RESEARCH PAPER

Evolution of Dielectric Properties of Apple Based Soil from Mainpat Block of Surguja District

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Abstract

Soil dielectric properties are essential parameters that influence its interaction with electromagnetic fields and microwave energy. These properties are heavily impacted by soil texture, moisture content, bulk density, porosity, organic matter, salinity, and mineral composition. In the current study, the evolution of dielectric properties of apple-based orchard soil obtained from the Mainpat Block of Surguja District, Chhattisgarh, India, was explored utilizing soil physical and chemical parameters at two depths: 0-15 cm and 15-30 cm. Surface soil had higher organic carbon, porosity, water holding capacity, and nutrients than subsurface soil. These properties considerably improve the dielectric constant and dielectric loss factor. The study found that apple orchard soils in Mainpat have excellent physicochemical properties for significant dielectric response, particularly in upper soil layers. These findings are useful for precision agriculture, soil moisture detection, remote sensing, irrigation planning, and crop management. At various moisture levels (dry soil, 10%, 20%, 30%, and 40%), the real and imaginary parts of the dielectric constant were measured. The dielectric constant increases significantly with moisture content due to the high permittivity of water compared to soil particles. Experimental results indicate a strong dependence of dielectric behavior on moisture, bulk density, and soil texture. Because top soil (0–15 cm) has more porosity, organic content, and nutrient availability than subsurface soil, it exhibited a greater dielectric response. The study comes to the conclusion that precision orchard management and soil moisture monitoring can both benefit from dielectric measurements. The findings are useful for precision agriculture, soil moisture sensing, and electromagnetic soil characterization.

Keywords: Apple soil, Dielectric constant, Mainpat Block, Soil moisture, Texture, Porosity.

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1. Introduction

Soil is a multiphase system composed of solid particles, water, and air, and its physical and electrical properties are determined by the interaction of these components. Soil dielectric properties define the soil's ability to collect and discharge electromagnetic energy. These properties are represented as follows:

- **Real part of permittivity (ε′):** ability to store electric energy
- **Imaginary part of permittivity (ε″):** energy loss within soil
- **Loss tangent (tan δ):** ratio of energy loss to storage

These properties real part (dielectric constant, ε′), imaginary part (dielectric loss factor, ε″) and loss tangent (tan δ) are important soil parameters that depend heavily on moisture content.

These properties are collectively represented as a complicated dielectric constant:

$$\varepsilon^{*} = \varepsilon' - j\,\varepsilon''$$

Where **ε′** represents the **dielectric constant (energy storage capability)** and **ε″** represents the **dielectric loss factor (energy dissipation)**. These parameters are frequency-dependent and are influenced by soil composition, moisture content, and temperature.

Water has a much higher dielectric constant (~80) than dry soil (~3-5) or air (~1). This significantly influences soil dielectric behavior. Soils with increased moisture retention, organic matter, clay, and porosity have a stronger dielectric response. As a result, even minor differences in soil moisture produce large changes in dielectric behavior. This makes dielectric measurements an effective, non-destructive approach for assessing soil moisture content.

Dielectric properties are commonly used in:

- Techniques for measuring soil moisture include TDR, FDR, and capacitance sensors.
- Remote sensing and microwave radiometry.
- Studies on ground penetrating radar (GPR).
- Precision agriculture and irrigation scheduling.
- Modeling environmental and hydrological conditions.

Accurate understanding of soil dielectric behavior aids in irrigation optimization, crop production improvement, and effective water resource management.

The dielectric response of soil is influenced by several interrelated factors:

1. **Soil Moisture Content:** The most significant factor influencing dielectric characteristics. Increased moisture improves polarization and conductivity.
2. **Soil Texture (Sand, Silt, and Clay Composition):** Clay soils hold more water, resulting in a higher dielectric constant. Sandy soils drain quickly, resulting in a lower dielectric constant.
3. **Bulk density and porosity:** Higher density lowers air gaps while increasing dielectric permittivity.
4. **Soil salinity and electrical conductivity:** Dissolved ions cause higher dielectric loss (ε″).
5. **Organic Matter Content:** Affects water retention and dielectric response indirectly.

The Mainpat Block in Surguja District is a significant horticultural zone in Chhattisgarh, where apple cultivation has been successful due to favorable weather conditions. Apple orchard soils experience continual litter deposition, root biomass, and organic inputs, all of which can influence dielectric behavior. Understanding the dielectric behavior of apple orchard soils may be useful with irrigation scheduling, soil health monitoring, and sensor-based farming.

Despite the growing importance of dielectric studies, there has been little research into the dielectric properties of orchard soils in plateau regions such as Mainpat. The majority of existing studies focus on agricultural plains or sandy soils, creating a gap in our understanding of soils with mixed texture and moderate organic content.

The current work is to determine the evolution of dielectric properties in apple-based soil as a function of depth, moisture content, and physical, chemical, and nutrient availability soil variables.

2. Study Area

Surguja district, Mainpat, located in the northern portion of Chhattisgarh state in India, has a distinct geographical significance. According to Chaohan et al. (2022), this location is located about 55 kilometers from Ambikapur and has an elevation of 3560 feet above the base. The area is a natural wonderland, with a little creek that changes the landscape as it flows towards the hill.
The area is roughly located between: Latitude: 22.8°N to 23.0°N and Longitude: 83.2°E to 83.4°E. The study region is situated between 1000 and 1100 meters above mean sea level. Mainpat enjoys relatively low temperatures and moderate humidity that are ideal for temperate fruit cultivation because of its high plateau climate. Mainpat Block is located in Surguja District, northern Chhattisgarh. It is dubbed the "Shimla of Chhattisgarh" because: High altitude plateau, Cool climate, Optimal circumstances for temperate fruits such as apples and Loamy soils with high organic residue content. Mainpat Block in Chhattisgarh's Surguja District is well-known for its apple growing, which is unique in central India due to the plateau climate.

Apple crops require:

- Soil is well-drained.
- Effective moisture retention.
- Provides balanced nutritional availability.

Understanding the dielectric properties of apple orchard soil is very significant because:

- Enables real-time monitoring of soil moisture.
- It enables precise irrigation for high-value crops.
- It promotes sustainable agriculture in plateau regions.

Mainpat Block, in Chhattisgarh's Surguja District, is a unique plateau region famed for apple growing due to its temperate climate and good soil. Unlike ordinary tropical plains, this location demonstrates:

- Moderate temperature variations.
- High soil moisture retention capacity.
- Balanced silt-clay composition.

Apple agriculture is highly susceptible to soil moisture and nutrient availability, hence dielectric soil characterization is particularly critical for:

- Schedule irrigation.
- Monitoring soil health levels.
- Sustainable orchard management.

Ultapani, located in Visarpani village, is a scenic spot in this block. Its located 5 kilometers before Mainpat Kamlesh Warpur chowk, on the right side of the Ambikapur Mainpat road. Ultapani, Visarpani settlement, is 1085 meters above sea level. During our field visit, we discovered a unique spot with groundwater levels close to the Earth's surface, making it particularly interesting.
During our field tour, we learned that this specific area is of special significance since it contains groundwater levels that are extremely close to the Earth's surface.
Soil formation, including rock weathering, plant and animal wastes, volcanic ash deposition, and human intervention, is crucial for supporting life on Earth. Rathore et al. (2023) emphasize the importance of soil as a key source of food and fiber, as well as a crucial environmental interface.
The majority of the study area's soils are silty clay loams with a noticeable amount of organic matter. Samples of soil were taken from specific apple orchards that reflected the region's typical agricultural conditions.

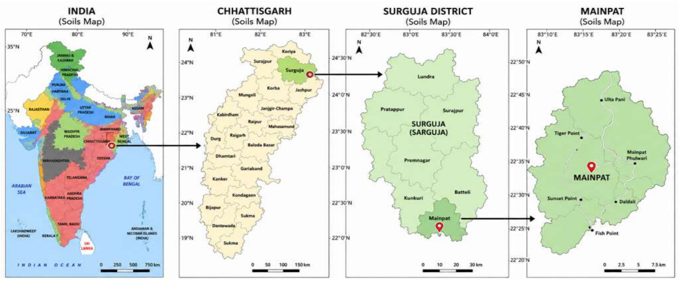
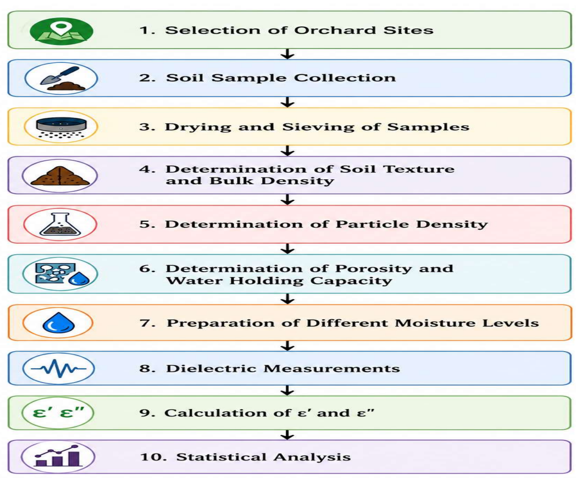


Fig.1. Location map showing India, Chhattisgarh, Surguja District, and Mainpat Block.

3. METHODOLOGY

Fig.2.Flow Chart of Methodology



3.1 Selection of Orchard Sites

The apple-growing areas of Mainpat Block in Surguja District, Chhattisgarh, were chosen as the orchard locations for this study. In order to guarantee that the orchards selected reflected the main soil and environmental parameters of the plateau region, site selection was done. During the selecting process, the following factors were taken into account:

- Existence of well-established apple orchards
- Topography and elevation variation
- Variations in the moisture and texture of the soil
- Availability for frequent soil sampling
- Standardized methods for agricultural management
- The accessibility of unaltered soil profiles

The chosen orchards offered ideal circumstances for dielectric characterisation research and represented typical apple growing zones of the Mainpat plateau.

3.2 Soil Sample Collection

Determine the precise sites for soil sample in the Mainpat block of the Surguja district, comprising the villages of Asgawan, Pidiya, Sapnadar, Laleya, Kuniya, and Narbadapur).

At each site, gather soil samples from various depths (e.g., 0-15 cm, 15-30 cm) using systematic sampling techniques. Two depths were used to get soil samples: Layer of the surface: 0–15 cm and Layer below the surface: 15–30 cm

A stainless steel auger and core sampler were used for the sampling process. Prior to sample, stones, roots, and surface debris were eliminated. For laboratory analysis, the gathered samples were appropriately labeled and kept in sealed plastic bags.Gather enough samples to guarantee statistical significance.

3.3 Drying and Sieving of Samples

The following procedures were used to treat the soil samples that were gathered:

- Room temperature air drying
- Elimination of stones and plant residues
- Using a mortar and pestle to gently grind
- Using a 2 mm sieve

To stop moisture absorption, prepared samples were kept in desiccators.

3.4 Determination of Soil Texture and Bulk Density

The orchard soils were primarily silty clay loam in texture, according to preliminary field research. Due to ongoing leaf litter deposition from orchard plants, the chosen sites displayed a moderate accumulation of organic materials. The hydrometer method was used to determine the texture of the soil. Sand, silt, and clay fraction percentages were computed.

Table.1.The measured soil texture values were:

Soil Depth	Sand (%)	Silt (%)	Clay (%)
0–15 cm	32	48	22
15–30 cm	32	50	18

Because fine-textured soils retain more moisture and show stronger polarization behavior, the increased silt and clay fractions were thought to be significant for dielectric investigations. Bulk density measurements were taken to evaluate compaction and porosity characteristics of orchard soils. Bulk density was determined using the core sampler method. The bulk density equation is:

$$\rho b= Vt/Ms$$

Where: ρb = bulk density (g/cm³), Ms= dry mass of soil and Vt = total volume of soil core.

Table.2.The measured bulk density values were:

Depth	Bulk Density (g/cm³)
0–15 cm	1.47
15–30 cm	1.51

The slightly higher bulk density in deeper layers indicates reduced pore spaces and lower organic matter compared to surface soils.

3.5 Determination of Particle Density

Particle Density (PD) refers to the mass of soil solids per unit volume of soil solids, excluding voids. This is a significant physical parameter utilized in soil characterization and the calculation of soil porosity.

$$\text{Particle Density } (\rho) = \frac{\text{Mass of soil solids}}{\text{Volume of soil solids}}$$

Table.3.The measured particle density values were:

Depth	Particle Density (g/cm³)
0–15 cm	2.49
15–30 cm	2.50

3.6 Determination of Porosity and Water Holding Capasity

The percentage of the total volume of soil that is made up of pore spaces that hold water and air is known as soil porosity.

$$\text{Porosity } (\%) = \left(1 - \frac{\text{Bulk Density}}{\text{Particle Density}}\right) x\ 100$$

Where:

- Bulk Density (BD) = $\frac{\text{Dry Soil Mass}}{\text{otal Soil Volume} \left(\frac{g}{cm^3}\right)}$
- Particle Density (PD) = $\frac{\text{Mass of soil solids}}{\text{Volume of soil solids}}$

Table.4.The measured porosity values were:

Depth	Porosity
0–15 cm	1.47
15–30 cm	1.51

Higher soil water retention capacity indicates optimal physical conditions. It is crucial for the soil's vitality.

Table.5.The measured water-holding capacity values were:

Depth	Water Holding Capasity (%)
0–15 cm	47.30
15–30 cm	46.81

3.7 Preparation of Different Moisture Levels

The moisture content was determined utilizing the oven drying technique. Fresh soil samples were desiccated at 105°C for 24 hours until a consistent weight was achieved.

The moisture content was determined using: Moisture Content (%) = $\left(\frac{\text{Weight of water}}{\text{Dry weight of soil}}\right)$ x 100

This study investigated the interaction of microwaves with apple-based soil exhibiting varying moisture levels (0%, 10%, 20%, 30%, and 40%) at X-Band frequency (9.87 GHz). The remote sensing of soil moisture depends on quantifying the electromagnetic energy reflected or emitted from the soil surface. Moisture content also influences effective skin depth. As moisture content increases, skin depth diminishes, potentially causing signal dispersion from thinner soil strata.

3.8 Dielectric Measurements

Dielectric studies were conducted within a specified frequency range, spanning from low radio frequencies to microwave frequencies, contingent upon equipment availability. The fluctuation of dielectric properties with frequency was noted due to the attenuation of polarization mechanisms at elevated frequencies.Microwave dielectric measurements were carried out at X-band frequency (9.87 GHz).

The samples were analyzed for chemical parameters such as pH, electrical conductivity, organic carbon, macronutrients and micronutrients by standard analytical methods .Also analyzed for their physical parameters soil texture, bulk density, particle density, porosity, moisture contents and water holding capasity. The dielectric constants were measured at the Department of physics in Uma Vindhyavasini Sanskar College, Latori, District-Surajpur, Chhattisgarh, using X band microwave set up.

Fig. 3: X- Band Microwave Test Bench Setup

The two-point method is the most well-known and extensively used technique for measuring complicated permittivity. It works best with "lossless" or medium-loss dielectrics. The dielectric constant and dielectric loss of the soil samples were determined at 9.87 GHz (X-band) microwave frequencies using a microwave bench and the two-point method. The reflex Klystron generates X band microwave radiation. The sample holder for X-band measurements was made from a regular wave guide. To connect the sample holder to the main line, one end was linked with a metallic flange, while the other end was carefully shorted.

First, without dielectric in the short-circuited line, the position of the first minimal DR in the slotted line was determined. A soil sample of a specific length and moisture content was inserted in the sample container, touching the short-circuited end. The first minimal D location on the slotted line was then measured, as well as the matching VSWR, r.The VSWR was measured with a VSWR meter. Connecting the VSWR meter enabled amplitude modulation of the microwave signal using pin diodes. The method was performed for another soil sample with the same moisture content and length.The dielectric constant was measured for various moisture contents(0%, 10%, 20%, 30%, and 40%).

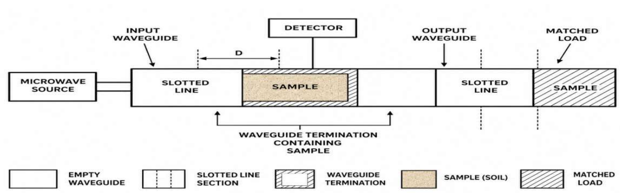


Fig. 4: Measurement of Dielectric Constant of a High-Loss Material

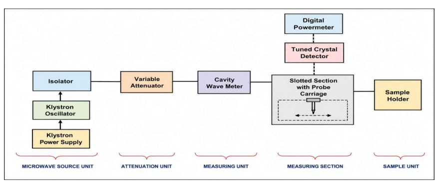


Fig. 5: Block diagram of experimental setup for measurement of dielectric properties

3.9 Calculation of ε′ and ε″

The dielectric constant is calculated using:

$$\square' = \square\square + \left(\frac{\square\square\square}{\square\square}\right)^{\square}$$

Where: ε′ = dielectric constant , g_s = guide factor , λg = guide wavelength and a = broad dimension of the waveguide

Dielectric loss factor is calculated using:

ε″ = ε′ tanδ

Where: ε′ = dielectric constant, tanδ = tangent loss and tanδ = $\left(\frac{\varepsilon''}{\varepsilon'}\right)$

3.10 Statistical Analysis

Statistical analysis is essential for evaluating the relationship between dielectric properties (dielectric constant ε′ and dielectric loss factor ε″) and soil parameters such as moisture content, bulk density, texture, organic matter and soil depth.

3.10.1 Dielectric Properties and different moisture contents (Dry % , 10%, 20%, 30%, and 40%)

Draging Depth Size	S.No.	Sample No.	Real Part of Dielectric Constant					Imaginary Part of Dielectric Constant				
			Dry soil	10%	20%	30%	40%	Dry soil	10%	20%	30%	40%
0-15 cm	1	S1	03.841	07.132	09.431	11.481	13.281	0.431	0.571	0.987	1.512	2.212
	2	S2	04.841	07.132	08.431	10.481	12.281	0.431	0.671	0.987	1.412	2.312
	3	S3	04.121	06.132	09.431	12.481	14.281	0.421	0.581	0.987	1.312	2.212
	4	S4	05.841	09.132	11.431	12.481	14.281	0.431	0.671	0.987	1.612	2.312
15-30 cm	5	S1	04.012	06.132	08.431	12.481	14.281	0.431	0.571	0.987	1.512	2.212
	6	S2	04.123	07.447	09.831	12.731	14.488	0.431	0.671	0.987	1.412	2.312
	7	S3	04.121	07.132	13.481	15.281	15.281	0.421	0.581	0.987	1.312	2.212
	8	S4	05.231	09.132	12.431	14.481	16.281	0.431	0.671	0.987	1.612	2.312

Table.6. Measured value real and imaginary part of dielectric constant of different moisture contents (Dry %, 10%, 20%, 30%, and 40%) for Mainpat of Surguja District

3.10.2 Graphical Analysis Required

Graphical analysis is a crucial instrument for visualizing the behavior of soil dielectric characteristics and comprehending the influence of variables such as moisture content, particle density, bulk density, porosity, water holding capacity, and soil texture. It assists in identifying trends, correlations, variances, and predictive linkages.

Dielectric Constant vs Moisture Content Graph

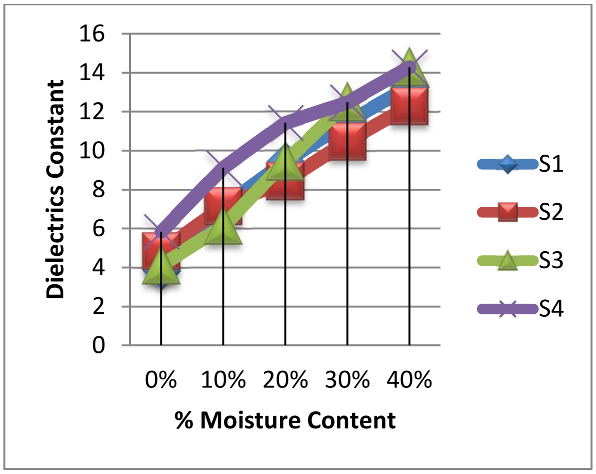


Fig.6: Variation of Real Part of Dielectric Constant with % of Moisture Content in Soil of Mainpat block in Surguja district at 0-15cm depth

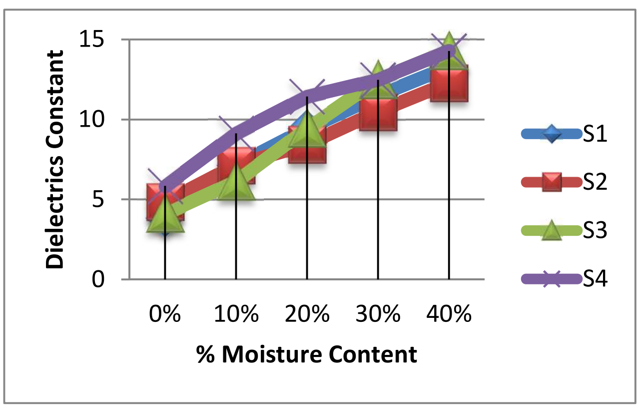


Fig.7 : Variation of Real Part of Dielectric Constant with % of Moisture Content in Soil of Mainpat block in Surguja district at 15- 30cm depth

Dielectric Loss vs Moisture Content Graph

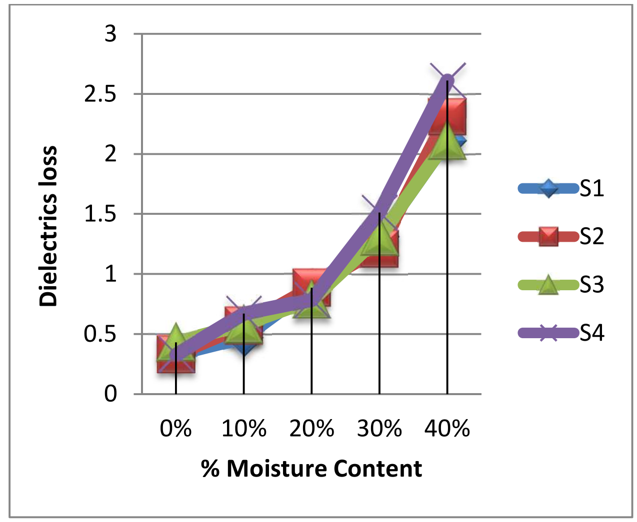


Fig.8: Variation of Real part of Dielectric Loss with % of Moisture Content in Soil of Mainpat block in Surguja district at

0-15cm depth

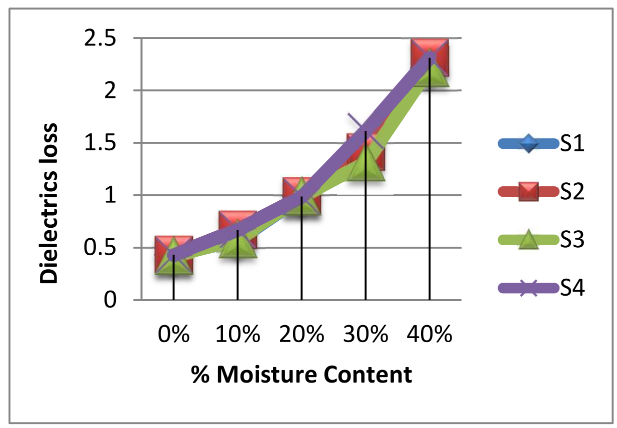


Fig.9: Variation of Real part of Dielectric Loss with % of Moisture Content in Soil of Mainpat block in Surguja district at 15-30 cm depth

Dielectric Constant vs Soil Texture Graph

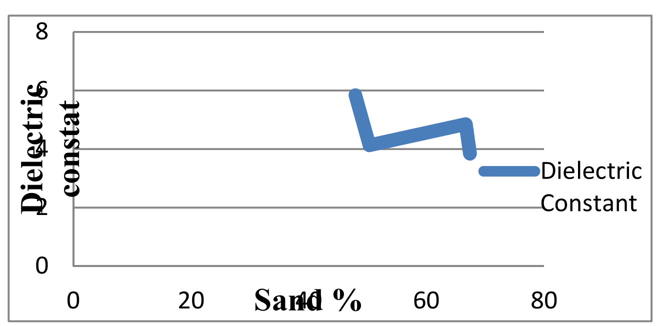


Fig.10: Variation of dielectric constant with % of sand in Soil of Mainpat block in Surguja district at 0-15cm depth

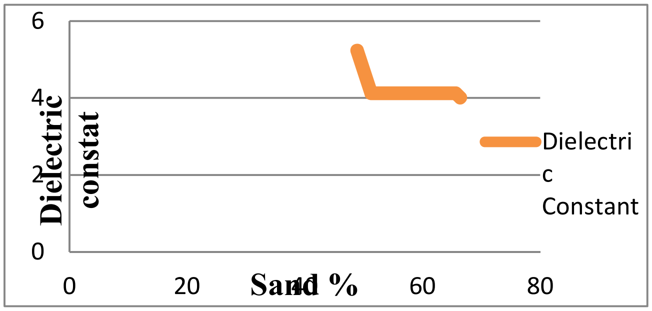


Fig.11: Variation of dielectric constant with % of sand in Soil of Mainpat block in Surguja district at 15-30 cm depth

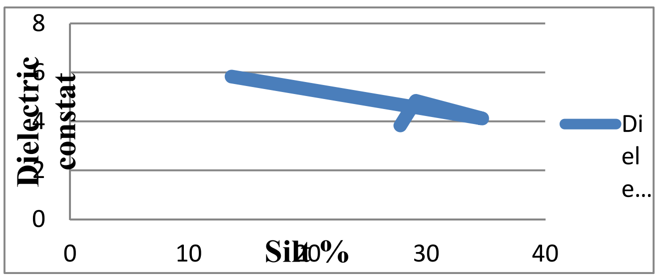


Fig.12: Variation of dielectric constant with % of silt in Soil of Mainpat block in Surguja district at 0-15cm depth

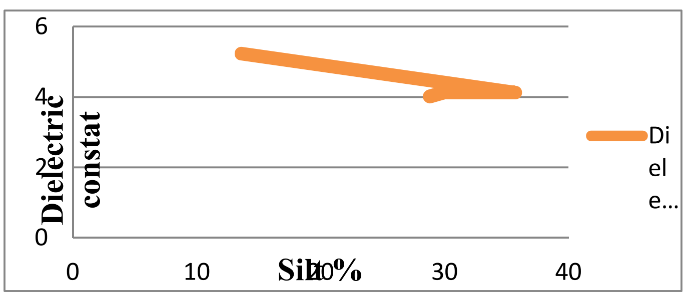


Fig.13: Variation of dielectric constant with % of silt in Soil of Mainpat block in Surguja district at 15-30 cm depth

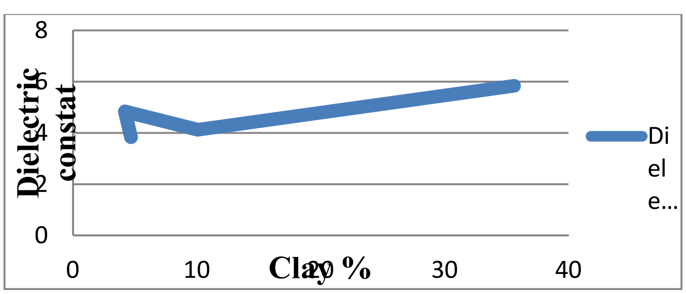


Fig.14: Variation of dielectric constant with % of clay in Soil of Mainpat block in Surguja district at 0-15cm depth

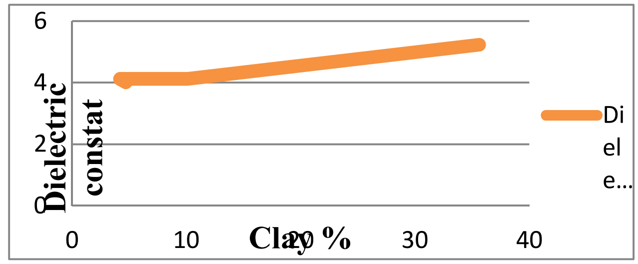


Fig. 15: Variation of dielectric constant with % of Clay in Soil of Mainpat block in Surguja district at 15-30 cm depth

Dielectric Constant vs Particle Density Graph

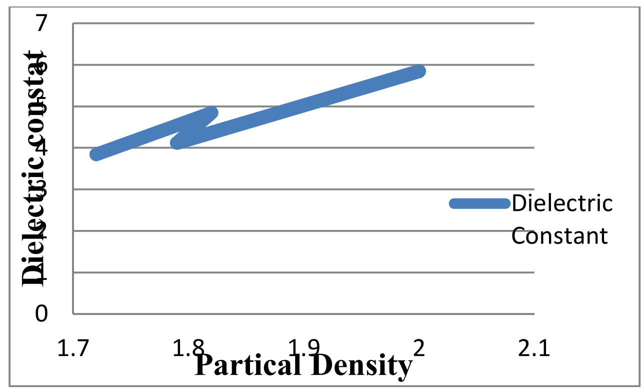


Fig. 16: Variation of dielectric constant with % of Partical density in Soil of Mainpat block in Surguja district at 0-15cm depth

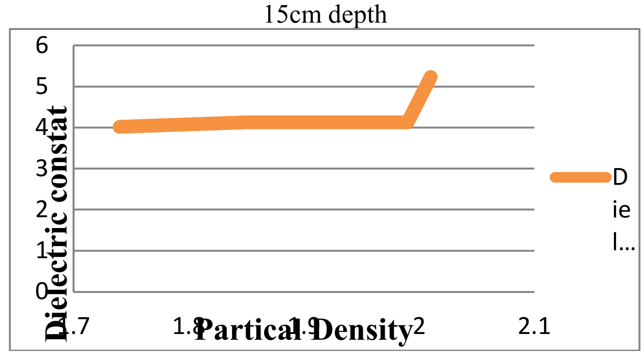


Fig.17: Variation of dielectric constant with % of Partical density in Soil of Mainpat block in Surguja district at 15-30 cm depth

Dielectric Constant vs Porosity Graph

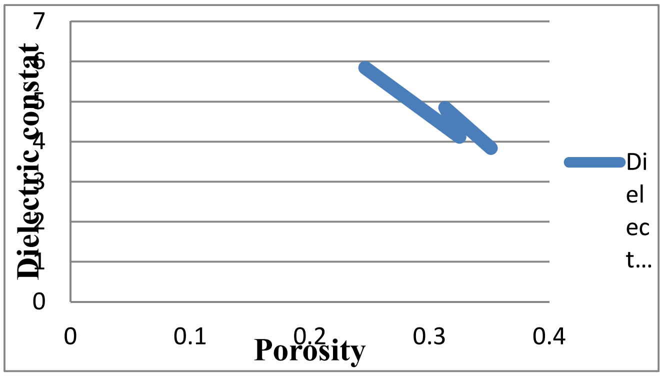


Fig.18: Variation of dielectric constant with % of porosity in Soil of Mainpat block in Surguja district at 0-15cm depth

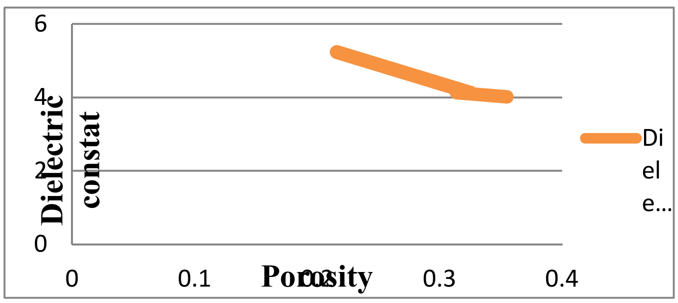


Fig.19: Variation of dielectric constant with % of porosity in Soil of Mainpat block in Surguja district at 15-30 cm depth

Dielectric Constant vs Bulk Density Graph

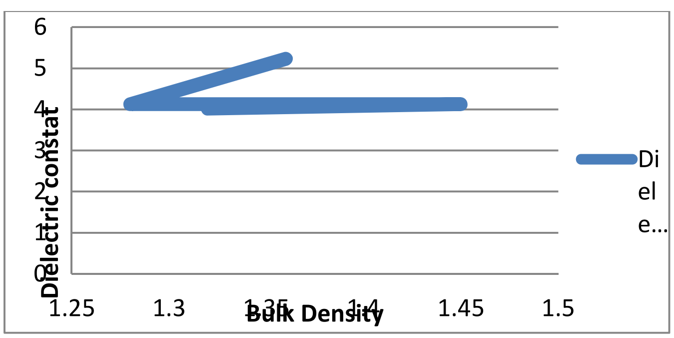


Fig.20: Variation of dielectric constant with % of Bulk Density in Soil of Mainpat block in Surguja district at 15-30 cm depth

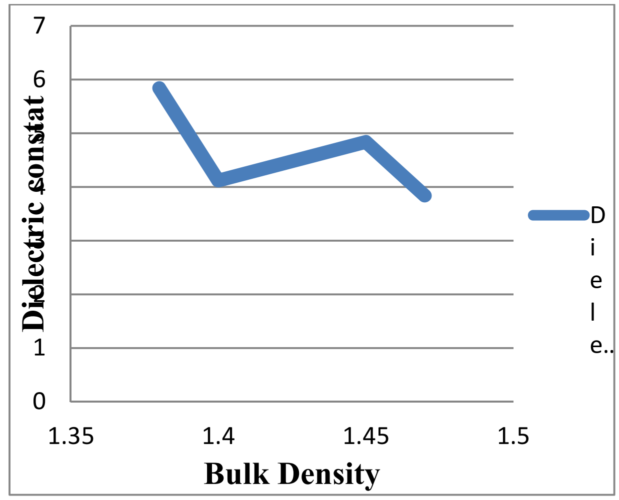


Fig.21: Variation of dielectric constant with % of Bulk Density in Soil of Mainpat block in Surguja district at 0-15cm depth

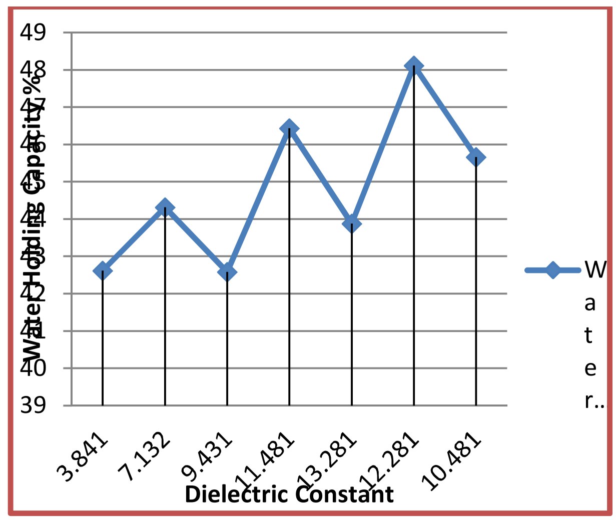


Fig.22: Variation of dielectric constant with % of Water Holding Capacity % in Soil of Mainpat block in Surguja .

4. Results and Discussion

4.1 Effect of Moisture Content

The dielectric constant significantly grew with increased moisture content. This is due to water's significantly higher dielectric constant in comparison to soil minerals and air.
In dry conditions, the dielectric constant remained low due to the lack of free water molecules. As moisture content rose from 10% to 40%, polarization escalated significantly, leading to elevated dielectric values.
The higher value in dielectric constant validates the robust interaction between microwave radiation and water molecules within soil pores.

4.2 Effect of Soil Texture

The greater silt and clay fractions in Mainpat apple soil resulted in enhanced dielectric constant. Clay minerals exhibit greater surface areas and heightened water adsorption capabilities, resulting in amplified polarization effects.
Soils with fine textures typically exhibit higher dielectric constants than sandy soils due to the substantial contribution of bound water molecules to dielectric relaxation.
The silty clay loam composition of Mainpat soil improved moisture retention and polarization characteristics.

4.3 Effect of Bulk Density

Increased bulk density decreases pore space and affects soil-water dynamics. The deeper soil layer (15–30 cm) exhibited a somewhat increased bulk density, influencing dielectric loss properties as a result of diminished air gaps.
Bulk density affects dielectric properties by decreasing air voids and enhancing particle compaction.
The lower soil layer had a somewhat elevated bulk density (1.51 g/cm³), signifying increased compaction. A higher bulk density typically enhances dielectric permittivity due to a diminished air volume.

4.4 Effect of Soil Depth

The surface soil (0–15 cm) exhibited an enhanced dielectric response due to:

- Enhanced porosity
- Enhanced moisture retention
- Enhanced microbial activity
- Increased organic matter

The subsurface soil demonstrated a somewhat diminished dielectric response attributable to compaction and decreased pore space.

4.5 Effect of Frequency

The dielectric constant diminished with rising frequency owing to diminished dipole polarization at elevated microwave frequencies.
The frequency dependence can be depicted by ε' diminishing with an increase in frequency.
This behavior exemplifies dielectric relaxation phenomena in diverse soils.

4.6 Dielectric Loss Behavior

The imaginary component of the dielectric constant augmented with rising moisture content due to:

- Ionic conduction
- Dipole relaxation
- Enhanced electrical conductivity

Dielectric losses became more significant at elevated moisture levels.

4.7 Importance in Precision Agriculture

Dielectric tests yield significant insights for:

- Irrigation timetable
- Monitoring of soil moisture
- Precision agriculture
- Remote Sensing
- Orchard administration
- Agroecology

The findings indicate that microwave dielectric methods can be efficiently employed for real-time assessment of orchard soils.

5. Conclusion

The evolution of dielectric properties of apple-based soil from Mainpat Block demonstrates strong dependence on moisture content, soil texture, frequency, and bulk density. The dielectric constant increased with increasing moisture and clay content, while it decreased with increasing frequency. The silty-clay nature of Mainpat apple soils contributes to enhanced dielectric response and water retention capability. These findings are useful for precision agriculture, microwave sensing, and soil quality assessment in temperate fruit-growing regions of Chhattisgarh.

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