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Frequency-Dependent Dielectric Properties of Agricultural Soils from Buldhana District, Maharashtra

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Abstract

Soils are heterogeneous dielectric materials, and their response to microwave radiation depends on texture, packing, organic matter, mineral composition, pore space, chemical environment, and frequency. A reliable local dielectric database is therefore useful for microwave soil studies, electromagnetic modelling, and remote-sensing interpretation. In the present work, ten surface soil samples collected from agricultural locations of Buldhana District, Maharashtra, India, were characterized at three microwave frequencies: C-band (4.7 GHz), J-band (5.8 GHz), and X-band (9.68 GHz). The measurements were performed using a klystron-based rectangular waveguide bench operated in the dominant TE10 mode, and the dielectric constant was evaluated by the VSWR double-minima method. In addition to microwave measurements, each soil sample was analysed for particle-size distribution, soil texture, pH, alkalinity, soil organic carbon, available major nutrients, calcium carbonate, and selected micronutrients. The measured dielectric constant ranged from 3.4601 to 4.9611 at C-band, 3.0238 to 3.8104 at J-band, and 1.8840 to 2.8970 at X-band. A clear decrease in dielectric constant with increasing frequency was observed for all samples. The average dielectric constant decreased from 4.0309 at 4.7 GHz to 2.3849 at 9.68 GHz, corresponding to an average reduction of about 40.33%. The results show that the microwave behaviour of Buldhana soils cannot be explained by a single soil property alone. Texture, organic carbon, exchangeable ions, calcium carbonate, and sample packing together influence the observed response. The study provides an experimentally measured dielectric dataset for Buldhana soils and demonstrates the suitability of the TE10 waveguide double-minima technique for comparative characterization of air-dried granular soils.

Keywords: soil dielectric constant; Buldhana district; microwave measurement; TE10 waveguide mode; VSWR double-minima method; soil texture; C-band; J-band; X-band; frequency dependence; electromagnetic soil characterization

1. Introduction

Soil is not a simple solid medium. It is a natural mixture of mineral particles, organic matter, trapped air, adsorbed water, soluble salts, and exchangeable ions. Because of this mixed composition, its behaviour under an applied electromagnetic field is complex and highly site specific. In microwave studies, this behaviour is commonly represented by complex relative permittivity, written as $\varepsilon^* = \varepsilon' - j\varepsilon''$. The real part, ε', is usually called the dielectric constant and represents the ability of the soil to store electromagnetic energy. The imaginary part, ε'', represents dielectric loss and is associated with energy dissipation within the medium [1, 3, 22].

The dielectric constant of soil has direct importance in microwave remote sensing, radar backscatter studies, soil-moisture estimation, electromagnetic wave propagation, and microwave heating. When a microwave signal encounters the soil surface, part of the signal is reflected, part is absorbed, and part may penetrate the medium. The relative amounts of reflection, absorption, and penetration depend strongly on the dielectric properties of the soil. Even small changes in the dielectric constant can change the phase velocity, impedance, and attenuation of microwave energy. For this reason, accurate dielectric measurements are essential for the interpretation of microwave observations [2, 4, 15].

Among the different soil properties, moisture is generally the strongest controlling factor because water has a high dielectric constant compared with dry mineral particles and air. However, even in air-dried soils, the dielectric response is not uniform. Clay minerals can retain bound water layers on their surfaces, organic matter can hold structured water and polar functional groups, and soluble salts can modify interfacial polarization. Consequently, dry or low-moisture soils may still show measurable differences in dielectric constant from one location to another [5, 31, 33].

The frequency of measurement is another key factor. At lower microwave frequencies, some polarization mechanisms have enough time to respond to the alternating electric field. As the frequency increases, slower polarization processes cannot follow the field reversal effectively, and the measured dielectric constant generally decreases. This phenomenon is related to dielectric dispersion and relaxation. In soils, dispersion is associated not only with free water but also with bound water, clay-water interaction, ion exchange surfaces, and interfacial effects between mineral particles and pore spaces [24, 25, 30].

Regional soil dielectric measurements are important because soils from different geological and climatic regions often show different dielectric behaviour. A model developed for one soil type may not perform equally well for another. The black cotton soils and associated medium-textured soils of Maharashtra, especially those derived from Deccan basaltic parent material, contain varying proportions of clay minerals, calcium carbonate, and exchangeable cations. These characteristics can influence the measured microwave dielectric constant. Therefore, regional datasets are required for better calibration of microwave models and for supporting local agricultural and environmental applications.

Buldhana District is part of the Vidarbha region of Maharashtra and is agriculturally important. The district includes rainfed cropping systems, medium to deep soils, and varied land use. Although microwave soil studies have been widely reported for several soil types, a focused dielectric dataset for Buldhana District soils is not available in the published local literature. The present study addresses this gap by measuring the dielectric constant of ten soil samples at three microwave frequencies using a controlled laboratory waveguide method.

The main purpose of this study is not only to report dielectric values but also to interpret them in relation to physical and chemical soil properties. The paper therefore combines particle-size analysis, chemical characterization, and microwave measurements. Such an integrated approach gives a more realistic understanding of why one soil sample may show a higher or lower dielectric response than another. The work is particularly useful for researchers working with microwave dielectric measurement, agricultural soil classification, and electromagnetic modelling of granular materials.

2. Study Area

Buldhana District is located in the Vidarbha sub-region of Maharashtra, India. The sampling locations used in this study fall within latitudes 19.8671°N to 19.9544°N and longitudes 76.0671°E to 76.2735°E. These coordinates represent agricultural fields selected to capture local variability in soil texture and soil chemistry. The sampling points were chosen away from roads, artificial fill, drainage channels, and obvious contamination sources so that the collected soils would represent field conditions more reliably.

The district forms part of the broader Deccan Plateau region. Basaltic parent material, semi-arid to sub-humid climate, and long-term agricultural use contribute to the development of medium to deep soils. In many parts of the district, soils show characteristics associated with Vertisols and related soil groups, including clayey behaviour, shrink-swell tendency, and calcium carbonate accumulation. However, field-level variability is common, and the present samples include both loam and sandy loam classes.

Agriculture is the major land-use activity in the district. Crops such as cotton, soybean, wheat, jowar, pulses, and other seasonal crops are commonly grown in the region depending on rainfall, irrigation availability, and soil depth. Because the soils are used intensively for agriculture, understanding their physical and electromagnetic behaviour has practical relevance. Microwave characterization can support future work on soil-moisture estimation, field-scale monitoring, and electromagnetic modelling.

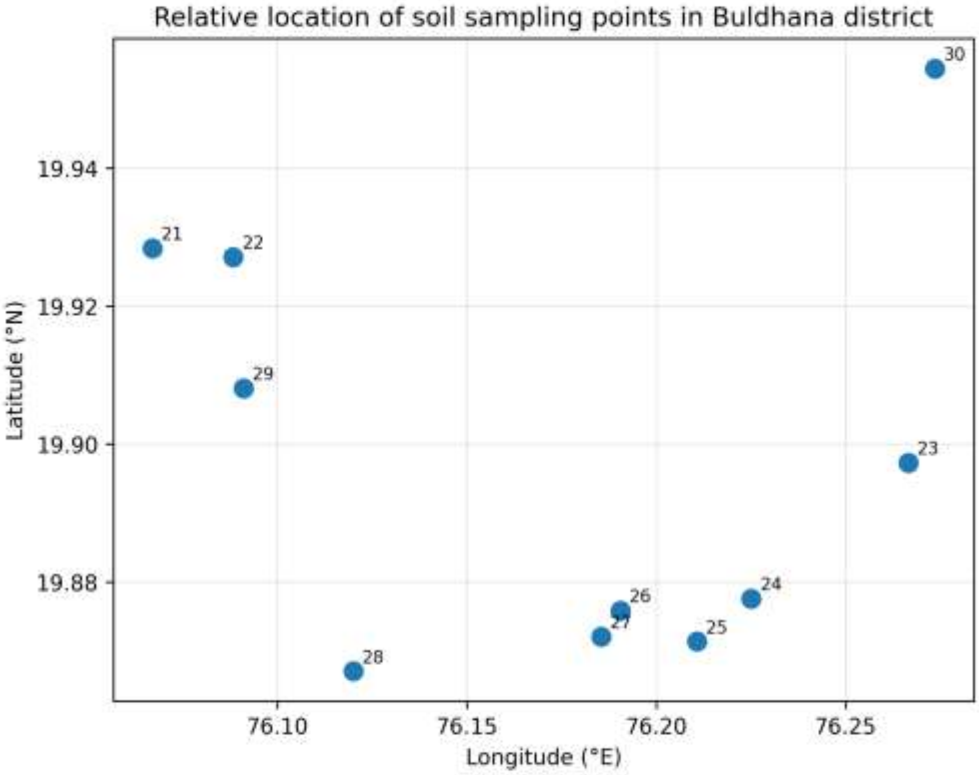

Figure 1. Relative location of the ten soil sampling points used in the present study.

2.1 Soil Collection and Sample Preparation

Ten surface soil samples were collected from agricultural fields in Buldhana District. Sampling was carried out from the 0-20 cm surface horizon because this layer is most relevant for agricultural activity and microwave interaction with near-surface soil. Approximately 2 kg of soil was collected from each location using clean tools. The samples were placed in labelled polyethylene bags and transported to the laboratory for further processing.

In the laboratory, the soils were air-dried at ambient temperature for about 72 hours. Large clods were gently broken by hand without grinding the mineral particles. Plant residues, roots, gravels, and visible impurities were removed. The soils were then passed through a 2 mm sieve to obtain a uniform granular fraction. The sieved samples were stored in airtight containers until texture, chemical, and dielectric measurements were performed. This preparation procedure was used to reduce sample-to-sample variation caused by large aggregates and coarse fragments.

3. Materials And Methods

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3.2 Soil Texture Analysis

Particle-size distribution was determined by the hydrometer method. The soil was dispersed using sodium hexametaphosphate solution to separate individual particles. Hydrometer readings were taken at standard time intervals, and the percentages of sand, silt, and clay were calculated after applying temperature and blank corrections. The textural class of each sample was assigned using the USDA soil textural triangle.

Texture analysis is important for dielectric studies because sand, silt, and clay differ in particle size, surface area, water retention, and surface charge. Sandy soils usually contain larger pores and less bound water, while clay-containing soils have higher surface area and greater capacity for adsorption and ion exchange. These features can influence dielectric constant even when the soil is air-dried.

3.3 Chemical Analysis

The chemical analysis included pH, alkalinity, soil organic carbon, available nitrogen, phosphorus, potassium, calcium carbonate, calcium, magnesium, sulphur, zinc, and iron. Soil pH was measured in a soil-water suspension using a calibrated pH meter. Organic carbon was determined by wet oxidation. Available nitrogen, phosphorus, and potassium were measured by standard soil-testing procedures. Calcium carbonate and micronutrients were determined using appropriate laboratory methods.

The chemical data are included because dielectric response can be influenced by more than texture. Organic matter, soluble ions, calcium carbonate, and exchangeable cations may change the polarization behaviour of the soil. Under air-dried conditions these effects are moderate, but they are still useful for explaining sample-to-sample differences.

3.4 Microwave Dielectric Measurement

Dielectric measurements were performed on a standard klystron-based microwave bench at three frequencies: 4.7 GHz (C-band), 5.8 GHz (J-band), and 9.68 GHz (X-band). The measurement system consisted of a klystron oscillator and power supply, isolator, variable attenuator, frequency meter, slotted waveguide section, travelling probe carriage, sample holder, crystal detector, and VSWR meter. Standard rectangular waveguides suitable for the selected frequency bands were used.

The soil sample was packed uniformly into the waveguide sample holder. Care was taken to keep the sample surface flat and to maintain comparable packing density for all samples. The sample holder was placed at the short-circuited end of the waveguide. Measurements were repeated to improve reliability, and the mean dielectric constant was used for reporting.

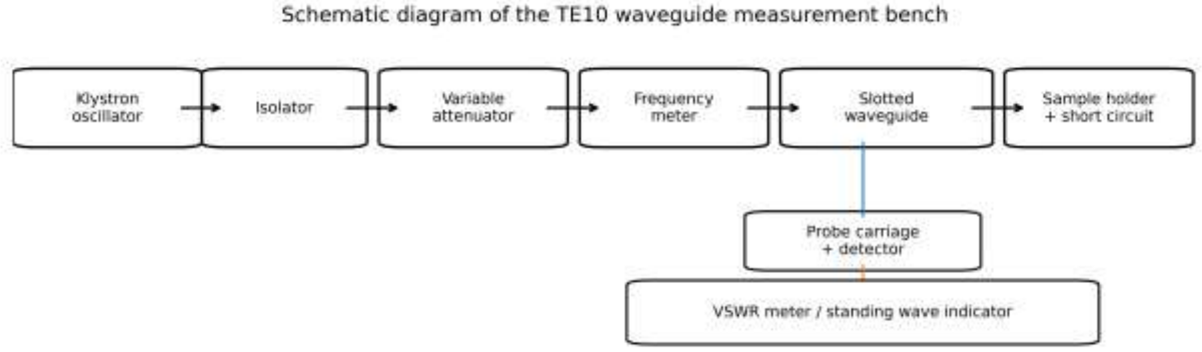

Figure 2. Schematic diagram of the TE10 waveguide bench used for microwave dielectric measurement.

3.5 Principle of the VSWR Double-Minima Technique

The double-minima method is based on the change in the standing-wave pattern produced by inserting a dielectric sample in a short-circuited waveguide. Without a sample, the positions of voltage minima are recorded along the slotted line. After the sample is inserted, the minima shift and broaden because the sample changes the wave impedance and phase condition inside the guide. The positions of two points on either side of the shifted minimum are identified where the detector reading corresponds to the double-minima condition.

The measured quantities include guide wavelength, sample thickness, shifted minimum position, and the distance between the two double-minima points. These values are used to calculate ε' and, where required, loss tangent. In the present manuscript, the main reported dielectric parameter is ε'. The method is suitable for comparative evaluation because all samples were tested using the same measurement procedure and sample-preparation protocol.

Measurement uncertainty may arise from sample thickness error, non-uniform packing, air gaps, imperfect short-circuit contact, frequency drift, and detector reading variations. To minimize these effects, the waveguide system was tuned before each measurement, the frequency was checked with the frequency meter, and each sample was measured under similar conditions.

3.6 Statistical Treatment

Descriptive statistics, including mean, standard deviation, minimum, and maximum, were calculated for the dielectric constant at each frequency band. Percentage decrease from C-band to X-band was calculated for each sample to quantify frequency dispersion. Pearson correlation coefficients were calculated between selected soil properties and dielectric constants at the three frequencies. Because the dataset contains only ten samples, the correlation results are treated as exploratory indicators rather than as final predictive models.

Graphs were prepared to visualize texture composition, frequency dependence, average dielectric values, clay-dielectric relationships, sampling locations, percentage decrease, and correlation patterns. These visualizations help present the data more clearly and support interpretation of the measured values.

4. Results

4.1 Soil Physical Properties and Texture

The physical properties and textural classification of the ten soil samples are presented in Table 1. Sand content ranged from 40% in Sample 23 to 58% in Sample 21. Silt content ranged from 26% in Sample 21 to 40% in Sample 25. Clay content ranged from 14% in Sample 26 to 24% in Sample 23. Eight samples were classified as loam, while Samples 21 and 24 were classified as sandy loam.

The dominance of loam and sandy loam textures indicates that the selected soils are medium textured rather than extremely sandy or extremely clayey. This is important for interpreting the dielectric data because a narrow textural range may reduce the strength of simple linear relationships between clay percentage and dielectric constant. In other words, the dielectric response is expected to be influenced by combined physical and chemical factors rather than by clay content alone.

Table 1. Location, physical properties, and textural classification of Buldhana District soil samples.

Sr.	Sample ID	Latitude (°N)	Longitude (°E)	Sand (%)	Silt (%)	Clay (%)	Soil Texture
1	21	19.93	76.07	58	26	16	Sandy Loam
2	22	19.93	76.09	46	38	16	Loam
3	23	19.9	76.27	40	36	24	Loam
4	24	19.88	76.23	54	30	16	Sandy Loam
5	25	19.87	76.21	42	40	18	Loam
6	26	19.88	76.19	52	34	14	Loam
7	27	19.87	76.19	50	32	18	Loam
8	28	19.87	76.12	44	34	22	Loam
9	29	19.91	76.09	48	36	16	Loam
10	30	19.95	76.27	46	34	20	Loam

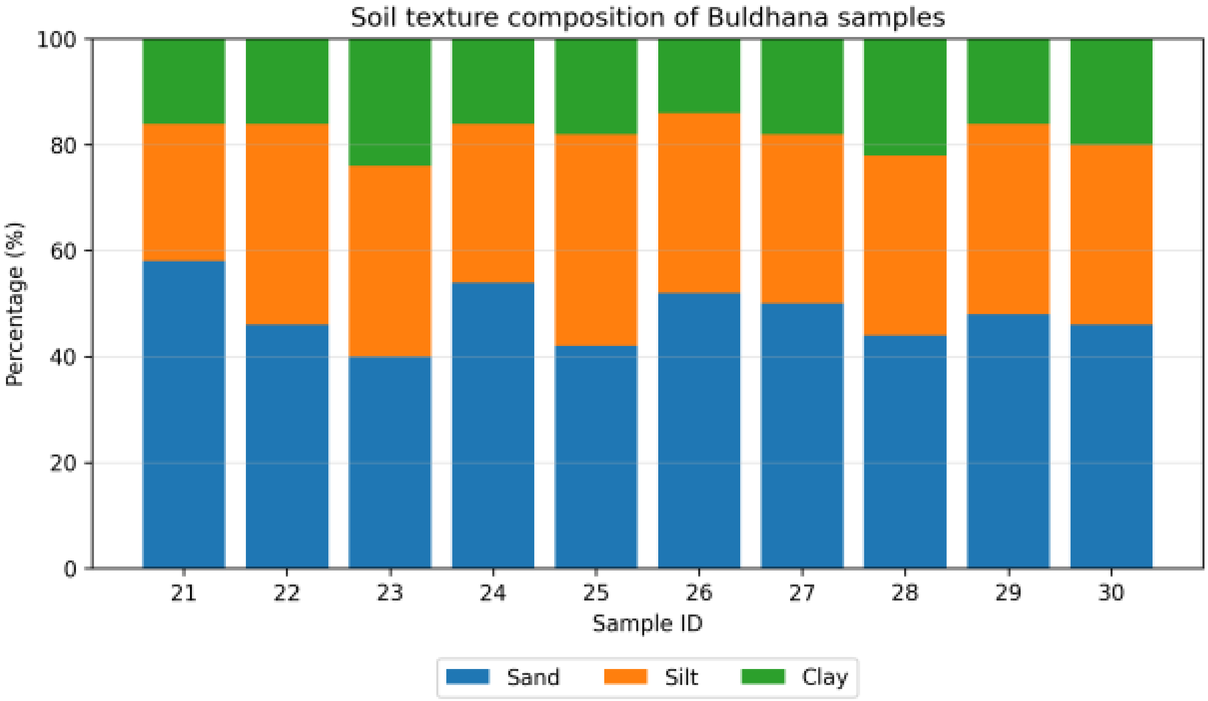

Figure 3. Sand, silt, and clay composition of the ten Buldhana soil samples.

4.2 Chemical Properties

The chemical properties of the samples are summarized in Tables 2a and 2b. The soils were slightly to moderately alkaline, with pH values ranging from 7.5 to 8.1. Such alkaline reaction is common in many basalt-derived soils of Maharashtra, particularly where calcium carbonate accumulation occurs. Calcium carbonate content ranged from 10.1% to 16.5%, indicating the presence of free lime in all samples.

Soil organic carbon ranged from 0.25% to 0.75%. The lowest SOC was observed in Sample 23, while the highest SOC was recorded in Sample 28. Available nitrogen varied widely from 83 to 544 kg/ha. Available phosphorus ranged from 4.11 to 22.0 kg/ha, and available potassium ranged from 303 to 616 kg/ha. The high potassium status in several samples is consistent with the nature of many black soils, which often contain potassium-bearing minerals and have high potassium retention capacity.

Among the micronutrient-related values, zinc showed considerable variation, from 0.03 ppm in Sample 29 to 1.96 ppm in Sample 28. Iron ranged from 0.50 ppm to 2.64 ppm. These chemical variations are useful because they may partly explain why soils with similar texture do not always show identical dielectric behaviour.

Table 2a. Major chemical properties of Buldhana District soil samples.

Sr.	Sample ID	pH	Alk.	SOC (%)	N (kg/ha)	P2O5 (kg/ha)	K2O (kg/ha)	CaCO3 (%)
1	21	7.5	0.25	0.26	139	14.8	360	10.1
2	22	8.1	0.18	0.29	92	4.11	303	10.2
3	23	7.9	0.27	0.25	83	5.56	314	13
4	24	7.9	0.14	0.68	152	22	616	12.8
5	25	8	0.65	0.6	406	16	325	10.7
6	26	7.9	0.12	0.35	356	16	392	15.2
7	27	7.7	0.38	0.45	280	4.6	504	16.5
8	28	7.9	0.47	0.75	544	21.05	436	14.2
9	29	7.6	0.27	0.28	294	11.83	549	10.4
10	30	7.9	0.36	0.35	130	5.08	347	11.5

Table 2b. Secondary and micronutrient properties of Buldhana District soil samples**.**

Sr.	Sample ID	Ca (ppm)	Mg (ppm)	S (ppm)	Zn (ppm)	Fe (ppm)
1	21	2.4	1.6	3.1	0.22	1.29
2	22	2.2	1.4	6.14	0.42	0.5
3	23	1.6	1	3.07	0.3	2.64
4	24	2.5	1.9	3.07	0.54	1.16
5	25	3.3	1.6	9	0.94	1.56
6	26	2.6	1.4	5.5	0.36	1.54
7	27	2.9	1.5	6.42	0.78	1.38
8	28	2.4	1.3	12.56	1.96	1.36
9	29	3.2	1.1	3.1	0.03	1
10	30	3.2	2.1	15.56	0.74	0.72

4.3 Dielectric Constant at C-, J-, and X-Bands

The measured dielectric constants are presented in Table 3. At C-band, ε' ranged from 3.4601 to 4.9611. The lowest C-band value was observed for Sample 23, while the highest value was observed for Sample 30. At J-band, ε' ranged from 3.0238 to 3.8104, with Sample 30 showing the lowest value and Sample 24 showing the highest value. At X-band, ε' ranged from 1.8840 to 2.8970, with Sample 26 showing the lowest value and Sample 30 showing the highest value.

A common pattern is visible in all samples: ε' decreases as the measurement frequency increases. This behaviour is consistent with dielectric dispersion. At 4.7 GHz, slower polarization mechanisms contribute more strongly to the measured dielectric constant. At 9.68 GHz, some of these mechanisms cannot respond fully to the rapidly alternating electric field, and the measured ε' becomes lower.

The result also shows that samples with similar texture may still differ in dielectric response. For example, Samples 21 and 24 are both sandy loam with 16% clay, yet Sample 24 has a much higher C-band and J-band dielectric constant. This difference may be related to its higher SOC and high available potassium. Similarly, Sample 23 has the highest clay content but not the highest dielectric constant, suggesting that clay percentage alone is not sufficient to explain all variations in the dataset.

Table 3. Measured dielectric constants and percentage decrease from C-band to X-band.

Sr.	Sample ID	Sand (%)	Silt (%)	Clay (%)	Soil Texture	ε' C-Band (4.7 GHz)	ε' J-Band (5.8 GHz)	ε' X-Band (9.68 GHz)	Decrease C to X (%)
1	21	58	26	16	Sandy Loam	4.1432	3.3001	2.5734	37.89
2	22	46	38	16	Loam	3.5576	3.1242	2.6815	24.63
3	23	40	36	24	Loam	3.4601	3.0282	1.9829	42.69

Sr.	Sample ID	Sand (%)	Silt (%)	Clay (%)	Soil Texture	ε' C-Band (4.7 GHz)	ε' J-Band (5.8 GHz)	ε' X-Band (9.68 GHz)	Decrease C to X (%)
4	24	54	30	16	Sandy Loam	4.8774	3.8104	2.7939	42.72
5	25	42	40	18	Loam	3.7116	3.3965	1.9405	47.72
6	26	52	34	14	Loam	3.5042	3.053	1.884	46.24
7	27	50	32	18	Loam	4.6841	3.292	1.9781	57.77
8	28	44	34	22	Loam	3.8137	3.6918	2.7343	28.3
9	29	48	36	16	Loam	3.596	3.3992	2.3829	33.73
10	30	46	34	20	Loam	4.9611	3.0238	2.897	41.61

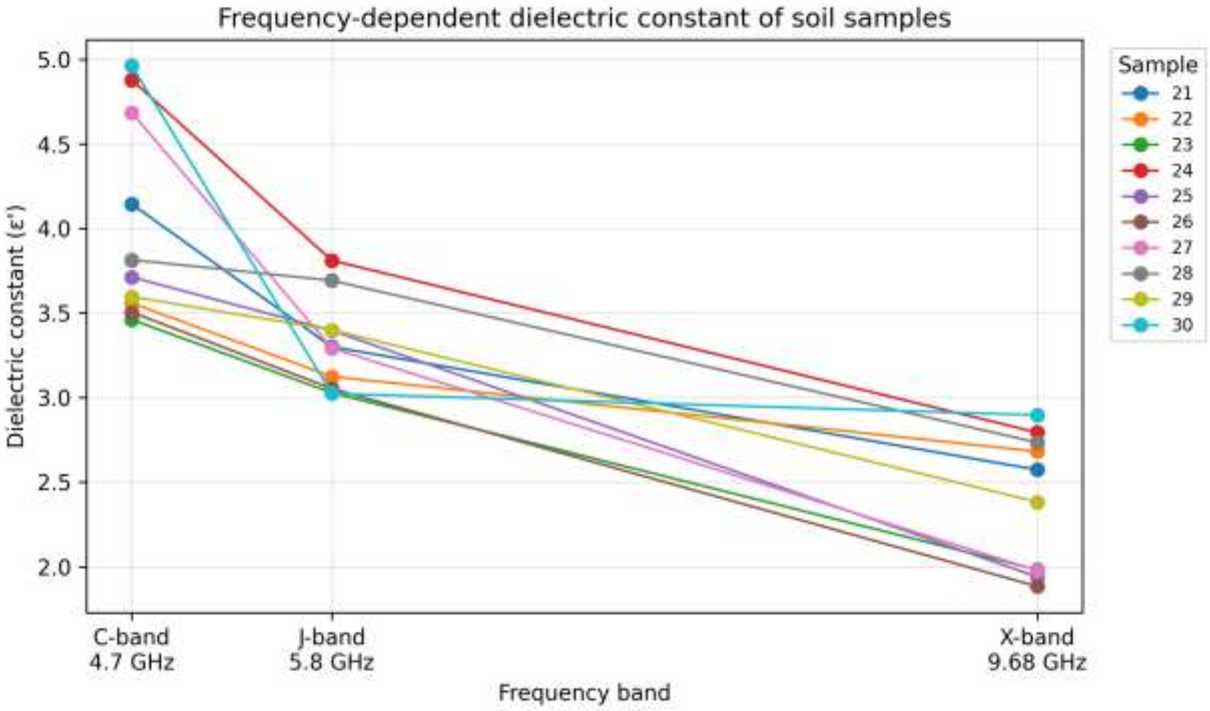

Figure 4. Frequency-dependent variation of dielectric constant for individual soil samples.

4.4 Descriptive Statistics of Dielectric Data

The descriptive statistics of dielectric constant at each frequency band are given in Table 4. The mean ε' was 4.0309 at C-band, 3.3119 at J-band, and 2.3849 at X-band. The standard deviation was highest at C-band, indicating greater sample-to-sample variation at the lower frequency. The observed decrease in the mean value from C-band to X-band supports the frequency-dispersion behaviour noted in the individual sample data.

The average reduction from 4.7 GHz to 9.68 GHz was approximately 40.33%. The smallest reduction was observed for Sample 22, while the largest reduction was observed for Sample 27. This difference in percentage reduction suggests that the sensitivity of soils to frequency change varies from sample to sample. Such variation may reflect differences in clay surface properties, organic carbon, carbonate content, exchangeable cations, and internal soil structure.

Table 4. Descriptive statistics of dielectric constant at the three microwave frequency bands.

Band	Mean ε'	SD	Minimum	Maximum
C-band (4.7 GHz)	4.0309	0.595	3.4601	4.9611
J-band (5.8 GHz)	3.3119	0.2736	3.0238	3.8104
X-band (9.68 GHz)	2.3848	0.4015	1.884	2.897

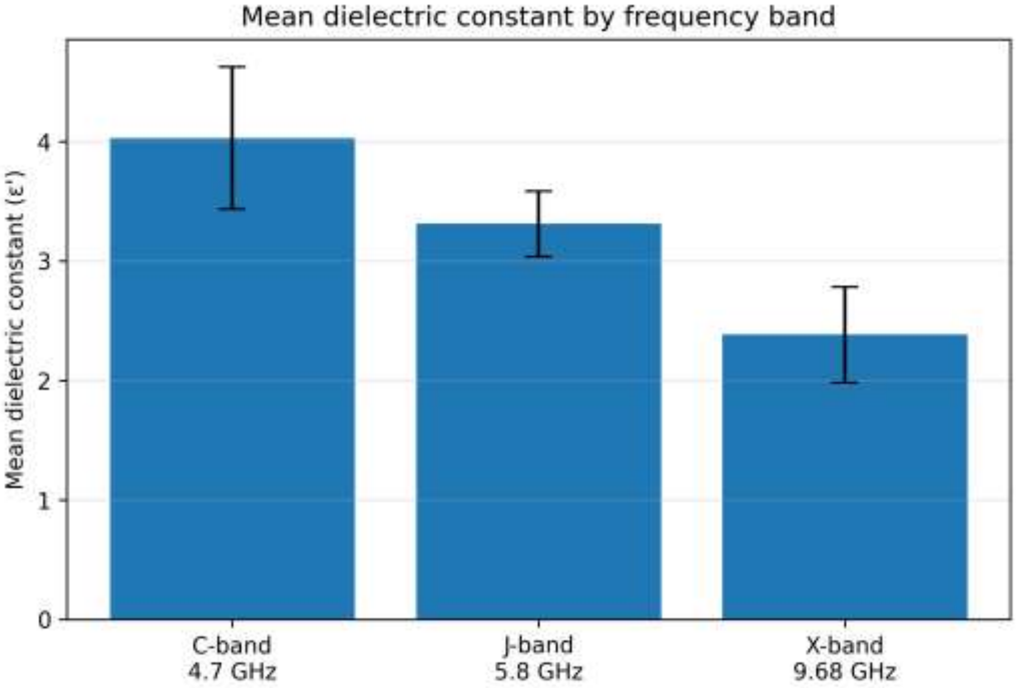

Figure 5. Mean dielectric constant at C-, J-, and X-band frequencies with standard deviation.

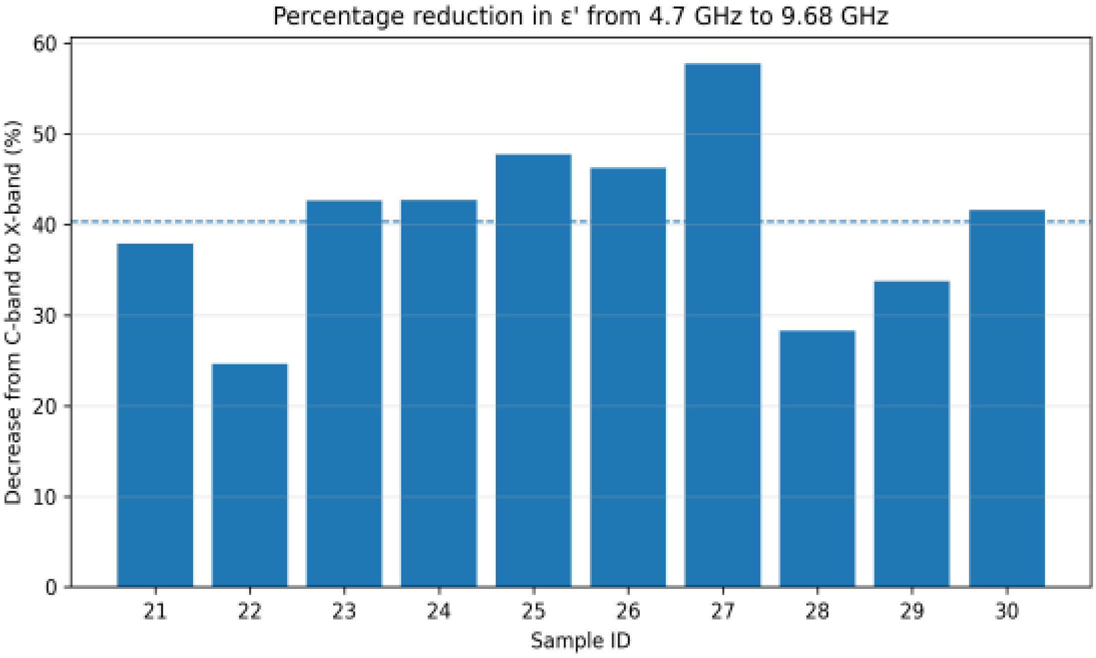

Figure 6. Percentage decrease in dielectric constant from C-band to X-band for each sample.

4.5 Correlation Analysis

Correlation analysis was used to examine the relationship between selected soil properties and dielectric constant. The results are shown in Table 5 and Figure 7. Since the number of samples is small, these correlations should be interpreted carefully. They are useful for identifying possible trends, but they should not be treated as a universal model.

In the present dataset, clay content did not show a strong direct linear correlation with dielectric constant. This finding does not contradict the general understanding that clay minerals influence dielectric behaviour. Rather, it indicates that in this particular set of ten air-dried samples, the clay range was relatively narrow and other factors also played important roles. SOC showed a strong positive correlation with J-band ε' (r = 0.81), and available potassium also showed a positive association with J-band ε' (r = 0.70). Magnesium showed a strong positive relation with C-band ε' (r = 0.82), while iron showed a negative relation with X-band ε' (r = -0.66). These observations may reflect combined chemical and physical effects, but they require further validation with a larger dataset.

The correlation pattern supports a more balanced interpretation of the results. The dielectric response of Buldhana soils is not controlled by only one variable. Instead, it appears to be the result of interactions among soil texture, organic matter, carbonate content, exchangeable ions, and the measurement frequency.

Table 5. Pearson correlation coefficients between selected soil properties and dielectric constant.

Parameter	r with C-band	r with J-band	r with X-band
Sand (%)	0.4	0.22	0.22
Silt (%)	-0.53	-0.25	-0.32
Clay (%)	-0.03	-0.06	0.02
pH	-0.17	-0.1	0.03
Alkalinity	0	0.18	-0.18
SOC (%)	0.29	0.81	0.19
N	-0.25	0.43	-0.24
P2O5	-0.01	0.77	0.15
K2O	0.43	0.7	0.17
CaCO3	0.18	0.05	-0.4
Ca	0.34	0.13	0
Mg	0.82	0.13	0.49
S	0.3	-0.07	0.34
Zn	0.13	0.45	0.21
Fe	-0.35	-0.12	-0.66

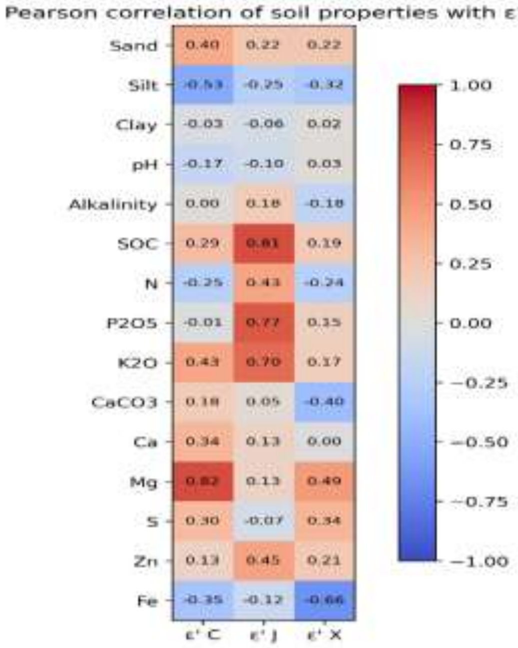

Figure 7. Correlation matrix showing the association of soil properties with dielectric constant at three frequency bands.

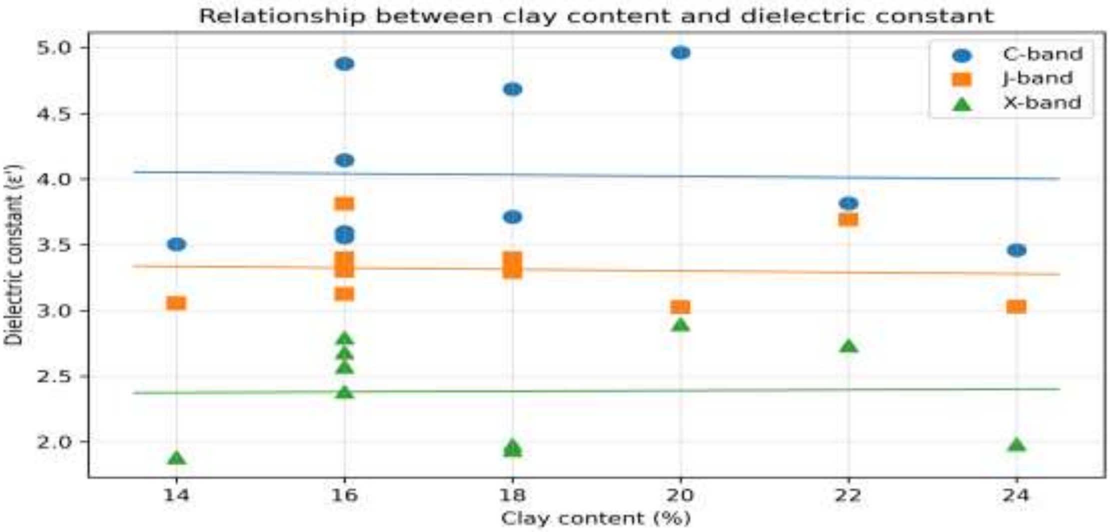

Figure 8. Relationship between clay content and dielectric constant at C-, J-, and X-band frequencies.

5. Discussion

5.1 Frequency Dependence of Dielectric Constant

The most consistent result of the study is the decrease in dielectric constant with increasing frequency. All ten samples followed the same general trend from C-band to X-band. This observation agrees with the dielectric relaxation concept and with earlier microwave soil studies [2, 4, 24, 30]. At lower microwave frequencies, dipolar and interfacial polarization mechanisms contribute more effectively to ε'. As frequency increases, these mechanisms become less able to follow the applied field, and the measured dielectric constant decreases.

The decrease was not identical for all samples. Some samples, such as Sample 27, showed a large reduction from C-band to X-band, whereas Sample 22 showed a smaller reduction. A large reduction suggests stronger frequency dispersion, which may be associated with a greater contribution from slower polarization processes at lower frequency. Such processes can be linked with bound water layers, ion-rich interfaces, and particle contact regions.

From an application perspective, this means that a dielectric value measured at one frequency cannot be directly transferred to another frequency without correction. For example, using a C-band dielectric value in an X-band model would overestimate the dielectric constant for these air-dried soils. Therefore, frequency-specific dielectric measurements are necessary when developing electromagnetic models for soil.

5.2 Influence of Texture

Soil texture is traditionally considered one of the key controls on dielectric behaviour. Clay minerals have high surface area and carry surface charge, which allows them to retain adsorbed water and exchangeable ions. For this reason, clay-rich soils often show higher dielectric constants than sandy soils when moisture conditions are similar [2, 4, 15].

In the present study, however, clay content alone did not show a strong linear relationship with ε'. This result deserves careful interpretation. The clay content of the samples varied only from 14% to 24%, which is a comparatively narrow range. Within such a range, other soil properties can mask the direct influence of clay. Sample 23, for instance, had the highest clay percentage but did not have the highest dielectric constant. This suggests that mineralogical type, carbonate content, SOC, packing behaviour, and chemical properties may have modified the expected clay effect.

The two sandy loam samples also illustrate the complexity of the relationship. Sample 21 and Sample 24 both had 16% clay, but Sample 24 showed a much higher dielectric constant at C- and J-bands. Its higher SOC and high available potassium may have contributed to greater polarization. This reinforces the need to interpret dielectric measurements using complete soil characterization rather than texture alone.

5.3 Influence of Chemical Properties

The chemical properties of the soils provide additional insight into the measured dielectric differences. Soil pH values were alkaline but varied within a narrow range, so pH alone is unlikely to explain the dielectric variation. Calcium carbonate content was relatively high in all samples. Calcium carbonate can influence dielectric response both directly, through its own dielectric properties, and indirectly, by affecting soil structure and the distribution of fine particles.

Organic carbon showed a notable association with J-band dielectric constant in the correlation analysis. Organic matter can influence dielectric behaviour by holding adsorbed water and contributing polar functional groups. Even in air-dried samples, organic-rich micro-regions may retain small amounts of bound water. Sample 28, which had the highest SOC, also showed a relatively high J-band and X-band dielectric constant. However, because the dataset is small, this relationship should be viewed as indicative rather than conclusive.

Available potassium showed a positive association with J-band ε'. This may be linked to ionic polarization or to the mineralogical background of potassium-bearing soil fractions. Similarly, magnesium showed a strong association with C-band ε'. These relationships require further study, ideally with controlled moisture levels and a larger number of samples. Still, the present results show that chemical properties should not be ignored in microwave dielectric interpretation of soils.

5.4 Comparison with Earlier Studies

The dielectric constant values measured in this study fall within the expected range for air-dried mineral soils at microwave frequencies. Hallikainen et al. [2] and Dobson et al. [4] reported that soil dielectric behaviour changes with texture, moisture, and frequency. Behari [33] summarized similar behaviour for wet and low-moisture soils, including Indian soil types. The present C-band range of 3.4601 to 4.9611 and X-band range of 1.8840 to 2.8970 are reasonable for air-dried granular soils.

The frequency trend observed here is also consistent with the theoretical and experimental literature. Earlier studies have shown that dielectric constant generally decreases with increasing frequency when relaxation mechanisms are present [24, 25, 30]. The average reduction of about 40.33% from 4.7 GHz to 9.68 GHz in the present data is therefore physically meaningful. It indicates that the Buldhana soils show measurable microwave dispersion even under air-dried conditions.

One difference between the present study and many classic datasets is that the current work focuses on a regional group of soils with a relatively narrow texture range and detailed chemical information. This helps explain why the simple clay-dielectric relationship is weaker here than in broader datasets containing a wider range of clay contents and moisture levels. Such local differences are exactly why regional dielectric datasets are useful.

5.5 Practical Applications of the Buldhana Soil Dielectric Dataset

The measured data can be used as a baseline dielectric reference for Buldhana District soils. In microwave remote-sensing studies, soil dielectric constant is one of the key inputs for interpreting radar backscatter and microwave emission. Although the present measurements were made on air-dried soils, they provide the dry-end reference needed for developing moisture-dependent dielectric models.

The dataset may also support precision agriculture research. Soil moisture estimation, field variability assessment, and electromagnetic modelling all require reliable knowledge of how local soils interact with microwave energy. In areas where field instrumentation is limited, laboratory dielectric measurements can help build local calibration datasets.

The results are also useful for microwave material-characterization laboratories. They demonstrate that a standard TE10 waveguide bench can detect measurable differences among soil samples and can be used for comparative soil studies. The method is particularly suitable for college and university laboratories because it uses widely available microwave bench.

5.6 Limitations of the Study

The present study has some limitations. First, only ten soil samples were analysed. This number is sufficient for a preliminary regional dataset but not enough to develop a universal predictive model. Second, the measurements were performed on air-dried soils. Field soils usually contain variable moisture, and moisture has a strong influence on dielectric constant. Therefore, the values reported here should be interpreted as baseline values rather than field-moist values.

Third, the study reports mainly the real part of permittivity, ε'. The dielectric loss factor, ε", and loss tangent are also important for attenuation and energy dissipation studies. Future work should include both real and imaginary components of complex permittivity. Fourth, clay mineralogy was not separately identified. Since different clay minerals have different surface properties, mineralogical analysis would help improve interpretation.

Despite these limitations, the study provides a useful foundation. It demonstrates measurable frequency dispersion, documents physical and chemical soil properties, and provides a dataset that can be expanded in future work.

6. Conclusion

The microwave dielectric properties of ten soil samples from Buldhana District were measured at C-band, J-band, and X-band frequencies using the TE10 waveguide VSWR double-minima method. The soils were also characterized for texture and selected chemical properties. The samples were mainly loam and sandy loam, with clay content ranging from 14% to 24%. The soils were slightly to moderately alkaline and contained measurable calcium carbonate, organic carbon, and available nutrients.

The dielectric constant decreased consistently with increasing frequency. Mean ε' decreased from 4.0309 at C-band to 3.3119 at J-band and 2.3849 at X-band. The average reduction from C-band to X-band was approximately 40.33%. This confirms that Buldhana soils show clear frequency-dependent dielectric behaviour under air-dried laboratory conditions.

The results also show that dielectric variation cannot be explained by a single soil property. Clay content is physically important, but in this dataset its direct linear correlation with ε' was weak because the clay range was narrow and other factors contributed. Organic carbon, potassium, magnesium, calcium carbonate, and sample-specific structure appear to influence the measured response. Therefore, combined physical and chemical characterization is necessary for meaningful dielectric interpretation.

The study provides a regional dielectric baseline for Buldhana District soils and demonstrates the usefulness of the waveguide double-minima method for soil characterization. Future work should include controlled moisture levels, more sampling locations, dielectric loss measurements, mineralogical analysis, and lower-frequency bands such as L- and S-band. Such extended work would help develop stronger soil-specific dielectric models for agricultural and remote-sensing applications.

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