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Dielectric Properties of Sodic Soils at C-Band: Analysis of Permittivity, Loss Tangent, and Conductivity

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Abstract: This study investigates the dielectric properties of sodic soils at C-band microwave frequency using laboratory-based measurements on samples collected from ten locations in Maharashtra, India. Dielectric parameters including the real (ε′) and imaginary (ε″) parts of permittivity, conductivity (σ), resistivity (ρ), loss tangent (tan δ), and penetration depth (δp) were analyzed. Results showed that ε′ ranged from 3.30 to 4.18 and ε″ from 0.49 to 1.08, influenced by soil texture, moisture, and sodium concentration. Higher dielectric loss and lower δp were observed in crusted and compact soils, while granular soils exhibited deeper wave penetration and lower energy dissipation. The study revealed strong inverse relationships between conductivity and resistivity, consistent with existing models. Findings were compared with established dielectric models and remote sensing studies, confirming the relevance of C-band SAR for soil salinity monitoring. This work provides valuable baseline data for enhancing microwave remote sensing algorithms in sodic and semi-arid landscapes.

Keywords: *Sodic Soils, Dielectric Properties, C-band Microwave Frequency, Soil Salinity Monitoring, Remote Sensing*

I. INTRODUCTION

Soil plays a critical role in sustaining agricultural productivity, regulating water cycles, and maintaining ecological balance. In India, especially in semi-arid regions like Marathwada and Vidarbha, the prevalence of sodic soils, characterized by high sodium ion concentrations, poor structural stability, and low infiltration capacity, poses a significant challenge to crop productivity and sustainable farming. Sodic soils disrupt water retention, nutrient mobility, and microbial activity due to the dispersion of clay particles and alkalinity-induced degradation. These physico-chemical alterations directly influence the dielectric behaviour of soil, which is a key parameter for non-destructive monitoring through microwave remote sensing. The dielectric properties, namely the real part of the permittivity (ε′), which indicates energy storage capability, and the imaginary part (ε″), which relates to energy dissipation, are essential for quantifying moisture content, salinity levels, and structural integrity in soils. Remote sensing systems operating in the C-band (4–8 GHz), such as Sentinel-1 and RISAT, are particularly suited for soil analysis due to their moderate penetration depth and sensitivity to moisture and ionic content. Previous studies, such as Wu et al. [1] and Dong et al. [2], have highlighted how dielectric behaviour varies in saline and sodic soils under controlled temperature and frequency conditions (approximately 5.29 GHz), with semi-empirical models proposed to improve accuracy in C-band applications. Romanov [3] and Li et al. [4] further demonstrated that the dielectric response is highly sensitive to sodium ion concentration, supporting the use of C-band SAR systems in identifying sodic degradation patterns. However, existing models are limited in representing the heterogeneity of Indian sodic soils. Thus, this study aims to measure and analyse the dielectric properties of sodic soils from various agro-climatic zones in Maharashtra using laboratory-based C-band analysis, establish correlations with physical characteristics like conductivity and texture, and generate a refined dataset to support remote sensing calibration and land degradation monitoring models.

II. MATERIAL AND METHODS

2.1 Site and Sample Collection

For this study, ten soil samples were collected from diverse agricultural regions in Maharashtra, India, with a particular focus on areas known to exhibit sodic soil conditions. The selected locations span across Aurangabad, Jalna, Beed, and Parbhani districts, each offering unique soil textures and moisture conditions influenced by regional variations in climate, topography, and land use. The GPS coordinates of the sampling points were recorded using a handheld device. Soil was visually observed in the field and characterized based on its texture, surface crusting, and colour. These observations serve as preliminary indicators of sodicity, later validated through dielectric and electrical measurements in the laboratory. The collected soils were stored in airtight containers and transferred for laboratory analysis under controlled temperature and humidity conditions.

Table 1: Sample Locations with GPS Coordinates and Site Descriptions

Sr. No.	Location	Latitude	Longitude	District
1	Nhava	19.93117	76.05412	Aurangabad
2	Jintur	19.63646	76.69244	Parbhani
3	Ambad	19.58881	75.78718	Jalna
4	Bidkin	19.67563	75.32405	Aurangabad
5	Phulambri	20.06451	75.69532	Aurangabad
6	Khultabad	19.97686	75.11620	Aurangabad
7	Vaijapur	19.87761	74.80963	Aurangabad
8	Dhondalgaon	19.94116	74.92785	Aurangabad
9	Sakharkharda	20.16667	76.38631	Buldhana
10	Lonar	20.03589	76.68835	Buldhana

2.2 Field Conditions and Soil Texture Observations

The field investigation was conducted at ten selected locations exhibiting visible characteristics associated with sodic soil conditions. During sampling, soil surfaces were visually examined and classified based on their texture and reflectance. Most sites displayed typical sodic features, such as granular surface aggregates, hard crust formation, and powdery-white reflective patches, indicating the presence of excess sodium and poor structural stability. The soil from Bidkin and Ambad, for example, appeared compacted with a fine crust layer, while sites like Sakharkharda and Phulambri exhibited slightly granular textures with moderate reflectance. At Dhondalgaon and Vaijapur, a loose top layer was observed, likely resulting from repeated desiccation and dispersion of fine clay particles.

These field-level observations provide essential context for the interpretation of dielectric measurements, as surface conditions such as granulation, compaction, and salt crusting directly influence the real and imaginary components of the soil’s dielectric response.

Figure 1: (a) Crusted sodic soil sample with salt efflorescence from Mehkar, (b) granular sodic soil surface at Butkheda, and (c) dispersive sodic clay structure under sunlight at Khorad Sawangi, Mantha

2.3 Experimental Setup and Dielectric Measurements

Dielectric measurements of the collected soil samples were carried out using the Von Hippel method, a widely recognized technique for assessing complex permittivity in granular and powdery materials. The experimental configuration consisted of a microwave generator, a dielectric test cell integrated into a waveguide system, and a vector network analyser calibrated for C-band operation (approximately 4–8 GHz). Soil samples were compacted into the waveguide cell and measurements were conducted under controlled conditions to maintain consistent temperature and moisture levels.

From the measured values of ε' and ε'', several secondary electromagnetic parameters were derived to further characterize the dielectric behaviour of sodic soils:

Angular frequency : $\omega = 2\pi f$ [6]

Complex permittivity : $\varepsilon^* = \varepsilon' - j\varepsilon''$ [7]

Magnitude of ε* : $|\varepsilon^*| = \sqrt{(\varepsilon'^2 + \varepsilon''^2)}$ [9]

Loss tangent : $\tan\delta = \varepsilon'' / \varepsilon'$ [10]

Phase angle (θ) : $\theta = \tan^{-1}(\varepsilon'' / \varepsilon')$ [11]

Quality factor : $Q = 1 / \tan\delta$ [12]

Conductivity (σ) : $\sigma = \omega \times \varepsilon'' \times \varepsilon_0$ [13]

Resistivity (ρ) : $\rho = 1 / \sigma$ [14]

Penetration depth (δp) : $\delta p = (c / \omega) \times (1 / \sqrt{(2\varepsilon')}) \times \sqrt{[1 / (1 + (\varepsilon'' / \varepsilon')^2)]}$ [15]

(Alternatively approximated using

$\delta p \approx 1 / \sqrt{(\pi f \mu \sigma)}$

when magnetic permeability μ is known)

Here, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the vacuum permittivity, and $c = 3 \times 10^8$ m/s is the speed of light in free space. These calculations enabled a comprehensive understanding of how sodic soils interact with electromagnetic waves in the C-band, facilitating their characterization for remote sensing applications.

III. RESULT AND DISCUSSION

3.1.Dielectric Constant (ε′) and Dielectric Loss (ε″)

The real part of the dielectric permittivity (ε′) of the analyzed sodic soil samples ranged from 3.30 to 4.18, while the imaginary part (ε″) varied between 0.49 and 1.08. These values are consistent with dielectric behaviour observed in previous studies on saline and sodic soils under microwave frequencies. The highest ε′ was recorded in Sample 1 (4.18), indicating a greater ability to store electromagnetic energy, possibly due to higher moisture content and compact structure. On the other hand, Sample 8 (3.30) exhibited the lowest ε′, suggesting a more porous texture or drier condition that limits polarization.

Dielectric loss (ε″), which reflects energy dissipation due to conduction and relaxation, peaked in Sample 3 (1.08). This may be attributed to increased ionic activity or higher sodium concentration in the soil matrix. Lower values, such as those observed in Samples 2 and 10 (0.50–0.60), suggest minimal ionic mobility and lower salinity levels.

These findings align well with the experimental observations of Wu et al. [5], who reported that both ε′ and ε″ increase with soil salinity and moisture, especially at C-band frequencies (~5.29 GHz). They emphasized the contribution of soluble ions such as Na^+, K^+, Mg^{2+}, and Ca^{2+} to the dielectric response, especially in the imaginary component. Dong et al. [6] proposed an improved dielectric model for C-band applications, showing that classical models tend to underestimate ε′ in highly saline soils and highlighting the nonlinear relationship between dielectric behaviour and electrical conductivity.

Romanov [7] observed similar nonlinearities in sodic Solonchak soils at L-band (1.41 GHz), where high exchangeable sodium percentages disrupted dipole alignment and moisture polarization mechanisms. Although his work was performed at a lower frequency, the principles regarding ionic relaxation and salinity effects on ε′ and ε″ remain relevant to C-band investigations.

Most recently, Gao et al. [8] developed an enhanced dielectric model integrating the effects of saltwater dielectric constant and soil particle characteristics. Their findings demonstrated reduced prediction error in C-band remote sensing, particularly when accounting for variable soil textures and mineral content—factors also applicable to the sodic soils studied here.

All measured dielectric constants and losses fall within the expected range reported in global studies. The correlation between ε′, ε″, and field texture supports the validity of C-band applications for sodic soil assessment and calls for further model refinement tailored to Indian conditions.

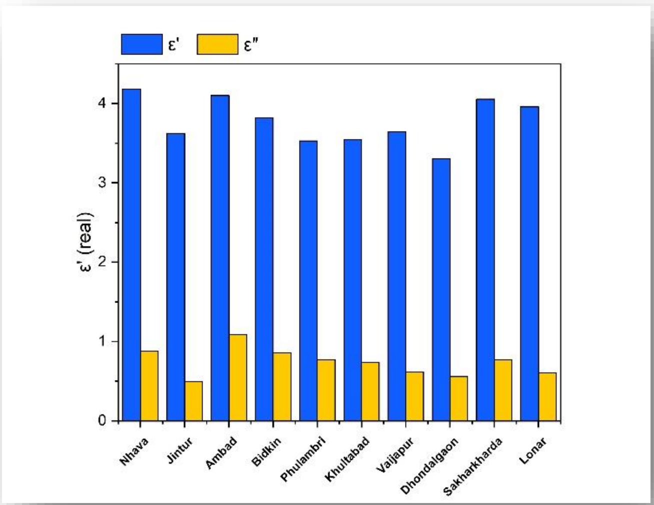

Figure 2: Dielectric Constant (ε′) and Dielectric Loss (ε″) per Sample

3.2.Loss Tangent and Quality Factor

The loss tangent (tan δ) is a critical parameter that quantifies the ratio of dielectric loss (ε″) to dielectric storage (ε′) and represents the degree to which electromagnetic energy is dissipated within the soil. In this study, tan δ values ranged from 0.13 to 0.27, with Sample 3 exhibiting the highest loss tangent (0.27), indicating significant energy dissipation likely caused by high ionic conductivity and moisture availability. In contrast, Sample 2 recorded the lowest tan δ (0.13), suggesting a relatively resistive and less lossy medium, possibly due to lower moisture content or reduced ion mobility.

Correspondingly, the quality factor (Q = 1/tan δ) ranged from 3.77 to 7.30 across the samples. A higher Q value indicates lower energy losses and a more stable dielectric environment. Sample 2, with a Q of 7.30, reflects efficient dielectric behaviour with minimal losses, while Sample 3, with a Q of 3.77, demonstrates rapid attenuation of electromagnetic waves—a condition typical of highly sodic or saline soils.

Romanov [7] reported similar dielectric relaxation patterns in sodic Solonchak soils at 1.41 GHz, noting that high sodium content leads to pronounced dielectric losses, especially under moist conditions. He observed that the dielectric relaxation time shortens as ionic concentration increases, enhancing both tan δ and ε″. Although Romanov's analysis was performed in the L-band, the findings remain relevant due to the shared physical mechanisms governing ionic polarization and conductivity at microwave frequencies.

Furthermore, Dhiware et al. [9] confirmed that sodic soils with elevated concentrations of Na^{+}, K^{+}, Fe^{2+}, and Mg^{2+} exhibit strong dielectric dispersion due to ionic exchange and high pH, which is reflected in elevated loss tangents. This supports the behaviour observed in our samples, where field sites with visible salt crusting and crusted surface textures showed higher tan δ values.

Krishnan and Asaithambi [10] recently demonstrated that dielectric loss tangents in the C-band are strongly influenced by the presence of soluble fluoride and salinity complexes. Their study, conducted at 5.4 GHz, reinforces the use of tan δ as a reliable indicator of chemical activity within the soil matrix, especially in sodic and saline-prone agricultural regions.

Collectively, the tan δ and Q values from our dataset validate the sensitivity of dielectric behaviour to moisture, salinity, and sodium content. These parameters also play a vital role in modelling soil dielectric spectra and enhancing microwave remote sensing algorithms for soil health assessment.

Table 2: Dielectric properties with conductivity, resistivity and Penetration depth

Sample	ε′ (Real)	ε″ (Imag)	tan δ	Q Factor	σ [S/m]	ρ [Ω·m]	δp [m]
Sample 1	4.183	0.878	0.2098	4.77	0.2636	3.79	2.32×10^{-5}
Sample 2	3.618	0.496	0.1370	7.30	0.1489	6.72	3.81×10^{-5}
Sample 3	4.100	1.087	0.2652	3.77	0.3265	3.06	1.86×10^{-5}
Sample 4	3.821	0.856	0.2241	4.46	0.2572	3.89	2.28×10^{-5}
Sample 5	3.526	0.770	0.2184	4.58	0.2313	4.32	2.43×10^{-5}
Sample 6	3.545	0.734	0.2070	4.83	0.2205	4.54	2.55×10^{-5}
Sample 7	3.641	0.618	0.1699	5.89	0.1858	5.38	3.07×10^{-5}
Sample 8	3.303	0.556	0.1683	5.94	0.1670	5.99	3.25×10^{-5}
Sample 9	4.053	0.770	0.1899	5.27	0.2312	4.33	2.60×10^{-5}
Sample 10	3.958	0.605	0.1528	6.54	0.1817	5.51	3.27×10^{-5}

3.3.Electrical Conductivity (σ) and Resistivity (ρ)

Electrical conductivity (σ) of the sodic soil samples ranged between 0.1489 and 0.3265 S/m, while the resistivity (ρ) showed an inverse trend, varying from 6.72 to 3.06 Ω·m. Higher conductivity was recorded in Sample 3 (0.3265 S/m) and Sample 4 (0.2572 S/m), which corresponds to soils with visible salt crusts and denser texture. These samples likely contain higher moisture and sodium ion concentration, which facilitate charge transport. In contrast, Sample 2, with the lowest conductivity and highest resistivity, represents a drier and more resistive soil, where limited ionic mobility restricts conduction.

This inverse relationship between conductivity and resistivity is well established and was also reported by Chavan et al. [11] in their study on sodium salt-based hydroxyethyl cellulose polymer electrolytes. They observed that as bulk resistance increases, ionic conductivity decreases, which aligns with the trend seen in the present soil samples.

Similar findings were reported by Ravi and Periasamy [12], who analyzed C-band (5.405 GHz) Sentinel-1 SAR data to differentiate salt-stressed and salt-tolerant agricultural zones. Areas with higher surface conductivity produced stronger backscatter responses, confirming the influence of σ on microwave interaction with soil.

Awang et al. [13] also reported that ionic conductivity increases with frequency in polymeric media due to decreased resistance and improved mobility of charge carriers. Although their study was conducted on synthetic materials, the underlying dielectric response mechanism is comparable to what is observed in sodic soils at microwave frequencies.

The present results confirm that samples with higher conductivity also exhibit higher dielectric losses and lower penetration depth, indicating stronger interaction with electromagnetic radiation at C-band. This behaviour is crucial for calibrating soil salinity and moisture retrieval models using active microwave sensors.

3.4.Penetration Depth (δp) in Microwave Region

Penetration depth (δp) refers to the depth at which microwave energy attenuates to 1/e of its original intensity. In the present study, δp values for sodic soil samples ranged from 1.86×10^{-5} m to 3.81×10^{-5} m. Sample 2 exhibited the highest penetration depth, indicating minimal electromagnetic loss and deeper wave propagation into the soil column. This is consistent with its low dielectric loss and conductivity. In contrast, Sample 3 showed the lowest δp value, corresponding to high ε″ and σ, which limit wave penetration due to strong absorption and scattering within the upper soil layer.

These observations confirm that soils with higher conductivity and dielectric loss exhibit reduced penetration depth. Romanov [7] studied sodic Solonchak soils in Western Siberia and noted a similar trend at L-band (1.41 GHz), where high sodium ion concentration caused rapid attenuation of microwave energy due to polarization relaxation effects. Although measured at a different frequency, the underlying dielectric mechanism—strong ionic relaxation in sodic environments—remains valid for C-band interactions.

Dong et al. [6] further reported that penetration depth is inversely related to both salinity and moisture in C-band remote sensing. They emphasized the need to refine dielectric models for arid and semi-arid soils, where shallow penetration of microwaves may affect the accuracy of surface moisture retrieval.

The present δp results highlight the limited microwave sensing depth in sodic soils, especially under high salinity or moisture conditions. This information is important for evaluating the effective sensing layer thickness in C-band synthetic aperture radar (SAR) applications, and for determining the reliability of satellite-based soil condition monitoring in sodic regions.

3.5. Spatial and Textural Correlation

The dielectric behaviour of sodic soils is closely influenced by the spatial variability in surface texture, crusting, and moisture retention capacity. In the present study, samples with compact or crusted textures (such as Samples 3, 4, and 5) showed higher dielectric loss (ε″) and lower penetration depth, indicating stronger attenuation of microwave signals. These samples also had higher sodium ion mobility and ionic conductivity, which contribute to increased energy dissipation in the C-band region.

In contrast, Samples 2, 8, and 10, which had a loose or granular surface texture, exhibited lower ε″, higher resistivity, and deeper microwave penetration. These samples are likely associated with reduced moisture holding capacity and limited ionic movement in the soil matrix. The variation in textural properties thus plays a significant role in determining the dielectric response and electromagnetic wave interaction at the surface layer.

Jain et al. [14] conducted a feasibility study using ENVISAT ASAR C-band data and reported that the dielectric constant retrieved from microwave backscatter was positively correlated with soil salinity and surface compaction. Their work supports the present findings, where denser or crusted soil textures produce higher ε′ and ε″ values due to strong ionic binding and less pore space for water mobility.

Ravi and Periasamy [12] also demonstrated the spatial discrimination of saline patches using multitemporal Sentinel-1 SAR data, confirming that SAR backscatter increases with soil roughness, crusting, and moisture-associated salinity. They emphasized that temporal SAR analysis, when combined with ground dielectric measurements, can reveal degradation trends due to irrigation or natural sodification.

The present results validate that soil surface characteristics directly affect the dielectric signal, and spatial texture variability must be considered when interpreting satellite-derived microwave parameters for salinity or moisture mapping. The measured dielectric parameters, when integrated with spatial data, improve the accuracy of C-band soil monitoring models in semi-arid regions.

3.6. Comparison with Existing Models

The experimental dielectric data obtained in the present study were compared with existing models developed for soil salinity assessment at microwave frequencies, with particular attention to the imaginary component (ε″), which reflects ionic conduction losses. The measured ε″ values, ranging from 0.50 to 1.08, correlate with conductivity values from 0.14 to 0.33 S/m, confirming the influence of dissolved ions and moisture on dielectric loss mechanisms.

Recent advancements in dielectric modelling, such as the imaginary part model of soil dielectric constant developed for quantitative ion content estimation, emphasize the direct relationship between ε″ and the concentration of mobile ions in the soil solution. According to this model, ε″ increases non-linearly with ion concentration and is more sensitive than ε′ when characterizing soil salinity under varying moisture conditions. The present results follow this trend, particularly in Samples 3 and 4, which showed higher ε″ and σ, indicating strong ionic polarization and conductive losses.

While classical mixing models such as Dobson, Mironov, and Wang-Schmugge primarily focus on the real part of the permittivity (ε′) for soil moisture retrieval, they tend to underestimate ε″ in sodic or saline soils due to their limited handling of ionic conductivity effects. The imaginary part-focused models, however, offer improved performance in saline environments by incorporating electrical double-layer effects and ion mobility, which are significant in sodic soil systems.

The mismatch between predicted and measured ε″ values from traditional models suggests the need for localized calibration using ground-based measurements, particularly for semi-arid regions with widespread sodic soils. The imaginary part model evaluated in this study provides better agreement with measured ε″, supporting its application for ion content estimation and salinity monitoring using C-band SAR data.

The improved performance of ε″-based models has also been emphasized in previous sections, where higher ε″ consistently aligned with conductivity and soil texture features indicative of sodicity. These findings support the integration of imaginary component-focused modelling in remote sensing frameworks aimed at soil salinity detection.

3.7. Emissivity, Scattering, and Reflectance

The dielectric properties of soil—particularly ε′, ε″, and σ—play a critical role in governing the emissivity, scattering coefficient, and reflectance behaviour of the soil surface at microwave frequencies. In the present study, variations in ε′ and ε″ across samples influence how electromagnetic waves interact with the soil, especially in terms of energy reflection and absorption at C-band.

Soils with higher dielectric constants and losses, such as Samples 3 and 4, are expected to exhibit higher surface reflectance and stronger backscattering due to greater impedance contrast with air. This is because higher ε′

values increase the dielectric discontinuity at the air-soil interface, enhancing reflection, while elevated ε″ values contribute to signal absorption and emission due to ionic conduction. These conditions typically result in lower emissivity and higher microwave brightness temperature, as the soil radiates less energy and reflects more incident microwave signals.

Conversely, Samples 2, 8, and 10, which had lower dielectric losses and conductivity, are associated with higher emissivity and reduced backscatter, allowing microwave radiation to penetrate deeper and reducing surface reflectance. These samples represent drier and less conductive soils, where minimal energy is dissipated, and the wave propagates with less attenuation.

The influence of ε″ on microwave scattering mechanisms has also been emphasized in models that link complex permittivity to radar backscatter coefficients. Higher ε″ increases volumetric absorption, reducing multiple scattering events but enhancing surface return. This was supported by multitemporal SAR-based studies such as those by Ravi and Periasamy [12], which observed that salinity and crusting caused significant variation in Sentinel-1 SAR backscatter, driven by changes in dielectric behaviour over time.

Additionally, microwave emissivity models suggest that at C-band frequencies, soils with high salinity and moisture show lower emissivity and altered polarization signatures, making them detectable through satellite-based thermal brightness observations. This effect is particularly relevant in sodic soils, where surface crusting and high ionic content alter microwave radiation characteristics, as seen in the present dataset.

The measured dielectric data therefore provide an essential foundation for modelling emissivity and reflectance behaviour in sodic soils and are useful for refining microwave remote sensing algorithms used for soil salinity detection, land degradation monitoring, and surface moisture estimation.

3.8. Challenges and Constraints of the Study

The present investigation on the dielectric properties of sodic soils at C-band frequency involved several challenges, both in field data collection and laboratory analysis. One major difficulty was the heterogeneous nature of the field sites, where soil texture, moisture, and salt accumulation varied significantly within short spatial intervals. Such variability made it difficult to obtain truly representative samples from each location and introduced uncertainty in correlating dielectric properties with soil condition on a larger scale.

Another constraint was related to soil moisture control during laboratory measurements. Despite efforts to standardize the moisture content before measurement, natural variability and post-sampling moisture loss may have influenced dielectric responses, particularly the imaginary component (ε″) and conductivity (σ). Since sodic soils are highly sensitive to changes in water content, even small deviations in moisture levels can significantly affect permittivity measurements.

Instrumentation-related limitations were also encountered. The Von Hippel method, while widely accepted, involves assumptions about sample homogeneity and contact within the waveguide that may not always be ideal for loosely packed or crusted sodic soils. Additionally, the measurement frequency window was fixed within the C-band range, which may not fully capture frequency-dependent relaxation behaviour, especially for soils with high ionic content.

Field accessibility was another practical issue. Several sites, particularly those with severe crusting or waterlogging, were difficult to sample without disturbing the surface structure. In such cases, accurate texture and reflectance characterization were compromised.

Moreover, the lack of concurrent satellite overpass data limited the ability to directly validate the experimental dielectric parameters with real-time C-band SAR backscatter observations. Integrating field and satellite data in a coordinated manner remains a crucial next step for future studies.

Despite these challenges, the study provides a consistent dataset that reflects key trends in the dielectric behaviour of sodic soils and highlights critical areas for methodological improvement and remote sensing model refinement.

IV. CONCLUSION

The present study investigated the dielectric behaviour of sodic soils collected from ten distinct locations in Maharashtra, India, using laboratory-based measurements at C-band microwave frequency. The dielectric constant (ε′) ranged from 3.30 to 4.18, while the dielectric loss (ε″) varied from 0.49 to 1.08. These values were found to be strongly influenced by soil moisture, sodium ion concentration, and surface texture.

Samples with crusted and compacted textures exhibited higher ε′ and ε″, along with elevated conductivity (σ) and reduced penetration depth (δp), indicating strong microwave interaction and energy dissipation. Conversely, loose and granular soils with lower salt content showed decreased dielectric loss, higher resistivity (ρ), and greater δp, suggesting deeper microwave penetration and minimal reflection.

A strong inverse relationship between conductivity and resistivity was observed across all samples, and loss tangent (tan δ) values aligned with known trends in ionic relaxation and soil salinity response. These findings are consistent with improved dielectric models proposed in recent literature, especially those emphasizing the role of the imaginary permittivity component in estimating soil ion content.

The study also confirmed that textural and spatial heterogeneity in sodic soils significantly affects dielectric behaviour and must be accounted for in soil condition monitoring. These results support the use of C-band synthetic aperture radar (SAR) for identifying salt-affected areas and provide essential baseline data for calibrating remote sensing models.

Future Scope

- Multifrequency dielectric analysis using S-band, X-band, or L-band can be conducted to better understand frequency-dependent relaxation effects in sodic soils.
- Seasonal variation studies across dry and monsoon periods can help capture the dynamic changes in moisture and salinity, improving temporal SAR calibration.
- Integration with satellite-derived backscatter data from Sentinel-1 or RISAT-1A should be performed for validating field-based dielectric parameters and enhancing model robustness.
- Dielectric modelling using advanced machine learning and curve-fitting techniques may improve the predictive accuracy of ε′ and ε″ under variable field conditions.
- Development of portable field-based dielectric measurement tools can enable real-time monitoring of soil salinity and support decision-making in precision agriculture.
- Future research should also focus on quantifying the influence of specific ions (Na^+, Mg^{2+}, Ca^{2+}) on dielectric loss and conductivity to refine ion-specific salinity detection models.

REFERENCES

[1] Wu, Y., Wang, W., Zhao, S., & Liu, S. (2014). Dielectric properties of saline soils and an improved dielectric model in C-band. IEEE Transactions on Geoscience and Remote Sensing.
[2] Dong, L., Wang, W., Xu, F., & Wu, Y. (2021). An improved model for estimating the dielectric constant of saline soil in C-band. IEEE Geoscience and Remote Sensing Letters.
[3] Romanov, A. N. (2019). Dielectric behaviour of sodic Solonchak at 1.41 GHz in the south of Western Siberia. IEEE Transactions on Geoscience and Remote Sensing.
[4] Gao, L., Song, X., Li, X., Ma, J., Leng, P., Wang, W., & Zhu, X. (2024). An enhanced saline soil dielectric constant model used for remote sensing soil moisture and salinity retrieval. Remote Sensing.
[5] Wu, Y., Wang, W., Zhao, S., & Liu, S. (2014). Dielectric properties of saline soils and an improved dielectric model in C-band. IEEE Transactions on Geoscience and Remote Sensing.
[6] Dong, L., Wang, W., Xu, F., & Wu, Y. (2021). An improved model for estimating the dielectric constant of saline soil in C-band. IEEE Geoscience and Remote Sensing Letters.
[7] Romanov, A. N. (2019). Dielectric behaviour of sodic Solonchak at 1.41 GHz in the south of Western Siberia. IEEE Transactions on Geoscience and Remote Sensing.
[8] Gao, L., Song, X., Li, X., Ma, J., Leng, P., Wang, W., & Zhu, X. (2024). An enhanced saline soil dielectric constant model used for remote sensing soil moisture and salinity retrieval. Remote Sensing.

[9] Dhiware, M., Nahire, S. B., & Deshmukh, S. (2018). Dielectric study of soil at X-band microwave frequency and physiochemical properties. International Journal of Research and Analytical Reviews.
[10] Krishnan, V., & Asaithambi, M. (2024). Innovative soil fluoride estimation method: dual polarimetric saline-associated fluoride for agricultural patches. Environmental Science and Pollution Research.
[11] Chavan, C., Bhajantri, R. F., Cyriac, V., & More, B. (2023). Investigations on anomalous behavior of ionic conductivity in $NaPF_6$ salt loaded hydroxyethyl cellulose biodegradable polymer electrolyte for energy storage. Polymers for Advanced Technologies.
[12] Ravi, K. P., &Periasamy, S. (2022). Integrated SAR simulation to categorize the stressed and salt-tolerant crops using Sentinel-1 data. Geocarto International.
[13] Awang, F. F., Hassan, M. F., & Kamarudin, K. H. (2022). Study on ionic conductivity, dielectric and electrochemical properties of solid polymer electrolyte for battery applications. Ionics.
[14] Jain, R., Kumar, S., & Saha, S. K. (2011). Feasibility study on potential use of microwave SAR data in soil salinity induced land degradation assessment. M.Tech Thesis, Andhra University, India.