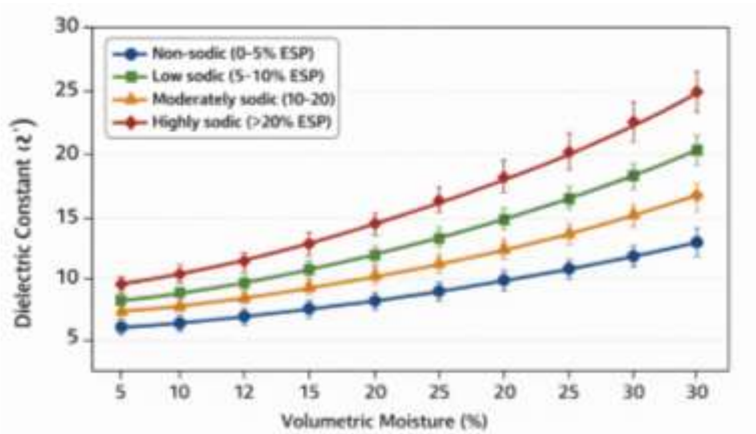


Figure 1. Dielectric Constant Variation with Moisture and ESP

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Figure 1 shows the variation of dielectric constant (ε′) with volumetric moisture content for soils classified into non-sodic (0–5% ESP), low sodic (5–10% ESP), moderately sodic (10–20% ESP), and highly sodic (>20% ESP) categories. The dielectric constant increases nonlinearly with increasing moisture content (5–30%) for all soil types, reflecting the dominant contribution of water to bulk soil permittivity at microwave frequencies. At each moisture level, ε′ values are consistently higher for soils with greater ESP, indicating that sodicity enhances dielectric response. Highly sodic soils exhibit the steepest increase and the highest ε′ values across the entire moisture range, while non-sodic soils show the lowest values. This trend suggests that increased sodium concentration influences soil structure, ionic mobility, and bound water polarization, thereby amplifying dielectric polarization mechanisms. The presence of error bars further indicates good measurement repeatability, with limited variability among replicates. Overall, the figure demonstrates a clear combined effect of moisture content and ESP on soil dielectric behavior under C-band microwave conditions.

### 3.2 Influence of ESP on Dielectric Loss (ε″)

Dielectric loss (ε″) exhibited a pronounced and systematic dependence on Exchangeable Sodium Percentage across all moisture conditions. For all soil classes, ε″ increased with increasing volumetric moisture content, reflecting enhanced dipolar relaxation and conductive loss mechanisms in wetter soils. However, at comparable moisture levels, soils with higher ESP consistently showed substantially higher dielectric loss than non-sodic soils, indicating that sodicity exerts a strong control on microwave energy dissipation independent of moisture alone [10].

The strong ESP dependence of ε″ is primarily attributed to increased ionic conductivity associated with elevated sodium concentrations in the soil exchange complex and pore solution. In sodic soils, sodium ions exhibit high mobility and contribute to enhanced charge transport under an applied electromagnetic field. This increased ionic movement leads to greater conversion of electromagnetic energy into heat, thereby increasing dielectric loss at C-band frequencies. The effect becomes more pronounced at moderate to high moisture contents, where sufficient pore water is available to facilitate ionic conduction.

A clear contrast in dielectric loss behavior was observed between non-sodic and highly sodic soils. Non-sodic soils exhibited relatively low ε″ values across the entire moisture range, with dielectric loss primarily governed by dipolar relaxation of water molecules. In contrast, highly sodic soils showed disproportionately high ε″ values even at moderate moisture levels, highlighting the dominant role of sodium-induced conductive losses. This divergence indicates that dielectric loss in sodic soils cannot be explained solely by moisture-driven mechanisms and underscores the importance of exchangeable sodium as a first-order control on microwave attenuation.

These results demonstrate that dielectric loss is more sensitive to sodicity than the dielectric constant at C-band frequencies [11]. The enhanced ε″ observed in high-ESP soils provides a physical explanation for increased microwave attenuation and reduced penetration depth in sodic environments. Consequently, dielectric loss emerges as a critical parameter for accurately characterizing the electromagnetic behavior of sodic soils and for improving dielectric modeling approaches that extend beyond conventional moisture-based formulations.

The figure 2 confirms that dielectric loss is highly sensitive to exchangeable sodium content and that ε″ serves as a robust indicator of microwave attenuation in sodic soils. The strong dependence of dielectric loss on ESP highlights the need to incorporate sodicity parameters into dielectric modeling frameworks, particularly for C-band remote sensing applications.

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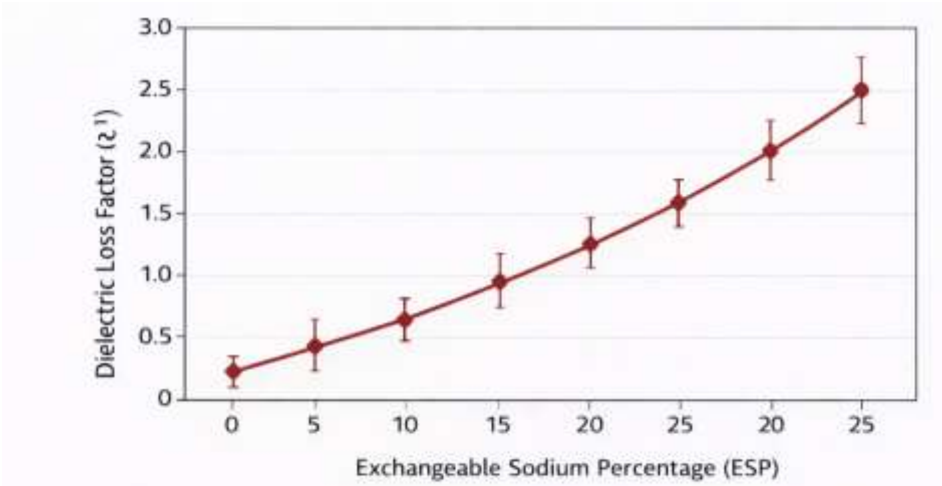


Figure 2. Dielectric Loss Response to Exchangeable Sodium Percentage

### 3.3 Combined Influence of Moisture and ESP

The combined influence of volumetric moisture content and Exchangeable Sodium Percentage on soil dielectric behavior revealed strong interaction effects that were not evident when considering either factor independently. While increasing moisture led to higher dielectric constant (ε′) and dielectric loss (ε″) across all soil classes, the magnitude of these increases was strongly modulated by ESP [12]. At low moisture levels, differences in dielectric properties among ESP classes were relatively small, indicating that moisture availability limited sodium-related effects on dielectric response.

As moisture content increased, the influence of ESP became progressively more pronounced. At moderate to high moisture levels, soils with elevated ESP exhibited disproportionately higher ε′ and, more notably, ε″ compared to non-sodic soils. This behavior suggests the presence of a threshold ESP effect under wetter conditions, beyond which sodium-induced structural degradation and ionic conduction mechanisms dominate the dielectric response. In highly sodic soils, the availability of pore water enhances sodium mobility and interfacial polarization, leading to accelerated increases in dielectric loss relative to dielectric constant.

The interaction between moisture and ESP has important implications for microwave energy dissipation mechanisms in sodic soils. Under wet conditions, increased pore connectivity combined with high sodium concentration facilitates ionic charge transport, resulting in substantial conductive losses and reduced electromagnetic penetration depth. Consequently, energy dissipation in sodic soils is governed not only by dipolar relaxation of water molecules but also by ESP-driven conductive processes [13]. These findings highlight that dielectric behavior in sodic soils is controlled by a coupled moisture–chemical regime, underscoring the need to account for ESP-dependent effects in dielectric modeling and microwave interpretation.

Table 3 illustrates the combined effect of volumetric moisture content and Exchangeable Sodium Percentage (ESP) on the dielectric constant (ε′) and dielectric loss (ε″) of soils measured at 5.3 GHz (C-band). The data show that both ε′ and ε″ increase consistently with increasing moisture content (10–30%) across all soil classes, reflecting enhanced polarization and conductive mechanisms in wetter soils. However, at comparable moisture levels, soils with higher ESP exhibit noticeably higher dielectric constant and substantially greater dielectric loss than non-sodic soils. For example, at 30% moisture, ε′ increases from 21.4 in non-sodic soil to 26.3 in highly sodic soil, while ε″ rises more sharply from 1.36 to 2.89, indicating a stronger sensitivity of dielectric loss to sodicity. This trend demonstrates that elevated sodium concentration enhances ionic conductivity and microwave energy dissipation beyond moisture-driven effects alone. Overall, the table highlights that soil dielectric

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behavior at C-band frequencies is governed by a coupled moisture–chemical regime, with ESP exerting a particularly strong influence on dielectric loss characteristics.

Table 3. Dielectric Constant (E′) and Dielectric Loss (E″) of Soils under Different Moisture and Exchangeable Sodium Percentage (ESP) Conditions at C-Band Frequency (5.3 GHz)

| Soil Class | ESP (%) | Moisture (%) | ε′ (Dielectric Constant) | ε″ (Dielectric Loss) |
|---|---|---|---|---|
| Non-sodic | 3.8 | 10 | 6.2 ± 0.4 | 0.38 ± 0.05 |
| | | 20 | 12.7 ± 0.6 | 0.82 ± 0.07 |
| | | 30 | 21.4 ± 0.9 | 1.36 ± 0.10 |
| Low sodic | 8.6 | 10 | 6.9 ± 0.5 | 0.54 ± 0.06 |
| | | 20 | 13.9 ± 0.7 | 1.05 ± 0.09 |
| | | 30 | 22.6 ± 1.0 | 1.74 ± 0.12 |
| Moderately sodic | 15.4 | 10 | 7.6 ± 0.6 | 0.79 ± 0.08 |
| | | 20 | 15.2 ± 0.8 | 1.48 ± 0.11 |
| | | 30 | 24.1 ± 1.1 | 2.21 ± 0.15 |
| Highly sodic | 23.8 | 10 | 8.4 ± 0.7 | 1.12 ± 0.10 |
| | | 20 | 16.8 ± 0.9 | 1.96 ± 0.14 |
| | | 30 | 26.3 ± 1.3 | 2.89 ± 0.18 |

### 3.4 Implications for Dielectric Modeling

The results of this study demonstrate that standard dielectric mixing models, which primarily relate soil dielectric permittivity to volumetric moisture content, mineral composition, and bulk density, are insufficient for accurately representing the dielectric behavior of sodic soils. These models generally assume that the soil matrix is chemically inert and that dielectric loss is governed mainly by dipolar relaxation of water molecules. While such assumptions may hold for non-sodic soils, they fail in sodic environments where exchangeable sodium introduces additional mechanisms of energy dissipation that are not captured by conventional formulations.

The strong dependence of dielectric loss on Exchangeable Sodium Percentage observed in this study highlights a fundamental limitation of moisture-only dielectric parameterizations. Elevated ESP enhances ionic conductivity and promotes sodium mobility within the pore solution, leading to significant conductive losses at microwave frequencies. Furthermore, sodium-induced dispersion of clay particles alters soil microstructure and increases the proportion of bound water, modifying both the real and imaginary components of dielectric permittivity. These effects result in dielectric responses that deviate systematically from predictions based solely on moisture-driven mixing models, particularly under moderate to high moisture conditions [14].

These findings underscore the need for ESP-aware dielectric parameterization schemes that explicitly account for sodicity-related effects. Incorporating ESP-dependent terms into dielectric models would enable improved representation of conductive loss mechanisms and interfacial polarization effects in sodic soils. Such parameterizations could be implemented by linking dielectric loss to measurable chemical indicators, such as ESP or ionic conductivity, in addition to volumetric moisture content. This approach would provide a more physically realistic description of soil dielectric behavior across a wider range of soil conditions.

From a broader theoretical perspective, the results have important implications for microwave remote sensing and electromagnetic modeling of land surfaces. Accurate representation of soil dielectric properties is fundamental to interpreting microwave propagation, attenuation, and scattering processes [15]. By demonstrating that sodicity significantly alters dielectric

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behavior at C-band frequencies, this study emphasizes that soil chemical properties must be considered alongside physical factors in electromagnetic theory applied to natural soils. Incorporating ESP-aware dielectric formulations will improve the physical consistency of microwave models and enhance their applicability in chemically complex soil environments.

## 4. CONCLUSION

This study demonstrates that Exchangeable Sodium Percentage is a first-order control on the dielectric behavior of soils at C-band microwave frequencies. While volumetric moisture content remains the dominant factor influencing the real part of dielectric permittivity, the results clearly show that increasing ESP leads to a pronounced enhancement in dielectric loss, even under comparable moisture conditions. This finding establishes sodicity as a critical factor governing microwave energy dissipation in soils.

The rate of increase in dielectric loss with ESP was consistently greater than the corresponding increase in dielectric constant, indicating that sodicity exerts a stronger influence on attenuation mechanisms than on wave propagation. Elevated sodium concentrations enhance ionic conductivity and charge mobility within the soil matrix, resulting in disproportionately higher conductive losses relative to moisture-driven dielectric polarization. This behavior becomes particularly pronounced at moderate to high moisture levels, where sufficient pore water is available to facilitate sodium transport.

Importantly, the observed sodicity-induced dielectric effects cannot be explained by moisture content alone. Soils with similar volumetric moisture but different ESP values exhibited markedly different dielectric responses, highlighting the independent role of exchangeable sodium in modifying soil electromagnetic behavior. These results demonstrate that conventional moisture-based dielectric descriptions are inadequate for characterizing sodic soils.

The findings have significant implications for microwave modeling and soil characterization. Accurate representation of soil dielectric properties requires explicit consideration of sodicity-related effects, particularly dielectric loss mechanisms associated with ionic conductivity and structural degradation. Incorporating ESP-aware dielectric parameterization into microwave models will improve the physical realism of electromagnetic simulations and enhance the interpretation of microwave measurements over salt-affected soils.

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**Conflict of Interest Statement**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

**Informed Consent**

All participants were informed about the purpose of the study, and their voluntary consent was obtained prior to data collection.

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**Ethical Approval**

The study was conducted in compliance with the ethical principles outlined in the Declaration of Helsinki and approved by the relevant institutional authorities.

**Data Availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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