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Investigating The Influence Of Texture And Color On Dielectric Properties Of Soil At Microwave Frequency

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Abstract
The present investigation conducted dielectric constant measurements at the X, J, and C bands of the microwave bench. Soil samples were collected from farming land of Buldhana region of Maharashtra state, India and subsequently evaluated for their physical and chemical properties. We have examined the influence of color and texture on the dielectric constant of soil samples. It was observed that soil texture significantly affects dielectric properties, with higher clay and silt content leading to increased dielectric constants due to greater water retention, while sandy soils exhibit lower values. Frequency-dependent behavior was observed, with the highest ε' and ε" values in the C band. The dielectric loss tangent (tan δ) increased with frequency, with red soil displaying a notable spike in loss at the C band, likely due to iron oxide interactions. These findings highlight the critical role of soil composition and color in determining dielectric behavior, providing valuable insights for applications in soil moisture sensing, precision agriculture, and remote sensing. The study underscores the importance of considering both dielectric constant and loss tangent in microwave-based soil analysis.
Keywords: *dielectric constant, microwave, organic matter, soil color, soil texture*

INTRODUCTION

Soil is a multifaceted natural resource, essential for sustaining terrestrial ecosystem and human activities. Its multifaceted composition organic matter, blend of minerals, water and air makes it one of the most dynamic and vital natural resources on earth. Soil is a complex and dynamic material that vary significantly across different regions and environments[1]. The important characteristics and behaviour of soil is useful to understand challenges in agriculture and geotechnical engineering. Soil testing refers to the qualitative analysis of soil and widely recognized as a scientific method for evaluating the inheriting fertility status of soil [2]. The relationship between soil texture and plant growth is well-documented. Variation in texture affects a ground vegetation, root development, and overall crop performance [3].
Soil texture defines the mixture of sand, silt and clay particle, plays a crucial role in shapes how the soil functions. The variation in texture of soil directly influences soil behaviour, including water retention, drainage efficiency, and nutrient -holding capacity [4]. Soil particles are classified by size, with sand particle ranging from 0.05 to 2 mm, silt ranges from 0.002 to 0.05 mm and the clay particles smaller than 0.002 mm. Fine textured soil which contains clay and silt retain more water due to their higher surface area compared to sand. Clay can hold up to 58% of their weight in water while sand retains less than 15% water [5].
Soil color provides valuable insights into soil properties, such as organic matter content, mineral composition, and drainage condition. The Munsell Soil Color System describes soil color using three parameters such as hue, value, and chroma [6]. Hue refers to the dominant spectral color, such as red, yellow, or brown, and is represented in the top right corner of the Munsell Soil Color Charts. Value indicates the lightness or darkness of the color, with a scale ranging from 0 (pure black) to 10 (pure white), and is represented along the vertical axis. Chroma measures the purity or intensity of the color, with lower values indicating more Grayness and higher values indicating greater saturation, this is depicted along the horizontal axis [7]. Darker soils typically indicate higher organic matter and fertility, while reddish or yellowish hues often suggest the presence of iron oxides. Greyish or bluish tones may signal poor drainage and reducing conditions [8]. High organic matter content in soil refers to brown and black soil due to the presence of humus, a complex organic substance made during decomposition. Red and yellow soils indicate the presence of iron oxides, such as hematite and goethite [9]. Grayish colors can be poor drained soil. White or light-colored soil may be rich in silica or calcium carbonate.
Microwave interact with material that depends on their electrical properties. When microwave hit a material then some energy bounce back, some passes through and some gets absorbed. The distribution

of the incident energy in proportion is defined as dielectric properties [10]. The dielectric properties consist of two key component real part (ε') which represent the dielectric constant that store energy. And imaginary part (ε") that is dielectric loss associated with energy dissipation[11]. The dielectric properties provide critical insights into material composition, moisture content, and structural characteristics, forming the basis for numerous technological applications in fields such as agriculture, geophysics, and telecommunications [12].

Understanding the dielectric response of soil, influenced by its physical and chemical properties, plays a crucial role in advancing soil moisture sensing, precision irrigation and surface modeling. The dielectric properties of soil depend on the presence of water content, temperature, texture, minerals and the organic matter present in it [13]. Texture of soil directly affects the dielectric constant and loss factor. Sandy soil has larger pore space and lower water retention which leads to lower dielectric constant, while the fine-texture such as clay retain more water due to their higher surface area, resulting in higher dielectric constant [14,15]. While the soil color and dielectric constant are not directly linked, but it provides valuable information about soil properties. The darker soils, often rich in organic matter tends to have higher dielectric constant due to their ability to hold water and their composition of electrically conductive materials. Conversely, lighter-colored soils, typically lower in organic and moisture content, generally exhibit a lower dielectric constant [16,17,18]

The dielectric loss tangent (tan δ) of soil measures how much electromagnetic (EM) energy is converted to heat when an alternating electric field is applied. In soil, tanδ is highly influenced by moisture content, frequency, soil composition, and temperature [19]. Wet soils exhibit significantly higher tanδ values as compared to dry soils, with sandy soils typically ranging from 0.01 (dry) to 0.3 (wet) at 1 GHz [20]. Clayey soils, due to bound water and surface conductivity, show even greater losses. Salinity further increases tan δ by enhancing ionic conduction, while organic matter contributes additional polar relaxation losses.

MATERIAL AND METHODS:

The soil samples were collected from different locations of Buldhana region of Maharashtra state at depth ranging from 0 – 20 cm in zigzag pattern. Zigzag sampling across the area created multiple transects, from which representative soils were collected. The number of transect and spacing depends on size and heterogeneity of study area. A bulk sample of about 1 to 2 kg was collected. For each site, soil from five pits along each transect was combined to represent the sampling area. This procedure was repeated for all sites [21]. The soil samples were first sieved by 300 microns to remove the coarser particles. Soil color is a valuable indictor of its properties and can provide insights. To identify the exact color of soil, we used Munsell soil color chart method. This is the standard tool for accurately identifying soil colors which contains a wide range of color chips organized by hue, value (lightness / darkness), and chroma (color intensity). To recognize the soil color, a small amount of moist soil was taken and held next to the color chips of Munsell chart to find the closest match.

Table 1 : Classification of soil texture

Sample	Color	Latitude	Longitude	Sand %	Silt %	Clay %
1	BLACK	20.311541^0	76.255527^0	60.22 %	20.23 %	19.55%
2	RED	20.633867^0	76.191684^0	70.43 %	22.30 %	7.27%
3	GRAYEISH ORANGE	20.377687^0	76.2375592^0	71.54%	21.78%	6.68%
4	LIGHT BROWN	20.462673^0	76.21873^0	68.30%	25.60%	6.10%
5	DARK YELLOWISH ORANGE	20.472814^0	76.214777^0	63.30%	29.60%	7.1%

EXPERIMENTAL SET UP:

1] Measuring the Dielectric properties of soil:

There are many methods for measuring dielectric constant of soil. In the present work, we used two-point method which is best known and most widely used for measuring dielectric properties of soil sample. It is appropriate to calculate dielectric constant and dielectric loss. The soil samples were measured by automated microwave bench setup at different microwave frequency bands (X, C, J) and utilized the two-point method for measuring dielectric constant and dielectric loss. The microwave bench setup consists of power supply, isolator, reflex klystron, slotted section, waveguide, attenuator, sample holder, frequency

meter, pc [22]. The block diagram of setup is as shown in Fig (1).
Fig 1: Automated microwave X band bench experimental setup

A reflex klystron served as the microwave source for this study. To establish a stable standing wave pattern within the waveguide assembly, the operating parameters were set at a beam voltage of 205 V, a beam current of 17 mA, and a repeller voltage of 77 V. An attenuator was employed to regulate the power output as required. A detector, connected to a circuit, measured the current along a slotted line, and converted it into digital values for computer processing. The probe, positioned within the slotted line, was carefully adjusted to its critical position to ensure consistent standing wave pattern measurements [23-25].
An empty sample holder was initially connected to the waveguide assembly, and the system was tuned to achieve a stable standing wave pattern. Subsequently, soil samples of varying thicknesses "1 cm, 2 cm, and 3 cm" were introduced into the sample holder under constant compaction. The probe was then traversed along the slotted line at regular intervals, and the corresponding power readings were recorded. This data acquisition process was facilitated by a microcontroller interface system and stored in an Excel sheet. The positions of three minima points were identified in the recorded data for each sample thickness, which subsequently enabled the calculation of the Voltage Standing Wave Ratio (VSWR).
This data is used for getting the outputs of VSWR values. The dielectric properties of solid material can be calculated for best fit of parameters. The guided wavelength λ_g is measured from the minima of the standing wave pattern.
$\beta = 2\pi / \lambda_g$
β= phase factor
The free space wavelength is determined using the relation
$1 / \lambda_0^2 = 1 / \lambda_g^2 + 1 / \lambda_c^2$
Where $\lambda_c = 2a$ 'a' is the inner broader side rectangular waveguide.
The real and imaginary parts of the complex dielectric constant are calculated using relation
$\varepsilon' = \lambda_0^2 \{1/ \lambda_c^2 + (\alpha^2 - \beta^2) / 4\pi^2\}$
$\varepsilon'' = \lambda_0^2 \alpha\beta / 2\pi^2$
ε′: - real part
ε′′: - imaginary part
α: - attenuation factor
A text file for computing dielectric constant was developed. The number of data text files, for different thickness in cm of samples were combined i.e. 1,2cm, 2,3cm, 1,3cm to get single input data file which can be used in the source code for calculating dielectric constant and loss.

2] Measuring Loss Tangent of soil sample:

Dielectric loss tangent, often denoted as tan δ (delta), is a measure of the energy loss in a dielectric material when it is subjected to an alternating electric field. In simpler terms, it quantifies how much electromagnetic energy is converted to heat as it passes through the material.

The dielectric loss tangent is defined as the ratio of the imaginary part to the real part of the complex permittivity of a material:

$\tan \delta = \varepsilon'' / \varepsilon'$

RESULT AND DISCUSSIONS

In this study, an experiment was conducted to see how much precisely one can measure the dielectric constat and dielectric loss of soil sample using waveguide cell method. The waveguide method has some specific source error and considering all the factors a number of readings were taken at band and the value of dielectric constant and loss which appears maximum number of times was taken as the true value of dielectric constant. The average of ε values was taken as true value of dielectric constant. Table 2 gives values of dielectric constant for Buldhana region.

Table 2 : Dielectric constant and loss at X, J, C band

Sample	X band		J band		C band		Loss tangent		
	ε′	ε″	ε′	ε″	ε′	ε″	X	J	C
Black	2.838	0.614	3.810	1.082	4.874	1.137	0.215	0.283	0.232
Red	2.668	0.507	3.578	0.818	4.534	1.108	0.187	0.226	0.344
Light Brown	2.647	0.663	3.344	0.892	4.343	1.057	0.161	0.275	0.248
Dark Yellowish Orange	2.78	0.458	3.483	0.966	4.432	1.184	0.207	0.336	0.288
Grayeish Orange	2.277	0.377	3.128	1.055	3.713	1.079	0.147	0.266	0.241

Table 3 : Classification of soil color

Sample	Color	huv	Value	Chroma
1	Black	1	0.1	0.4
2	Red	11.5	1.67	8.17
3	Light Brown	12.9	6.42	5.17
4	Dark Yellowish Orange	14.11	7.09	11.85
5	Grayeish Orange	18.9	6.84	11.32

Dielectric Behavior of Soils Across Microwave Frequencies

This experimental study revels connection between color and texture to their dielectric response focusing across X, J, and C band microwave frequency. Dark colored soils, particularly with black hues, contain evaluated organic matter and often include metal oxides. This helps to enhance both the real (ε') and imaginary (ε”) components of complex permittivity. The black soil reaches maximum ε' value of 4.87 in the C band, reflecting the combined effect of organic oxides which increases soils water holding capacity while meatal oxide can provide additional charge carriers that boost dielectric losses as shown in Fig (2) and (3).

Red soils behaved differently due to their iron oxide and primarily hematite (Fe_2O_3) content while their energy storage (ε') was moderate, but it showed an unusual spike in energy loss(ε”=1.56) at C band as shown in Fig (3). The iron oxide particles create interfacial polarization effects at grain boundaries and demonstrate resonant behaviour in certain frequency range. Intermediate soil colors, including grayish orange and light brown varieties, display transitional dielectric properties that reflect their mixed composition. The greyish orange soil, for instance, showed ε' values of 2.65 (X-band), 3.34 (J-band), and 4.34 (C-band), representing a middle ground between the extreme responses observed in black- and light-colored soils.

The experimental data demonstrates significant variations in dielectric behavior based on soil texture composition sand, silt and clay content across X, J, and C frequency band. Sandy soil consistently exhibits

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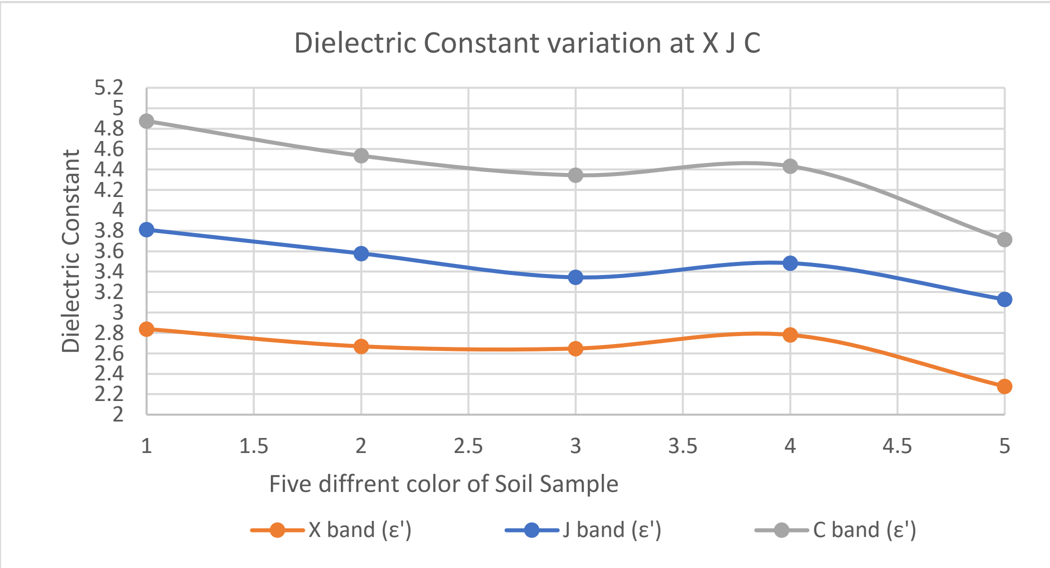
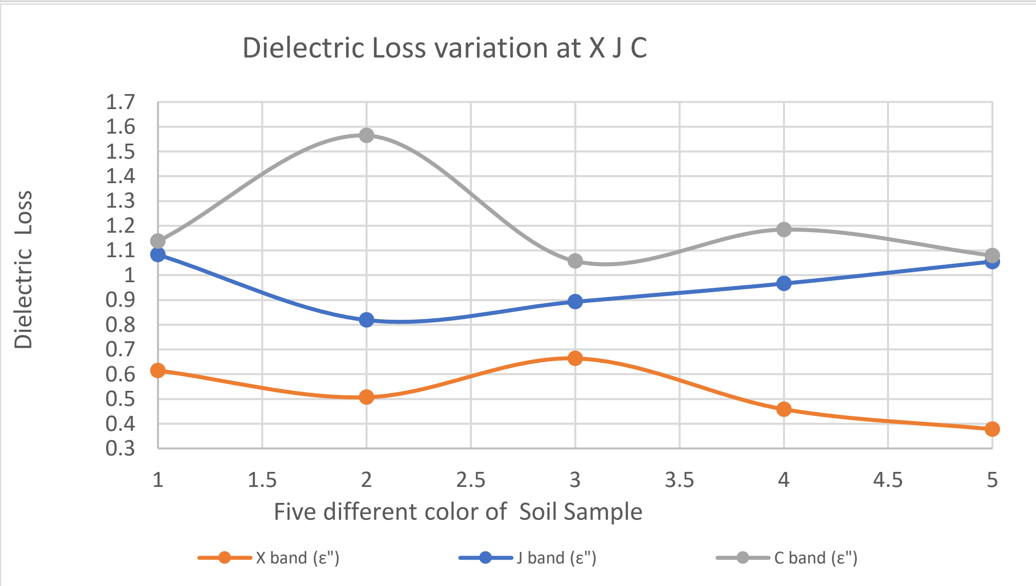
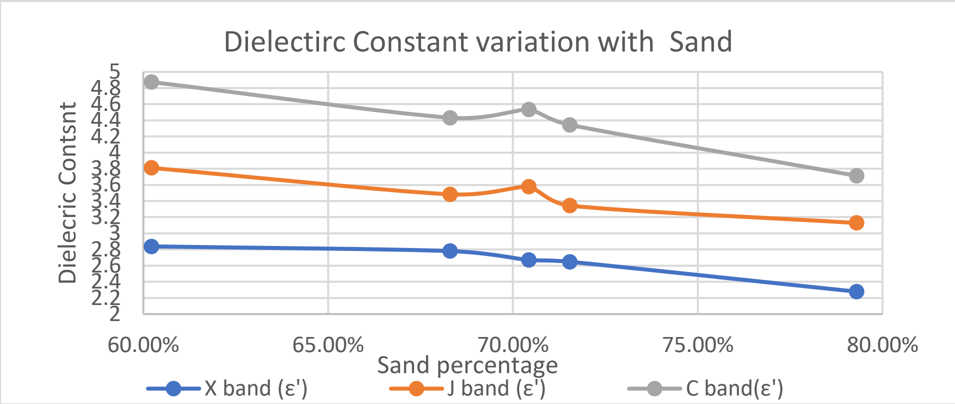
lowest dielectric constant and loss across all frequency bands. Increasing sand content from 60.2 % to 79.3% resulted in ε' decreasing from 2.48 to 2.28 in X band, 3.81 to 3.13 in J band and 4.87 to 3.71 in C band because large sand particles provide minimal surface area for water retention and generate weaker interfacial polarization effects compared to finer particles as shown in Fig (4) and (7).
Clay particles measured the strongest influence on dielectric properties due to their extremely high specific surface area and water retention capacity. Even modest clay content (19.6%) produced substantially higher permittivity values than sandy soils, with the C-band being particularly sensitive to clay effects (ε'=4.87) as shown in fig (6). This enhanced response stems from multiple mechanisms such as formation of tightly-bound water layers on clay surfaces, increased ionic mobility along charged particle surfaces, and strong interfacial polarization at particle boundaries. The X-band measurements proved especially effective for characterizing clay-bound water interactions.
Silt content showed an intermediate influence on dielectric properties, with effects more pronounced than sand but less dominant than clay as shown in fig (5). The J-band measurements appeared particularly responsive to silt-related dielectric behavior, likely due to silt's transitional particle size creating distinct polarization effects at these frequencies. Silt's moderate surface area and charge characteristics generate dielectric responses that bridge the gap between sand and clay behavior.





Fig(2) Variation of dielectric constant with five soil sample Fig (3) Variation of dielectric loss with five soil sample



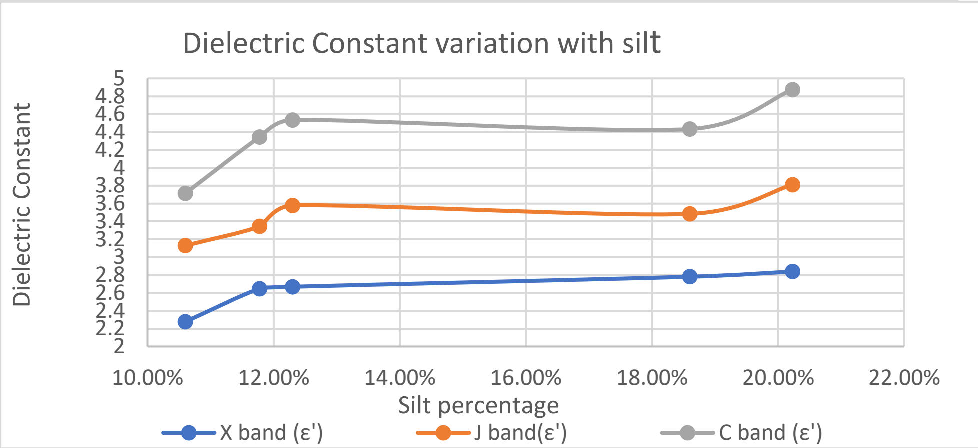


Fig (5) Variation of dielectric constant

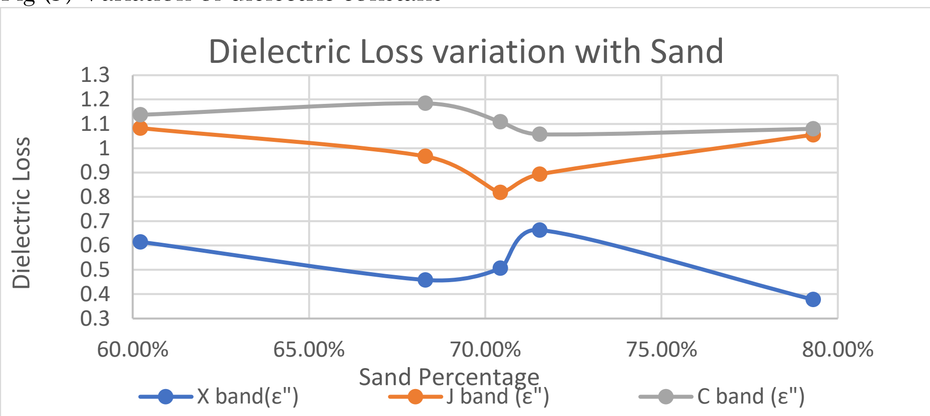


Fig (6) Variation of dielectric constant with % of Clay of Sand

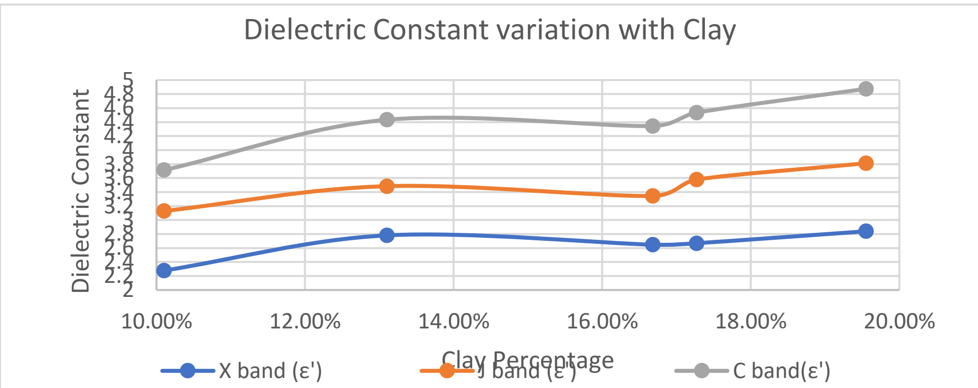
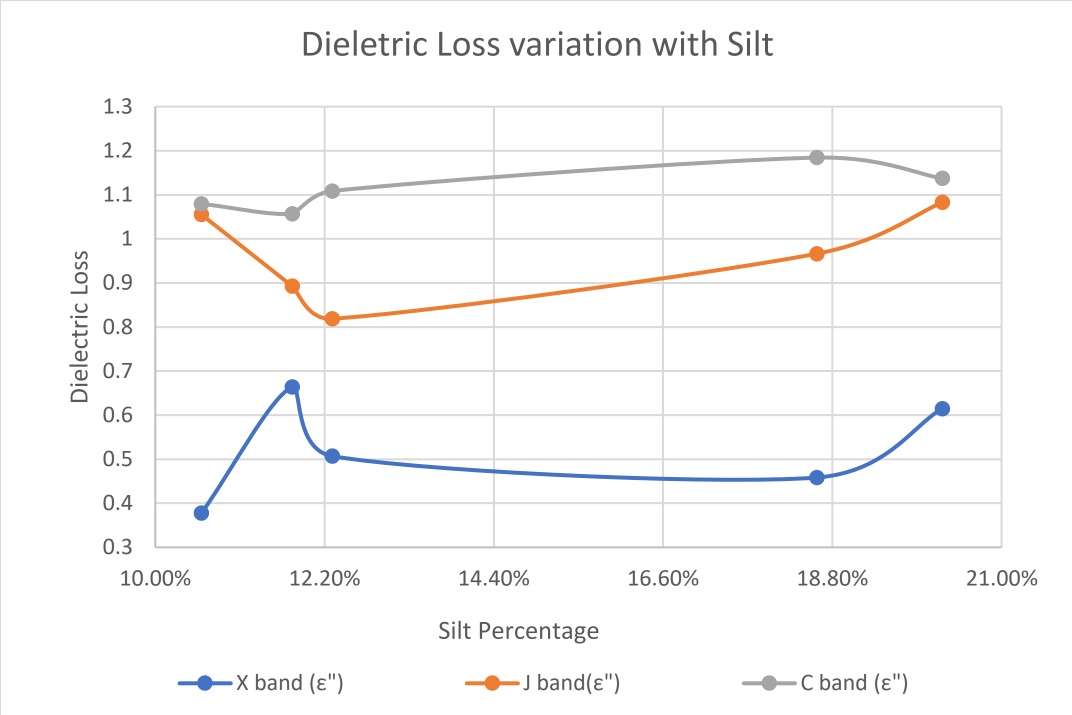
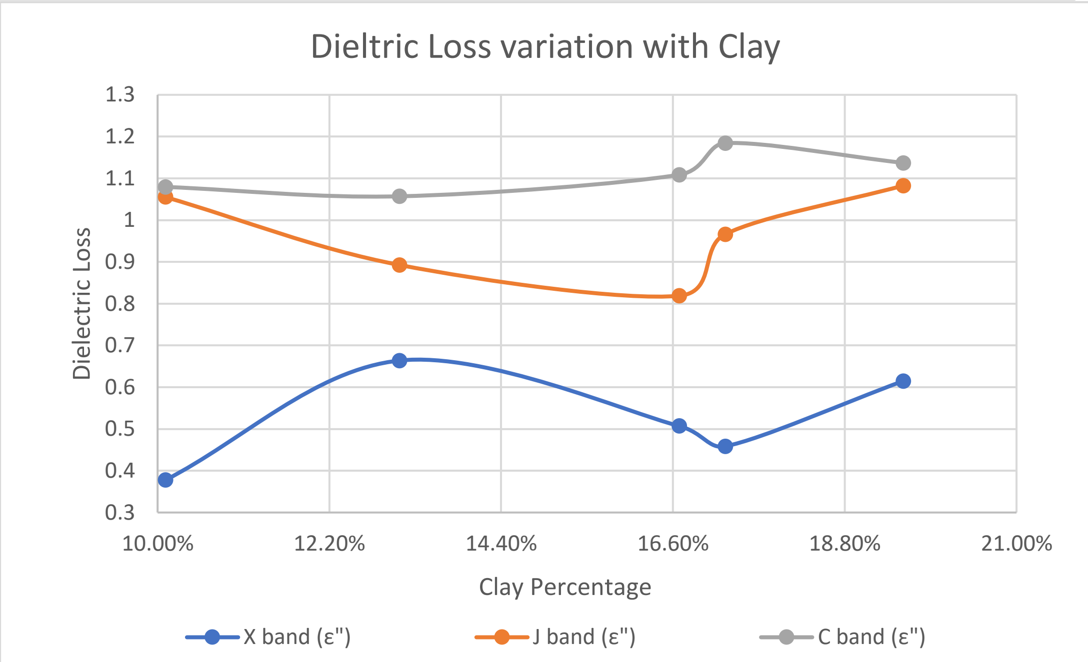


Fig (7) Variation of dielectric loss with %



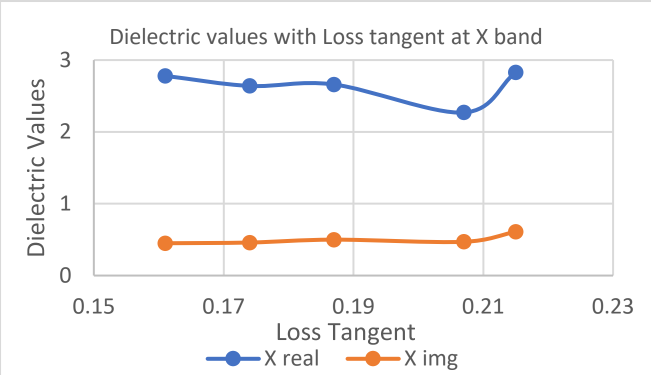


Fig(8) Variation of dielectric loss with % of Silt Fig (9) Variation of dielectric loss with % of Clay

Loss Tangent

The loss tangent, representing the ratio of energy lost to energy stored, increases progressively from X to J to C measurements, with values ranging from 0.161 to 0.344 as shown in Fig (11, 12, 13) . This pattern is accompanied by corresponding growth in both the real and imaginary components, strongly suggesting that the materials exhibit frequency-dependent or field-strength-dependent dielectric responses.

The black samples demonstrate particularly high energy storage capacity, reaching a real component value of 4.87 in the C measurements, but this is coupled with significant energy losses as evidenced by a loss tangent of 0.283 in the J measurements as shown in fig (11) and (12). In contrast, the red samples show extreme dissipation characteristics in the C measurements, achieving both the highest loss tangent 0.344 and largest imaginary component 1.56 observed. The light brown samples maintain notably low-loss properties in the X measurements, with a minimum loss tangent of 0.161 as shown in fig (10), suggesting potential suitability for applications requiring minimal energy dissipation.



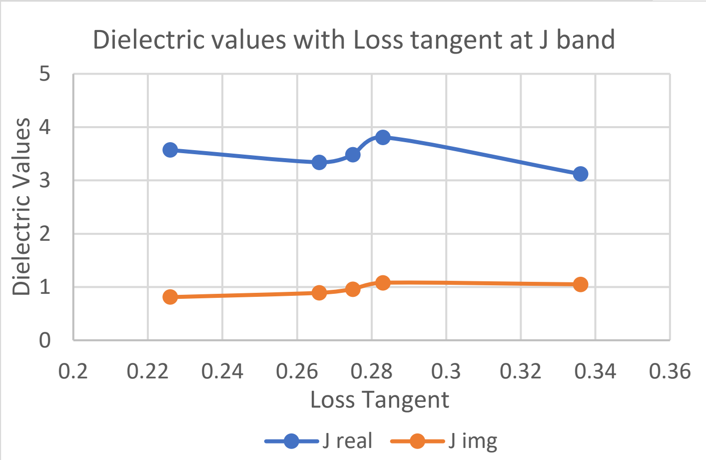


Fig (10)Dielectric values with Loss tangent at X band Fig (11) Dielectric values with Loss tangent at J band

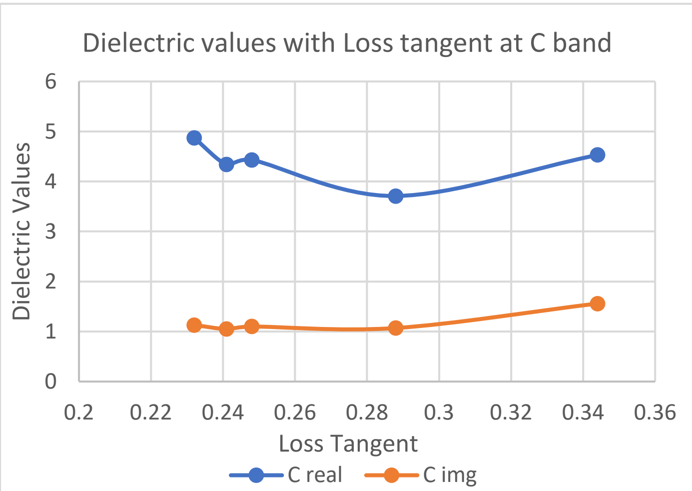


Fig (12) Dielectric values with Loss tangent at C band

CONCLUSIONS

The dielectric properties of soil are significantly influenced by its texture, color, and frequency. The dielectric constant increases with higher silt and clay content due to their greater water retention capacity, while sandy soils exhibit lower dielectric constants because of larger pore spaces and reduced moisture retention. Black soil, characterized by high organic matter and metal oxides, demonstrates the highest dielectric constant, confirming that darker soils generally have stronger dielectric responses.

Frequency dependent behavior is evident, with the highest dielectric values observed in the C band, followed by the J and X bands. The dielectric loss tangent (tan δ), which represents energy dissipation, increases progressively from the X band to the C band, indicating greater losses at lower frequencies. Notably, red soil shows an unusual spike in dielectric loss at the C band, likely due to iron oxide interactions. The study finds no consistent trend between dielectric loss and soil texture, suggesting that other factors such as mineral composition and bound water effects play a more dominant role. These findings highlight the complex interplay between soil composition, color, and electromagnetic frequency in determining dielectric behavior.

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