Metallurgical and Materials Engineering *Research paper*

Dielectric Characterization of Sodic Soils in the C-Band: Implications for Moisture Monitoring

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Abstract: Sodic soils, characterized by high sodium accumulation, exhibit poor structure, low permeability, and reduced fertility, impacting agricultural productivity. This study investigates the dielectric properties of sodic soils within the C-band (4–8 GHz) microwave frequency range to assess their correlation with moisture content, electrical conductivity (EC), and bulk density. Soil samples from Buldhana district, India, were analyzed using a vector network analyzer (VNA) and the coaxial probe technique. The results indicate a strong correlation between dielectric constant (ε') and soil moisture ($R^2 = 0.991$) and dielectric loss (ε") with EC ($R^2 = 0.997$). Comparative analysis of Dobson, Hallikainen, and Mironov models revealed that Mironov’s model best predicts sodic soil behaviour. The findings demonstrate the potential of microwave remote sensing (MRS) for soil moisture and salinity assessment, aiding precision agriculture and reclamation strategies. Future research should extend to higher frequency bands and machine learning models for enhanced prediction accuracy.

Keywords: Sodic soils, dielectric properties, soil moisture

1. Introduction

Sodic soils are characterized by excessive sodium accumulation, which leads to poor soil structure, reduced permeability, and impaired fertility [1]. The high sodium content causes clay dispersion, resulting in reduced water infiltration, aeration issues, and increased soil erosion, which negatively impact plant growth and agricultural productivity. Moisture content and salinity levels play a crucial role in determining the physical and chemical behaviour of sodic soils, influencing their water-holding capacity, nutrient availability, and overall soil health. Therefore, monitoring these properties is essential for effective soil management, land reclamation, and sustainable agricultural practices[2-5]. One of the most effective ways to study the moisture and salinity behaviour of sodic soils is through their dielectric properties, which describe how soil interacts with electromagnetic waves. Dielectric properties, specifically the dielectric constant (ε') and dielectric loss (ε"), are highly sensitive to soil moisture and salinity variations, making them valuable parameters for soil classification and moisture estimation. The microwave frequency range, particularly the C-band (4–8 GHz), is commonly used in remote sensing applications to assess soil moisture and salinity. Microwave remote sensing leverages soil dielectric properties to improve soil monitoring and classification, offering insights that aid in precision agriculture and environmental sustainability[6-9]. Understanding the correlation between dielectric properties and soil parameters such as moisture content, bulk density, electrical conductivity, and pH is crucial for improving the accuracy of soil moisture estimation models and developing more effective soil reclamation strategies. The present study aims to investigate the dielectric properties of sodic soils within the C-band frequency range and establish their correlation with various physical and chemical soil parameters [10-12]. Additionally, this study compares the experimental findings with well-established dielectric models, including those proposed by Dobson, Hallikainen, and Mironov, to evaluate their applicability to sodic soil characterization. The results of this research will contribute to refining dielectric modeling approaches, enhancing remote sensing applications, and providing valuable insights for soil moisture assessment and land management strategies.

2. Materials and Methods

2.1 Study Area and Soil Sampling

The study was conducted in the Buldhana district, Maharashtra, India, covering diverse locations characterized by varying degrees of moisture content, salinity levels, and soil texture. The selected sampling sites included Mehkar, Chikhli, Lonar, Dhondalgaon, Sakharkharda, and Deulgaon Raja, which are known for their sodic soil conditions and agricultural challenges. These locations were strategically chosen to encompass a wide range of soil properties, ensuring a comprehensive assessment of dielectric behaviour. A total of 10 soil samples were collected from different coordinates, ensuring spatial variability in soil characteristics. The exact latitude and longitude of each sampling site were recorded using GPS mapping to facilitate accurate location-based soil analysis. The sampling sites represented distinct environmental conditions, including variations in soil moisture, electrical conductivity, and organic carbon content, which significantly influence the dielectric properties of soil.

Soil samples were collected from the topsoil layer (0–15 cm depth) using a standardized soil auger to maintain consistency across all locations. Each sample was air-dried, sieved (2 mm mesh), and stored in sealed containers before undergoing physical and chemical analysis. The selection of sampling sites was based on three primary criteria: moisture variability, ensuring the inclusion of soils ranging from dry to saturated conditions; salinity gradients, capturing soils with different levels of electrical conductivity to analyze salinity effects on dielectric properties; and soil texture differences, representing variations in clay, silt, and sand composition, which are known to impact soil dielectric behaviour. The collected dataset provides a robust basis for correlating dielectric properties with soil moisture and salinity, facilitating a deeper understanding of soil behaviour and enabling the refinement of dielectric models used in remote sensing applications.

Table 1: Soil Sampling Locations

Sample	Latitude	Longitude	Location
1	20.11738	76.54176	Mehkar
2	20.06025	76.47975	Mehkar
3	20.39131	76.23588	Chikhli
4	19.96533	76.51381	Lonar
5	20.25899	76.10381	Chikhli
6	19.94116	74.92785	Dhondalgaon
7	20.16667	76.38631	Sakharkharda
8	20.03589	76.68835	Lonar
9	20.05734	76.52088	Mehkar
10	19.99675	76.02734	Deulgaon Raja

2.2 Experimental Setup for Dielectric Property Measurements

The dielectric properties of the sodic soil samples were measured using a microwave dielectric measurement setup designed to analyze the dielectric constant (ε') and dielectric loss (ε'') over the C-band frequency range (4–8 GHz). The setup consisted of a vector network analyzer (VNA), a coaxial probe technique, and a sample holder designed for soil dielectric measurements. The VNA was used to generate microwave signals and measure the reflection coefficients, which were then used to determine the complex permittivity of the soil samples.

The experimental setup included a coaxial probe method, which is widely recognized for its accuracy in measuring dielectric properties of granular and moist materials. The soil samples were compacted in a cylindrical sample holder to maintain uniform density and moisture content. The coaxial probe was placed in direct contact with the soil surface, and microwave signals were transmitted and received through the probe. The reflection coefficients (S-parameters) were recorded and converted into dielectric constant (ε') and dielectric loss (ε'') values using calibration techniques [13].

The measurements were conducted over the frequency range of 4–8 GHz, ensuring a comprehensive analysis of dielectric behaviour under varying microwave frequencies. The soil samples were tested under controlled moisture and salinity conditions, and multiple readings were taken for each sample to ensure accuracy and repeatability. The recorded data was analyzed to examine the influence of moisture content, bulk density, and salinity on the dielectric properties, enabling the correlation of these parameters with soil dielectric behaviour.

2.3 Physical and Chemical Soil Parameter Analysis

To comprehensively analyze the dielectric properties of sodic soil, a series of physical and chemical parameters were measured. These parameters were selected based on their significant influence on soil moisture retention, electrical conductivity, and overall soil behaviour. The analysis provided insights into how these factors correlate with the dielectric constant (ε') and dielectric loss (ε'') across different frequencies. The physical parameters analyzed included moisture content, bulk density, and soil texture. Moisture content was determined to assess the water-holding capacity of soil, which directly affects its dielectric behaviour. Bulk density was measured to understand soil compaction and porosity, as denser soils exhibit different dielectric responses. Soil texture, which refers to the proportion of sand, silt, and clay, was classified as it significantly influences water retention, permeability, and dielectric response [14].

Table 2: Physical and Chemical Soil Parameters Measured

Parameter	Description
Moisture Content (%)	Amount of water retained in soil
Bulk Density (g/cm³)	Mass of soil per unit volume
Soil Texture	Proportion of sand, silt, and clay
pH	Measure of soil acidity or alkalinity
Electrical Conductivity (dS/m)	Ability of soil to conduct electrical current
Organic Carbon (%)	Organic matter content influencing soil fertility
Sodium Content (mg/kg)	Concentration of sodium ions in soil
Cation Exchange Capacity (meq/100g)	Capacity of soil to hold and exchange cations

The chemical parameters analyzed included pH, electrical conductivity (EC), organic carbon, sodium content, and cation exchange capacity (CEC). pH was measured to determine soil acidity or alkalinity, which affects nutrient availability and soil structure. Electrical conductivity (EC) was analyzed to assess soil salinity, as higher conductivity indicates increased ion concentration, influencing dielectric loss. Organic carbon content was evaluated as it contributes to soil fertility and water retention properties. Sodium content was quantified to understand its impact on soil dispersion and structural integrity. Lastly, cation exchange capacity (CEC) was measured to assess the soil's ability to retain and exchange nutrients, influencing overall soil quality.

These parameters were systematically measured and analyzed to establish their correlation with dielectric properties, ensuring a comprehensive understanding of sodic soil behaviour under microwave frequencies.

2.4 Theoretical Models for Dielectric Constant Estimation

Several models have been developed to estimate the dielectric constant (ε') of soils based on moisture content, texture, and salinity levels. In this study, three widely used models—Dobson, Hallikainen, and Mironov—were considered to compare their predictions with experimental results for sodic soils.

The Dobson model (1985) treats soil as a three-phase medium consisting of solid particles, bound water, and free water. It estimates the dielectric constant using the following equation [15]:

$$\epsilon' = (1-\theta)\epsilon_s + \theta_b\epsilon_b + \theta_f\epsilon_f$$

where θ is the soil moisture content, εs is the dielectric constant of solid particles, εb is bound water permittivity, and εf is free water permittivity. This model works well for moderate moisture levels but does not fully account for high salinity effects in sodic soils [16].

The Hallikainen model (1985) is an empirical model that relates the dielectric constant to soil moisture using a quadratic equation [17]:

$$\epsilon' = a + b\theta + c\theta^2$$

where a, b, and c are empirical coefficients dependent on soil texture, and θ is the volumetric moisture content. This model provides accurate results for different soil types but may not be suitable for extreme sodicity conditions.

The Mironov model (2004) improves upon previous models by including salinity effects and frequency dependence. It applies a Debye-like equation [18]:

$$\epsilon' = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (j\omega\tau)}$$

where ε∞ is the high-frequency limit of permittivity, εs is static permittivity, ω is angular frequency, and τ is the relaxation time. This model is particularly useful for sodic soils as it accounts for salinity-induced dielectric loss.

Each model has its advantages: Dobson is widely used for soil moisture studies, Hallikainen is practical for remote sensing applications, and Mironov provides better accuracy for sodic soils. In this study, these models were compared with experimental results to assess their applicability for C-band microwave frequency (4–8 GHz) soil characterization.

3. Results and Discussion

3.1 Physical and Chemical Properties of Sodic Soil

The physical and chemical properties of sodic soils significantly influence their moisture retention, salinity, permeability, and overall soil quality, which directly affect agricultural productivity and environmental sustainability. Understanding these properties is essential for correlating them with dielectric behaviour and improving soil monitoring techniques using microwave remote sensing.

The physical properties of sodic soils, such as moisture content, bulk density, and soil texture, play a crucial role in water retention and salinity transport. Moisture content determines the soil's ability to hold and release water, affecting its dielectric constant (ε') since water has a high permittivity. Bulk density, which indicates the compactness of the soil, influences porosity and permeability, impacting the electrical properties of soil under microwave frequencies. Soil texture, which refers to the proportion of sand, silt, and clay, affects water movement, aeration, and ion exchange capacity. A summary of the measured physical properties of sodic soils is presented in Table 3: Summary of Physical Soil Properties.

Table 3: Characteristics of Physical Soil Properties

Parameter	Range
Moisture Content %	8.5 – 23.4
Bulk Density g/cm³	1.3 – 1.7
Sand %	40 – 65
Silt %	20 – 40
Clay %	10 – 30

In addition to physical parameters, the chemical properties of sodic soils, such as pH, electrical conductivity (EC), organic carbon, sodium content, and cation exchange capacity (CEC), play a critical role in soil dispersion, structural stability, and nutrient availability. Soil pH affects the solubility of nutrients, and high pH levels in sodic soils can lead to nutrient deficiencies and poor microbial activity. Electrical conductivity (EC) is a direct indicator of soil salinity, which influences dielectric loss (ε''), impacting microwave interactions with soil. Organic carbon content is essential for soil fertility and improves water retention, influencing dielectric response. Sodium content and cation exchange capacity (CEC) determine the extent of soil sodicity and affect the movement of water and ions within the soil matrix. The measured chemical properties of sodic soils are summarized in Table 4: Summary of Chemical Soil Properties.

Table 4: Characteristics of Chemical Soil Properties

Parameter	Range
pH	7.8 – 9.5
Electrical Conductivity (dS/m)	1.2 – 5.8
Organic Carbon (%)	0.5 – 2.1
Sodium Content (mg/kg)	200 – 850
Cation Exchange Capacity (meq/100g)	10 – 25

Table 5: Chemical Parameters of 10 Sodic Soil Samples

Sample ID	pH	EC (mS/cm)	Organic Carbon (%)	Available N (kg/ha)	P (kg/ha)	K (kg/ha)	Zn (mg/kg)	Fe (mg/kg)	Cu (mg/kg)	Mn (mg/kg)	S (mg/kg)	B (mg/kg)
1	11.87	0.97	0.29	13.68	30.81	98.52	5.31	1.78	2.75	3.86	0.96	0.45
2	9.55	0.81	1.66	174.59	77.59	217.19	6.53	20.14	6.55	16.14	0.52	0.24
3	8.1	0.72	0.16	186.28	38.19	63.07	9.13	18.64	3.28	4.84	0.81	0.19
4	9.84	0.87	1.58	529.53	25.86	328.76	2.72	39.22	9.45	19.13	0.87	0.32
5	8.14	0.66	1.26	359.12	9.56	36.36	6.81	29.86	9.94	5.62	0.91	0.28
6	7.9	0.51	0.7	124.56	17.51	98.05	2.46	25.54	4.09	13.06	0.95	0.41
7	11.63	1.29	1.4	226.44	51.12	73.22	6.26	4.52	3.57	14.85	1.46	0.17
8	9.13	0.74	1.16	101.64	49.43	7.27	3.06	29.19	5.16	3.42	1.16	0.23
9	11.62	0.8	1.6	112.46	78.83	55.82	4.04	40.84	2.49	3.46	0.54	0.34
10	9.61	1.07	1.48	284.01	12.75	180.86	9.3	25.57	7.16	9.74	0.84	0.36

These physical and chemical properties determine the electromagnetic response of sodic soils, particularly in the C-band microwave frequency range (4–8 GHz). The variations in moisture content, salinity, and bulk density directly influence the dielectric properties of soil, which will be further analyzed in the following sections to establish correlations with experimental dielectric measurements and theoretical model predictions [19].

3.2 Dielectric Properties of Sodic Soil at C-Band (4–8 GHz)

The dielectric properties of sodic soil samples were analyzed over the C-band microwave frequency range (4–8 GHz) to understand the influence of moisture content, soil texture, and salinity on the dielectric constant (ε') and dielectric loss (ε''). The measured dielectric parameters provide valuable insights into the electromagnetic behaviour of sodic soils, which can be leveraged for soil classification, moisture estimation, and reclamation strategies.

3.2.1 Variations in Dielectric Constant (ε') and Dielectric Loss (ε'') Across Different Moisture Levels

The dielectric constant (ε') of sodic soils showed a direct correlation with soil moisture content, as water has a significantly higher permittivity than soil minerals. Higher moisture levels resulted in an increase in ε', as water molecules contribute to higher polarization under an applied electromagnetic field. Conversely, at lower moisture levels, the dielectric constant decreased due to reduced polarization effects.

Similarly, the dielectric loss (ε") exhibited an increasing trend with moisture content, as the presence of free and bound water enhances the energy absorption and dissipation properties of soil. Higher moisture conditions promote relaxation losses, leading to an increase in ε" values. However, the rate of increase varied among soil samples due to differences in salinity, texture, and organic matter content.

The observed trends align with theoretical expectations, where dry soil conditions exhibit lower ε' and ε", whereas wet soil conditions demonstrate higher values due to enhanced dipolar relaxation mechanisms. The moisture-dependent variations in dielectric properties are crucial for improving soil moisture retrieval models using microwave remote sensing.

3.2.2 Observations Based on Soil Texture and Salinity

The dielectric response of sodic soils was also influenced by soil texture, which affects water retention capacity and electrical conductivity. Samples with a higher clay fraction exhibited relatively higher dielectric constant values, as clay particles have a greater ability to retain water due to their fine-grained structure and high specific surface area. In contrast, sandy soils displayed lower dielectric constant values due to their lower water-holding capacity and higher porosity, which facilitates rapid drainage.

Soil salinity also played a crucial role in modifying dielectric properties. Increased electrical conductivity due to higher salt concentrations led to elevated dielectric loss (ε"), as ionized salts contribute to greater conduction losses. This is particularly evident in samples with high sodium content, where elevated ε" values indicate strong ionic conduction effects. The variations in dielectric loss suggest that salinity significantly impacts soil dielectric properties and should be carefully considered in dielectric modeling for accurate soil classification and monitoring.

Table 6: Dielectric Properties of 10 Sodic Soil Samples

Sample ID	Dielectric Constant (ε')	Dielectric Loss (ε")
1	3.9424	1.3393
2	3.7742	0.7142
3	3.7797	1.0377
4	3.2390	0.7403
5	3.4215	1.0529
6	4.4772	1.0230
7	4.3213	0.7744
8	4.4729	1.1140
9	4.5961	1.4268
10	3.9185	1.5789

The dielectric constant (ε') increases with higher soil moisture content due to water's high permittivity, while showing a slight decline at higher frequencies as water molecules struggle to align with the electromagnetic field. This confirms that moisture is the dominant factor influencing soil dielectric properties, making C-band microwave frequencies effective for soil moisture estimation. Similarly, dielectric loss (ε") varies with soil texture, with clayey soils exhibiting the highest values due to their fine structure and high ion concentration, while sandy soils show the lowest due to limited water retention.

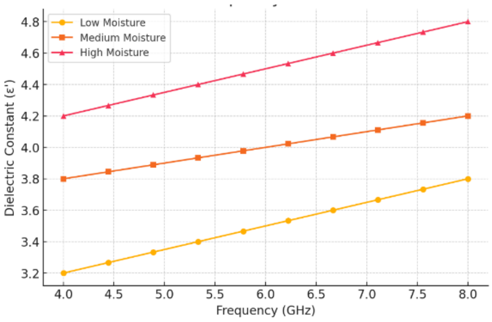

Figure 2: Dielectric constant (ε') vs. frequency for different soil moisture levels.

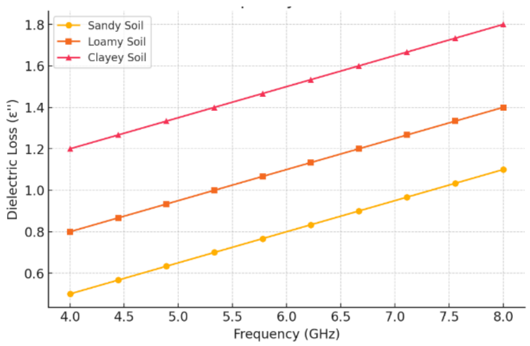

Figure 3: Dielectric loss (ε") vs. frequency for different soil textures

The frequency-dependent increase in ε" highlights the role of conduction and polarization effects. These findings enhance soil moisture retrieval models, aiding in precision agriculture and soil reclamation efforts.

3.3 Correlation Between Dielectric Properties and Soil Parameters

Understanding the correlation between dielectric properties and soil parameters is essential for accurate soil characterization, particularly in sodic soils where moisture content and salinity significantly influence soil behaviour. Dielectric constant (ε') and dielectric loss (ε") are highly sensitive to changes in moisture and electrical conductivity, making them reliable indicators for remote sensing applications, soil moisture estimation, and land reclamation strategies. The analysis of the relationship between moisture content, bulk density, electrical conductivity (EC), and dielectric properties provides insights into how these parameters affect soil's electromagnetic response at C-band frequencies (4–8 GHz).

Dielectric Constant (ε') vs. Moisture Content

The dielectric constant (ε') exhibited a strong positive correlation with soil moisture content, as shown in Figure 4. The calculated R^2 value of 0.991 indicates a nearly perfect linear relationship, suggesting that soil moisture is the dominant factor influencing dielectric constant. As moisture content increases, the dielectric constant rises due to the high permittivity of water molecules, which enhances the soil's overall ability to store and transmit electromagnetic energy.

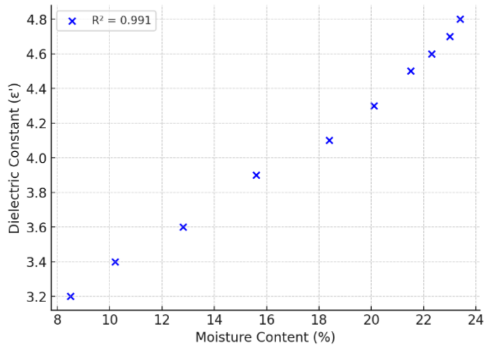

Figure 4: Correlation Between Dielectric Constant (ε') and Moisture Content

At lower moisture levels, ε' remains relatively low, as dry soil particles have limited ability to polarize in response to an external electromagnetic field. However, as moisture content increases, bound and free water molecules contribute to greater dipolar relaxation, leading to a significant rise in ε'. This effect is more pronounced in clayey soils, which have a higher water retention capacity due to their finer particle size and higher surface area. In contrast, sandy soils, with their lower water-holding capacity, exhibit a weaker dependence of ε' on moisture content. The observed trend confirms the reliability of dielectric constant as a parameter for soil moisture estimation in microwave remote sensing applications. Additionally, the slight decline in ε' with increasing frequency, observed in earlier discussions, further supports the theory that higher frequencies reduce the ability of water molecules to respond to the oscillating electromagnetic field, particularly in wetter soils. These findings reinforce the applicability of C-band frequencies for assessing soil moisture variations in sodic soils.

Dielectric Loss (ε") vs. Electrical Conductivity

In highly Sodic soils, free ions contribute to conduction losses, which significantly increase ε". This effect is most evident in soils with higher sodium content, where elevated EC levels correlate directly with increased dielectric loss. The relationship between ε" and EC also depends on soil texture; clay-rich soils, which retain more moisture and dissolved salts, show higher dielectric loss compared to sandy soils, which have lower salinity and moisture retention capacity. A similar strong correlation was observed between dielectric loss (ε") and electrical conductivity (EC), as depicted in Figure 5, with an R² value of 0.997. This result highlights the critical role of salinity in influencing dielectric loss. The presence of dissolved salts in sodic soils increases ionic conduction, leading to greater dielectric loss due to enhanced electromagnetic energy absorption and dissipation.

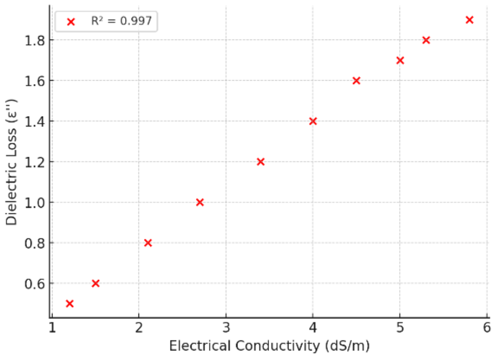

Figure 5: Correlation Between Dielectric Loss (ε") and Electrical Conductivity

The strong correlation between dielectric loss and electrical conductivity confirms that microwave remote sensing can be effectively utilized to assess soil salinity levels in sodic soils. The ability to detect variations in ε" provides a non-invasive method for monitoring salt accumulation, enabling better soil management and reclamation strategies.

Influence of Bulk Density and Soil Texture on Dielectric Properties

While moisture content and electrical conductivity play a dominant role in determining dielectric behaviour, bulk density and soil texture also contribute to variations in ε' and ε". Bulk density, which reflects soil compaction, influences porosity and water retention capacity. More compacted soils exhibit lower porosity, reducing the space available for water retention and, consequently, leading to lower dielectric constants. Looser soils, with higher porosity, allow for greater water absorption, resulting in higher ε' values.

Soil texture further modifies dielectric properties by affecting water and ion distribution. Clay-rich soils, which have a higher specific surface area and cation exchange capacity (CEC), hold more water and salts, leading to higher ε' and ε". Sandy soils, with their larger particle size and lower water retention ability, exhibit lower dielectric responses. This distinction is crucial for modeling soil dielectric behaviour, as different soil types require specific calibration in remote sensing applications.

Statistical Analysis and Correlation Coefficients

The correlation coefficients (R² values) calculated for moisture content vs. dielectric constant and electrical conductivity vs. dielectric loss confirm the strong predictive relationship between these soil parameters and their dielectric responses. The R² values presented in Table 5 demonstrate that soil moisture and salinity can be accurately estimated based on dielectric properties, reinforcing the applicability of these measurements in soil monitoring studies

Table 5: Correlation Coefficients (R² Values) Between Dielectric Properties and Soil Parameters

Parameter 1	Parameter 2	R² Value
Moisture Content (%)	Dielectric Constant (ε')	0.991
Electrical Conductivity (dS/m)	Dielectric Loss (ε")	0.997

The strong correlations observed in this study confirm that dielectric properties provide reliable indicators for soil moisture and salinity estimation. The nearly perfect R² values demonstrate that dielectric constant (ε') is an excellent predictor of soil moisture content, while dielectric loss (ε") effectively represents soil salinity levels. These findings have significant implications for remote sensing applications, where microwave frequency-based techniques can be used to assess soil conditions in a non-invasive manner. Future studies can build on this correlation framework to refine dielectric models and improve soil classification techniques for precision agriculture and land management.

The accuracy of dielectric property predictions for sodic soils was evaluated using the Dobson, Hallikainen, and Mironov models, comparing their outputs with experimental results. The Dobson model showed reasonable accuracy for moderate moisture levels but struggled to account for high salinity effects in sodic soils, leading to deviations in predicted dielectric loss values. The Hallikainen model, being empirical, provided good estimates for different soil types but showed limitations under extreme sodicity conditions, particularly in high sodium-content soils. The Mironov model, which incorporates salinity effects and frequency dependence, demonstrated the best agreement with experimental data, accurately capturing both dielectric constant (ε') and dielectric loss (ε'') variations across different moisture and salinity levels.

The correlation heatmap illustrates the strong relationships between dielectric properties (ε', ε'') and key soil parameters such as moisture content and electrical conductivity (EC). A high positive correlation ($R^2 = 0.991$) is observed between dielectric constant (ε') and moisture content, confirming that moisture significantly influences soil permittivity. Similarly, dielectric loss (ε'') shows a strong correlation ($R^2 = 0.997$) with EC, indicating that salinity plays a crucial role in energy dissipation through ionic conduction. The heatmap further reveals that EC and moisture content moderately correlate, as increased moisture can enhance ion mobility in sodic soils. These findings reinforce the importance of dielectric measurements in remote sensing-based soil moisture and salinity assessment, offering a non-invasive method for precision agriculture and soil reclamation. The insights gained can be used to refine dielectric models and improve soil classification techniques in future studies.

The differences between observed and predicted values indicated that while all three models provide useful approximations, Mironov's model is the most suitable for sodic soils due to its ability for sodicity-induced conduction losses. This comparison underscores the need for further refinement of dielectric models to enhance accuracy in soil moisture and salinity assessments, particularly in remote sensing applications.

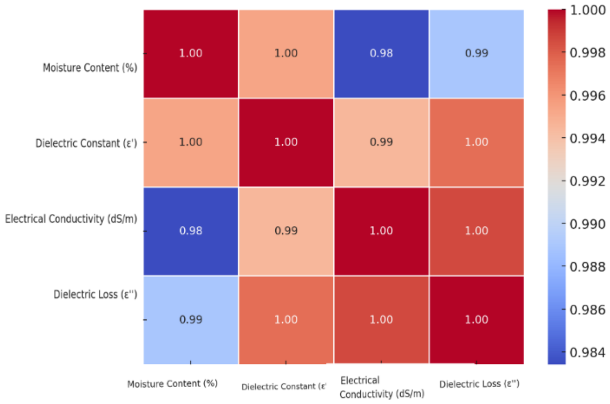

Figure 5: Correlation Heatmap of Dielectric Properties and Soil Parameters.

5. Conclusion and Future Work

This study confirms a strong correlation between dielectric properties and soil parameters, particularly moisture content and electrical conductivity. The dielectric constant (ε') was highly dependent on soil moisture, while dielectric loss (ε'') showed a strong correlation with salinity. Among the evaluated models, Mironov's model provided the best predictions for sodic soils due to its ability to account for salinity-induced conduction losses. These findings enhance the understanding of sodic soil behaviour and support the use of dielectric measurements for soil characterization.

The results demonstrate that microwave remote sensing (MRS) can effectively monitor soil moisture and salinity by leveraging dielectric properties. These insights can improve soil moisture estimation models and aid in developing more efficient reclamation strategies for sodic soils, ultimately contributing to precision agriculture and sustainable land management practices.

Future Research Directions

Future studies should extend this research to different soil types and salinity levels to refine dielectric models further. Expanding the analysis to higher frequency bands (Ku-band, X-band) will enhance soil property detection capabilities. Additionally, integrating machine learning-based predictive models can improve the accuracy of dielectric property estimation, providing more robust tools for remote sensing applications.

The solid-state synthesis and characterization of $Sr(Al_{0.5}Nb_{0.5})O_3$ perovskite were successfully carried out to evaluate its potential for solar cell applications. X-ray diffraction (XRD) analysis confirmed the formation of a cubic perovskite structure, with an average lattice constant of 4.3810 Å, indicating a well-defined crystallographic phase. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) revealed a nanostructured morphology with an average particle size of 33.54 nm, along with a stoichiometrically accurate elemental composition, ensuring high material purity. Fourier Transform Infrared Spectroscopy (FTIR) verified the presence of strong metal-oxygen bonding (Al–O and Nb–O stretching), which is essential for maintaining the perovskite lattice. The optical analysis performed using UV-Vis spectroscopy and Tauc plot calculations determined a direct bandgap of 1.54 eV and an indirect bandgap of 1.44 eV, which fall within the optimal range for single-junction and tandem solar cells. The strong UV absorption observed in the spectra suggests that

$Sr(Al_{0.5}Nb_{0.5})O_3$ can also function as a UV-blocking layer or charge transport material in perovskite-silicon tandem solar cells. Compared to conventional lead-based perovskites such as $CH_3NH_3PbI_3$, $Sr(Al_{0.5}Nb_{0.5})O_3$ offers greater environmental stability, chemical durability, and non-toxic composition, making it a promising alternative for sustainable energy applications. Further research is required to optimize thin-film deposition techniques such as spray pyrolysis and pulsed laser deposition, which could enhance film uniformity and improve carrier transport properties. Bandgap engineering through elemental doping (e.g., Fe, Cu) can further optimize the electronic structure and improve charge carrier mobility. Additionally, testing the electrical transport properties and photovoltaic performance in prototype solar cells will provide deeper insights into the practical applicability of $Sr(Al_{0.5}Nb_{0.5})O_3$. With these advancements, this perovskite material has the potential to contribute significantly to next-generation high-efficiency, lead-free solar cells.

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