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Physico-Chemical Characsterization and X-Band Dielectric Behaviour of Agricultural Soils from Mantha Taluka, Jalna District, Indiass

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Abstract
This study investigates the physico-chemical properties and X-band dielectric behaviour of agricultural soils collected from Mantha Taluka, Jalna district, Maharashtra, India. Thirty surface soil samples obtained from four representative villages were analyzed for physical properties, including texture and moisture content, and chemical properties such as pH, electrical conductivity, organic carbon, macronutrients, secondary nutrients, and micronutrients. X-band dielectric measurements were performed at a fixed frequency of 9.685 GHz using a microwave waveguide technique to determine dielectric constant, dielectric loss, loss tangent, electrical conductivity, and penetration depth. The results reveal notable village-wise variation in soil texture, moisture status, and chemical fertility parameters. Dielectric properties exhibited strong sensitivity to soil moisture content and texture, with higher dielectric constant observed in moisture-rich and finer-textured soils. Correlation analysis confirmed that soil moisture and clay fraction are the dominant factors controlling X-band dielectric response. The findings demonstrate the potential of X-band dielectric measurements for agricultural soil assessment and microwave-based soil moisture monitoring in semi-arid regions.

Keywords: Agricultural soils; X-band dielectric properties; soil moisture; soil texture;

Introduction

Soil is a heterogeneous dielectric medium whose physical and chemical properties strongly influence agricultural productivity, water retention, nutrient availability, and related biogeochemical processes. Soil texture, moisture content, bulk density, pH, electrical conductivity (EC), organic carbon, and nutrient status directly affect root growth, microbial activity, and crop performance. In semi-arid agricultural regions, characsterized by irregular rainfall, high evapotranspiration, and intensive fertilizer inputs, accurate assessment of soil physico-chemical properties is essential for sustainable soil management and long-term agricultural productivity [1], [2]. Conventional laboratory-based soil analyses provide reliable point-scale information; however, the time required for analysis and the limited spatial coverage restrict their application for large-area soil assessment [3].

The electrical and dielectric properties of soils are widely used as indicators of soil physical and chemical conditions. Dielectric permittivity represents the interaction of electromagnetic waves with soil constituents and depends strongly on soil moisture, texture, salinity, and organic matter content. At microwave frequencies, the dielectric response is dominated by dipolar polarization of water molecules, with additional contributions from bound water associated with clay minerals and ionic conduction related to dissolved salts [4], [5]. Therefore, dielectric measurements provide a physics-based approach for investigating soil moisture dynamics and related soil properties, supporting applications in agricultural monitoring, hydrology, geophysics, and microwave remote sensing [6].

Microwave sensing techniques are effective for soil investigations because of their penetration capability and sensitivity to near-surface moisture variations. Among the commonly used microwave bands, the X-band frequency range (8–12 GHz) offers high spatial resolution and sensitivity to surface soil moisture, making it suitable for field-scale agricultural studies. X-band sensors are extensively employed in active microwave systems, such as synthetic aperture radar (SAR), for crop monitoring and soil moisture estimation. At X-band frequencies, soil dielectric behaviour is influenced not only by volumetric moisture content but also by soil texture, particularly clay fraction, and electrical conductivity, which affect bound-water polarization and conductive loss mechanisms [7], [8].

Early studies on soil dielectric behaviour at microwave frequencies established strong relationships between dielectric constant and soil moisture content, forming the basis for empirical and physically based dielectric models [5], [9]. These studies demonstrated that clay mineralogy influences dielectric response through bound-water effects, while bulk density controls the effective permittivity of the soil–air–water system [10]. Subsequent investigations reported that soil salinity and ionic conduction contribute to dielectric losses, especially at higher microwave frequencies where conductive mechanisms become significant [11], [12]. While much of this work has focused on L-band and C-band frequencies, fewer experimental studies have examined soil dielectric behaviour at X-band frequencies.

Studies combining detailed physico-chemical soil characterization with controlled X-band dielectric measurements for agricultural soils in semi-arid regions are relatively limited. In particular, the combined influence of soil texture, moisture content, nutrient status, and electrical conductivity on X-band dielectric response has not been examined extensively for Indian agricultural soils. This situation constrains the physical interpretation of X-band SAR observations and the application of dielectric models for soil moisture estimation

and agricultural monitoring [7], [13].

Thirty soil samples collected from four representative villages were analyzed for physical properties (soil texture and moisture content), chemssical properties (pH, EC, organic carbon, and macronutrients), as well as secondary nutrients and micronutrients. X-band dielectric measurements were performed at a fixed frequency of 9.685 GHz using a microwave waveguide technique to determine the real and imaginary components of permittivity, loss tangent, electrical conductivity, resistivity, and penetration depth. The objectives of this study are to evaluate the physico-chemical status of agricultural soils in the study area, analyze their dielectric behaviour at X-band frequency, and establish quantitative relationships between dilectric parameters and key soil properties. The results are expected to support agricultural soil assessment and X-band microwave remote sensing applications in semi-arid environments.s

Study Area and Soil Sampling Study Area Description

The present study was conducted in Mantha Taluka of Jalna district, located in the Marathwada region of Maharashtra, India. The taluka lies in a semi-arid agroclimatic zone and is characterized by low to moderate monsoonal rainfall, high summer temperatures, and pronounced seasonal variability in soil moisture. The climate is dominated by a short rainy season followed by extended dry periods, which strongly influence soil water availability and agricultural practices. The soils of the region are developed mainly from basaltic parent material and are extensively cultivated under both rainfed and limited irrigated conditions. Major crops grown in the area include cotton, sorghum, soybean, and pulses. The geographical setting and spatial distribution of the sampling villages within Mantha Taluka are shown in Figure 1, which presents the location of the study area within Jalna district and Maharashtra state.



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Figure 1. Location map of the study area (Mantha Taluka, Jalna District, Maharashtra, India) showing the soil sampling villages.

Four villages, namely Kendhali, Vidoli bk., Pandhurna, and Helas, were selected for soil sampling to represent the agricultural variability of Mantha Taluka. These villages were chosen based on their spatial distribution, dominant cropping patterns, and differences in soil management practices. Together, they provide a representative coverage of the agricultural soils of the taluka and allow assessment of spatial variations in soil physico-chemical properties and dielectric behaviour across the study area.

Soil Sampling

Soil sampling was carried out during the post-monsoon period to ensure representative field moisture conditions relevant to agricultural activity and microwave dielectric measurements. A total of thirty surface soil samples were collected from cultivated fields across the four selected villages. At each location, soil samples were collected from a depth of 0 to 15 cm using a stainless-steel auger after removing surface litter and plant residues. This depth corresponds to the active root zone and is most relevant for crop growth as well as for microwave interaction with the soil surface.

After collection, the soil samples were air dried at room temperature, gently disaggregated, and passed through a 2 mm sieve to remove gravel and coarse organic matter. The processed samples were then used for physical, chemical, and dielectric analyses. The geographic coordinates of each sampling location were recorded using a handheld global positioning system device. The village-wise distribution of sampling locations along with their geographic details is provided in Table 1, which summarizes the spatial information of the soil sampling sites within Mantha Taluka.

Table 1. Geographical details of soil sampling locations in Mantha Taluka, Jalna district (Maharashtra), India

Sr. No.	*Village Name*	*Taluka*	*District*	*State*	*Latitude (N)**	*Longitude (E)**	*Number of Soil Samples*
1	*Kendhali*	*Mantha*	*Jalna*	*Maharashtra*	*19.56°*	*76.68°*	*8*
2	*Vidoli bk.*	*Mantha*	*Jalna*	*Maharashtra*	*19.52°*	*76.72°*	*7*
3	*Pandhurna*	*Mantha*	*Jalna*	*Maharashtra*	*19.58°*	*76.63°*	*7*

4	*Helas*	*Mantha*	*Jalna*	*Maharashtra*	*19.54°*	*76.70°*	*8*
	Total						*30*

Materials and Methods Physical Properties Analysis

The physical properties of the agricultural soil samples were analyzed to evaluate textural composition and moisture status, which are key parameters governing soil dielectric behaviour. Soil texture was determined by estimating the relative proportions of sand, silt, and clay using standard mechanical analysis methods, and the soils were classified according to established textural classes. The sand, silt, and clay contents obtained for all samples collected from the four villages are summarized in Table 2, which presents the physical properties of agricultural soils from Mantha Taluka.

Table 2. Physical properties of agricultural soil samples collected from four villages of Mantha Taluka, Jalna district (Maharashtra), India

Sample No.	*Village*	*Sand (%)*	*Silt (%)*	*Clay (%)*	*Soil Texture Class*	*Moisture Content (%)*
S1	*Kendhali*	*52*	*18*	*30*	*Sandy clay*	*12.6*
S2	*Kendhali*	*48*	*32*	*20*	*Sandy clay loam*	*14.2*
S3	*Kendhali*	*40*	*36*	*24*	*Sandy clay*	*15.8*
S4	*Kendhali*	*36*	*44*	*20*	*Sandy clay loam*	*16.4*
S5	*Kendhali*	*44*	*36*	*20*	*Sandy clay loam*	*14.9*
S6	*Kendhali*	*34*	*42*	*24*	*Sandy clay loam*	*17.2*
S7	*Kendhali*	*50*	*32*	*18*	*Sandy clay loam*	*13.8*
S8	*Kendhali*	*42*	*36*	*22*	*Sandy clay*	*15.3*
S9	*Vidoli bk.*	*32*	*44*	*24*	*Sandy clay loam*	*17.6*
S10	*Vidoli bk.*	*36*	*40*	*24*	*Sandy clay loam*	*16.9*
S11	*Vidoli bk.*	*40*	*36*	*24*	*Sandy clay*	*15.7*
S12	*Vidoli bk.*	*48*	*28*	*24*	*Sandy clay*	*14.1*
S13	*Vidoli bk.*	*34*	*42*	*24*	*Sandy clay loam*	*17.3*
S14	*Vidoli bk.*	*38*	*40*	*22*	*Sandy clay loam*	*16.2*
S15	*Vidoli bk.*	*44*	*36*	*20*	*Sandy clay loam*	*15.0*
S16	*Pandhurna*	*36*	*44*	*20*	*Sandy clay loam*	*16.8*
S17	*Pandhurna*	*40*	*36*	*24*	*Sandy clay*	*15.9*
S18	*Pandhurna*	*48*	*28*	*24*	*Sandy clay*	*14.4*
S19	*Pandhurna*	*34*	*42*	*24*	*Sandy clay loam*	*17.5*
S20	*Pandhurna*	*38*	*40*	*22*	*Sandy clay loam*	*16.1*
S21	*Pandhurna*	*44*	*36*	*20*	*Sandy clay loam*	*15.2*
S22	*Pandhurna*	*36*	*44*	*20*	*Sandy clay loam*	*16.7*
S23	*Helas*	*34*	*42*	*24*	*Sandy clay loam*	*17.4*
S24	*Helas*	*40*	*36*	*24*	*Sandy clay*	*15.6*
S25	*Helas*	*48*	*28*	*24*	*Sandy clay*	*14.0*
S26	*Helas*	*36*	*44*	*20*	*Sandy clay loam*	*16.9*
S27	*Helas*	*38*	*40*	*22*	*Sandy clay loam*	*16.3*
S28	*Helas*	*44*	*36*	*20*	*Sandy clay loam*	*15.1*

S29	*Helas*	*42*	*36*	*22*	*Sandy clay*	*15.8*
S30	*Helas*	*34*	*42*	*24*	*Sandy clay loam*	*17.2*

The distribution of sand, silt, and clay fractions across the study area was illustrated using a USDA soil textural triangle, as shown in Figure 3, which highlights the range of textural classes represented by the sampled soils.

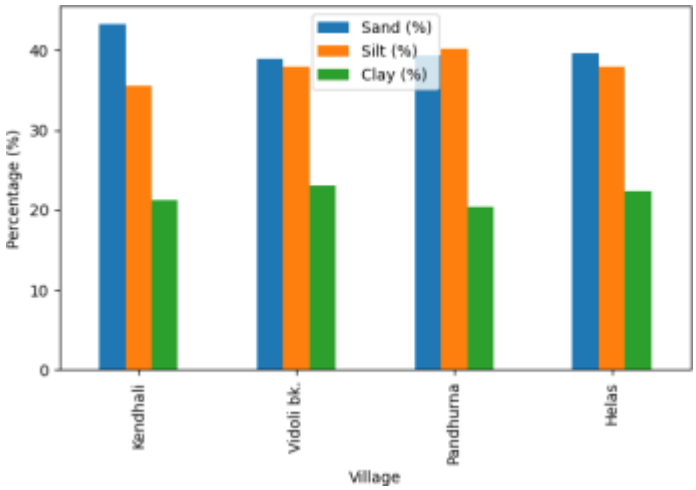


Figure 3. USDA soil showing sand–silt–clay distribution of agricultural soil samples.

In addition, the comparative variation in sand, silt, and clay percentage composition among the sampling locations is depicted using a bar chart in Figure 4, facilitating direct comparison of textural variability between villages.

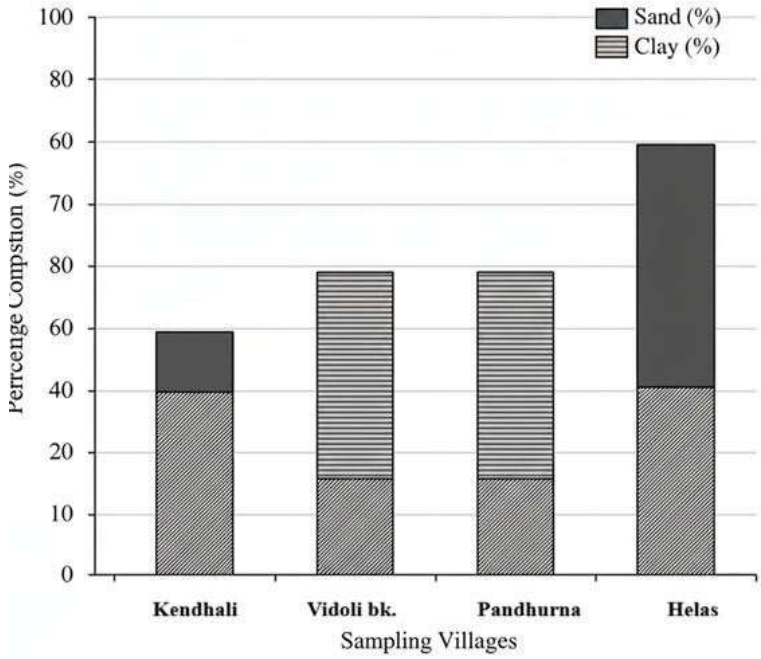


Figure 4. Bar chart of sand, silt, and clay percentage composition of agricultural soils from the study area.

Soil moisture content was determined using the gravimetric method by measuring the mass difference between fresh and oven-dried soil samples. Soil moisture is a critical physical parameter that influences soil structure and water retention and directly affects electromagnetic wave interaction at microwave frequencies. The measured moisture content values were subsequently used to examine their relationship with dielectric parameters.

The observed variability in soil texture and moisture content across the study area is consistent with earlier findings that vegetation cover and land-use practices exert a strong influence on soil physical properties. Joshi et al. [14] reported that different vegetation types significantly affect soil texture distribution, moisture content, and related physical properties through variations in litter input, root activity, and soil aggregation processes. Similar observations were reported by Das et al. [15], who demonstrated that biomass-derived amendments and organic inputs modify soil pore structure and moisture retention behaviour, thereby altering soil hydro-physical properties. Studies conducted in agroforestry and landscape-scale systems have further shown that soil physical characteristics vary systematically with vegetation cover and management history. Karki et al. [16] reported that soil texture and moisture behaviour are influenced by long-term vegetation patterns and associated organic matter inputs in Himalayan agroforestry systems. More recently, Surendran et al.
[17] highlighted that variations in soil texture and physical properties across different landscapes are closely linked

to land-use practices and vegetation-driven organic carbon dynamics.

The physical property analysis carried out in the present study provides a necessary basis for interpreting the dielectric behaviour of agricultural soils at X-band frequency. The influence of soil texture and moisture content on electromagnetic response, as reported by Joshi et al. [14] and Das et al. [15], supports the relevance of the present measurements for understanding soil–microwave interactions in semi-arid agricultural environments.

Chemical Properties Analysis

The chemical properties of the agricultural soil samples were analyzed to evaluate soil reaction, salinity status, organic matter content, and nutrient availability, which are essential indicators of soil fertility and soil dielectric behaviour. Soil pH and electrical conductivity were determined using standard electrochemical techniques in soil–water suspensions to assess soil reaction and soluble salt concentration. Soil pH controls nutrient availability and microbial activity, while electrical conductivity reflects the concentration of soluble ions in the soil solution and has a direct influence on electrical conduction mechanisms under microwave excitation. The measured pH and EC values for all soil samples collected from Mantha Taluka are summarized in Table 3, which presents the chemical properties of the agricultural soils.

Table 3. Chemical properties of agricultural soil samples collected from Mantha Taluka, Jalna district (Maharashtra), India

Sample No.	*pH*	*EC (dS m⁻¹)*	*Organic Carbon (%)*	*Available N (kg ha⁻¹)*	*Available P (kg ha⁻¹)*	*Available K (kg ha⁻¹)*
S1	*8.1*	*0.42*	*0.48*	*210*	*18.2*	*345*
S2	*8.3*	*0.46*	*0.52*	*225*	*19.6*	*352*
S3	*8.0*	*0.38*	*0.55*	*238*	*21.4*	*368*
S4	*8.2*	*0.41*	*0.50*	*220*	*20.1*	*360*
S5	*8.4*	*0.49*	*0.46*	*205*	*17.8*	*340*
S6	*8.1*	*0.44*	*0.53*	*230*	*22.0*	*372*
S7	*8.2*	*0.40*	*0.49*	*215*	*18.9*	*350*
S8	*8.3*	*0.47*	*0.47*	*208*	*17.5*	*342*
S9	*8.0*	*0.36*	*0.58*	*245*	*23.6*	*380*
S10	*7.9*	*0.34*	*0.61*	*255*	*24.2*	*392*
S11	*8.1*	*0.39*	*0.56*	*240*	*22.1*	*370*
S12	*8.2*	*0.41*	*0.54*	*232*	*21.0*	*365*
S13	*8.0*	*0.37*	*0.59*	*248*	*23.4*	*385*
S14	*7.8*	*0.33*	*0.63*	*260*	*25.1*	*400*
S15	*8.1*	*0.38*	*0.57*	*242*	*22.6*	*375*
S16	*8.2*	*0.45*	*0.51*	*225*	*20.4*	*360*
S17	*8.3*	*0.48*	*0.49*	*215*	*18.7*	*348*
S18	*8.1*	*0.43*	*0.52*	*228*	*21.1*	*368*
S19	*8.0*	*0.40*	*0.55*	*235*	*22.5*	*372*
S20	*8.2*	*0.46*	*0.50*	*220*	*19.9*	*355*
S21	*8.1*	*0.42*	*0.53*	*232*	*21.8*	*365*
S22	*8.3*	*0.49*	*0.48*	*210*	*18.3*	*340*
S23	*7.9*	*0.35*	*0.62*	*255*	*24.6*	*390*
S24	*8.0*	*0.37*	*0.60*	*248*	*23.9*	*385*
S25	*8.1*	*0.39*	*0.58*	*242*	*22.7*	*375*
S26	*7.8*	*0.34*	*0.65*	*265*	*26.0*	*405*

S27	*7.9*	*0.36*	*0.61*	*252*	*24.2*	*392*
S28	*8.0*	*0.38*	*0.59*	*245*	*23.5*	*380*
S29	*8.1*	*0.40*	*0.56*	*238*	*22.0*	*370*
S30	*8.2*	*0.43*	*0.54*	*230*	*21.2*	*365*

Soil organic carbon content was estimated using standard wet oxidation procedures to assess the organic matter status of the soils. Organic carbon plays a key role in regulating nutrient cycling, soil aggregation, and moisture retention, and it indirectly influences soil dielectric behaviour through its interaction with water and mineral surfaces. Variations in organic carbon content observed across the study area are indicative of differences in vegetation cover, crop residue management, and long-term land-use practices. Similar relationships between soil organic carbon and soil physico-chemical properties under different land-use systems have been reported by Padalia et al. [14] and Manral et al. [15], who demonstrated that organic matter inputs strongly influence soil chemical characteristics and nutrient dynamics.

Available macronutrients, namely nitrogen, phosphorus, and potassium, were determined using standard soil testing protocols suitable for agricultural soils. Available nitrogen represents the readily mineralizable nutrient pool, while available phosphorus and potassium indicate the soil's capacity to supply essential nutrients for crop growth. The concentrations of available N, P, and K measured in the present study are included in Table 3, enabling comparison of nutrient status among the sampled villages. Previous studies have shown that macronutrient availability is closely linked to soil organic carbon content, microbial activity, and land-use history. Manral et al. [16] reported strong associations between soil physico-chemical properties and nutrient fluxes under different vegetation systems, while Singh et al. [17] demonstrated that disturbances in vegetation cover significantly alter soil chemical properties and nutrient availability.

The observed variation in pH, EC, organic carbon, and macronutrient content across the study area reflects differences in cropping practices, vegetation inputs, and soil management history. These chemical parameters are also relevant for interpreting soil dielectric behaviour, as ionic concentration directly affects soil electrical conductivity, while organic carbon and nutrient status influence moisture retention and soil structure. Therefore, the chemical property analysis carried out in this study provides an essential framework for understanding the relationship between soil chemistry and X-band dielectric behaviour in agricultural soils of semi-arid regions.

Secondary Nutrients and Micronutrients

Secondary nutrients and micronutrients were analyzed to evaluate the nutritional balance of the agricultural soils and their influence on soil chemical conditions and dielectric behaviour. Exchangeable calcium and magnesium were determined using standard extraction procedures, as these base cations play an important role in soil aggregation, structural stability, and cation exchange processes. Available sulfur was analyzed to assess its contribution to plant nutrition and its association with organic matter turnover and microbial activity. The concentrations of calcium, magnesium, and sulfur measured in soils from the four villages are presented in Table 4, which summarizes the secondary nutrient status of agricultural soils from Mantha Taluka.

Table 4. Secondary nutrients and micronutrient status of agricultural soil samples from Mantha Taluka, Jalna district (Maharashtra), India

Sample No.	*Ca (cmol(+)/kg)*	*Mg (cmol(+)/kg)*	*S (mg kg⁻¹)*	*Zn (mg kg⁻¹)*	*Fe (mg kg⁻¹)*	*Cu (mg kg⁻¹)*	*Mn (mg kg⁻¹)*
S1	*16.8*	*5.4*	*11.2*	*0.48*	*4.2*	*0.72*	*6.8*
S2	*17.2*	*5.6*	*10.8*	*0.52*	*4.0*	*0.74*	*6.5*
S3	*18.0*	*5.8*	*12.1*	*0.55*	*4.5*	*0.76*	*7.0*
S4	*17.6*	*5.5*	*11.5*	*0.50*	*4.3*	*0.73*	*6.7*
S5	*16.5*	*5.2*	*10.4*	*0.46*	*3.9*	*0.70*	*6.2*
S6	*18.2*	*5.9*	*12.6*	*0.58*	*4.7*	*0.78*	*7.3*
S7	*17.0*	*5.4*	*11.0*	*0.49*	*4.1*	*0.72*	*6.6*
S8	*16.9*	*5.3*	*10.9*	*0.47*	*4.0*	*0.71*	*6.4*
S9	*18.5*	*6.1*	*13.4*	*0.62*	*5.0*	*0.80*	*7.8*
S10	*19.0*	*6.3*	*14.0*	*0.65*	*5.3*	*0.82*	*8.1*
S11	*18.2*	*6.0*	*13.1*	*0.60*	*4.8*	*0.79*	*7.5*
S12	*17.8*	*5.8*	*12.4*	*0.57*	*4.6*	*0.77*	*7.2*

S13	*18.7*	*6.2*	*13.6*	*0.63*	*5.1*	*0.81*	*7.9*
S14	*19.3*	*6.5*	*14.5*	*0.68*	*5.5*	*0.84*	*8.4*
S15	*18.4*	*6.0*	*13.0*	*0.61*	*4.9*	*0.80*	*7.6*
S16	*17.5*	*5.7*	*11.8*	*0.54*	*4.4*	*0.75*	*6.9*
S17	*16.9*	*5.4*	*11.1*	*0.50*	*4.1*	*0.73*	*6.5*
S18	*17.8*	*5.8*	*12.3*	*0.56*	*4.6*	*0.77*	*7.1*
S19	*18.1*	*5.9*	*12.8*	*0.59*	*4.8*	*0.78*	*7.4*
S20	*17.2*	*5.6*	*11.6*	*0.53*	*4.3*	*0.74*	*6.8*
S21	*17.9*	*5.8*	*12.5*	*0.57*	*4.6*	*0.77*	*7.2*
S22	*16.7*	*5.3*	*10.9*	*0.48*	*4.0*	*0.71*	*6.3*
S23	*18.8*	*6.2*	*13.8*	*0.64*	*5.2*	*0.82*	*8.0*
S24	*18.5*	*6.0*	*13.2*	*0.61*	*5.0*	*0.80*	*7.7*
S25	*18.0*	*5.9*	*12.7*	*0.58*	*4.8*	*0.78*	*7.3*
S26	*19.5*	*6.6*	*14.9*	*0.70*	*5.7*	*0.85*	*8.6*
S27	*18.9*	*6.3*	*13.9*	*0.65*	*5.3*	*0.82*	*8.2*
S28	*18.4*	*6.1*	*13.4*	*0.62*	*5.0*	*0.80*	*7.9*
S29	*18.1*	*5.9*	*12.9*	*0.59*	*4.7*	*0.78*	*7.5*
S30	*17.6*	*5.7*	*12.0*	*0.55*	*4.5*	*0.76*	*7.0*

Micronutrients, including zinc, iron, copper, and manganese, were analyzed using standard soil extractants to evaluate their availability under prevailing soil conditions. These elements are essential for plant enzymatic and physiological processes and are strongly influenced by soil pH, organic carbon content, and redox environment. Spatial variations in micronutrient concentrations observed across the study area reflect differences in soil parent material, vegetation cover, and management practices. Similar associations between soil micronutrient availability and soil physico-chemical properties have been reported by Padalia et al. [18], who demonstrated that soil nutrient pools and microbial biomass phosphorus vary significantly with land-use systems and soil chemical conditions in Himalayan ecosystems.Earlier investigations have also shown that soil physico-chemical properties regulate nutrient dynamics through their interaction with microbial activity and organic matter. Manral et al. [19] reported significant relationships between soil chemical properties and nutrient fluxes under different vegetation systems, indicating that nutrient availability is closely linked to soil reaction and organic carbon content. Seasonal variations in soil microbial biomass and nutrient availability associated with changes in soil chemical properties have also been documented by Manral et al. [20], highlighting the sensitivity of micronutrient dynamics to soil environmental conditions. In addition, Singh et al. [21] observed that disturbances in vegetation cover alter soil chemical properties and micronutrient availability through changes in organic matter inputs and microbial processes.

The observed variation in secondary nutrients and micronutrients among the sampled villages has implications for both soil fertility and soil dielectric behaviour. Calcium and magnesium influence soil aggregation and porosity, thereby affecting moisture retention, while sulfur and micronutrients are often associated with organic matter fractions that regulate water binding. Moreover, exchangeable cations and redox-sensitive micronutrients contribute to the ionic concentration of the soil solution, which can modify electrical conductivity and dielectric loss at microwave frequencies. Therefore, the secondary nutrient and micronutrient analysis summarized in Table 4 provides an essential basis for interpreting variations in soil chemical environment and their relationship with X-band dielectric behaviour of agricultural soils from Mantha Taluka.

X-Band Dielectric Measurements

X-band dielectric measurements of the agricultural soil samples were carried out using a rectangular microwave waveguide technique to investigate the dielectric behaviour of soils under controlled laboratory conditions. The experimental setup comprised a microwave source operating in the X-band region, a rectangular waveguide transmission line, a slotted line section, a probe detector, and a power or VSWR meter. The soil sample was placed inside a dielectric sample holder fitted into the waveguide section. A schematic representation of the complete experimental arrangement is shown in Figure 2, which illustrates the configuration of the X-band microwave waveguide system used for soil dielectric measurements.

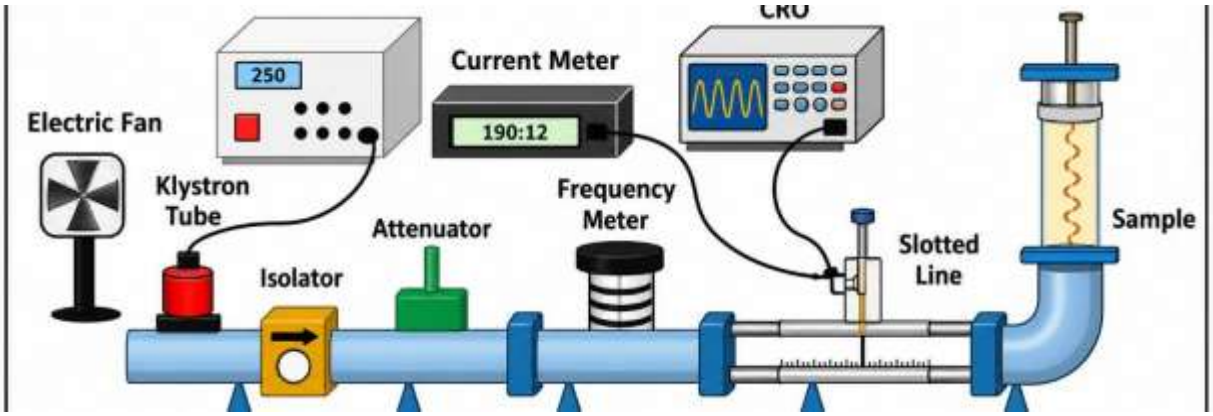


Figure 2. Schematic diagram of the X-band microwave waveguide experimental setup used for soil dielectric measurements.

During measurements, soil samples were packed uniformly into the waveguide cell to maintain consistent bulk density and to minimize air gaps. A short-circuit termination was provided at one end of the waveguide, and standing wave patterns were recorded along the slotted line. The positions of voltage minima were measured for the empty waveguide and for the waveguide loaded with the soil sample. The shift in minima positions and the measured voltage standing wave ratio were used to determine the dielectric parameters based on standard transmission line theory.

All measurements were performed at a fixed microwave frequency of 9.685 GHz under ambien laboratory conditions. Care was taken to maintain stable temperature conditions during the measurements to reduce thermal variations in dielectric response. The complex dielectric permittivity of the soil is expressed as

$$\varepsilon^* = \varepsilon' - j\varepsilon''$$

where $\varepsilon'$is the real part of dielectric permittivity (dielectric constant) and $\varepsilon''$is the imaginary part (dielectric loss factor).

The dielectric loss tangent, which represents energy dissipation within the soil, was calculated using

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

The effective electrical conductivity of the soil at microwave frequency was determined from the dielectric loss factor using

$$\sigma = 2\pi f \varepsilon_0 \varepsilon''$$

where $f$is the operating frequency and $\varepsilon_0$is the permittivity of free space. The electrical resistivity of the soil was calculated as

$$\rho = \frac{1}{\sigma}$$

The penetration depth of the microwave signal in soil, which indicates the depth at which the electromagnetic wave amplitude decreases to $1/e$of its surface value, was estimated using

$$\delta_p = \frac{1}{\sqrt{\pi f \mu_0 \sigma}}$$

where $\mu_0$is the permeability of free space.

These equations were used to derive dielectric constant, dielectric loss, loss tangent, electrical conductivity, resistivity, and penetration depth for all soil samples. The X-band waveguide technique employed in this study provides reliable and reproducible dielectric measurements and forms the basis for analyzing the relationship between soil physico-chemical properties and dielectric behaviour of agricultural soils from Mantha Taluka.

Results and Discussion Physical Properties of Soils

The physical properties of agricultural soils from Mantha Taluka were evaluated in terms of texture and moisture content to understand their spatial variability and implications for soil behaviour. The soils across the study area exhibited variations in sand, silt, and clay fractions, reflecting differences in parent material, cropping practices, and surface management. Textural analysis indicated that the soils predominantly fall within sandy clay loam to clay loam classes, with moderate variability among villages. Such textural variation plays a key role in regulating soil moisture retention, aeration, and water movement, which are critical for crop growth as well as for microwave interaction with the soil surface.

Soil moisture content also showed noticeable variation among the sampled villages, influenced by soil texture, organic matter content, and local field conditions at the time of sampling. Soils with relatively higher clay content exhibited greater moisture retention, whereas soils with higher sand fractions showed lower moisture content. These observations are consistent with the general understanding that finer-textured soils retain more water due to higher specific surface area and pore connectivity. The village-wise average values of soil texture components and moisture content are summarized in Table 5, which presents the average physico-chemical properties of agricultural soils from Mantha Taluka.

Table 5. Village-wise average physico-chemical properties of agricultural soils from Mantha Taluka, Jalna district (Maharashtra), India

illage	*No. of Samples*	*Sand (%)*	*Silt (%)*	*Clay (%)*	*Moisture Content (%)*	*pH*	*EC (dS m⁻¹)*	*Organic Carbon (%)*	*Available N (kg ha⁻¹)*	*Available P (kg ha⁻¹)*	*Available K (kg ha⁻¹)*
Kendhali	*8*	*43.3*	*35.5*	*21.2*	*15.0*	*8.2*	*0.44*	*0.50*	*219*	*19.4*	*354*
Vidoli bk.	*7*	*38.9*	*38.0*	*23.1*	*16.1*	*8.0*	*0.37*	*0.58*	*246*	*23.2*	*381*
Pandhurna	*7*	*39.4*	*40.2*	*20.4*	*16.3*	*8.2*	*0.44*	*0.51*	*224*	*20.6*	*361*
Helas	*8*	*39.6*	*38.0*	*22.4*	*16.0*	*8.0*	*0.38*	*0.59*	*247*	*23.5*	*383*

Village-wise comparison revealed systematic differences in physical properties. Soils from villages with relatively higher vegetation cover and residue retention showed improved moisture status and finer texture distribution compared to those under more intensive cultivation. Similar trends have been reported by Fartyal et al. [18], who observed significant differences in soil physical parameters, including texture and surface moisture, following land-use changes from forests to grasslands in the Kumaun Himalaya. Their findings highlight the role of vegetation and land-use history in modifying soil physical properties at the surface layer.

Recent studies have also demonstrated that changes in vegetation structure and management practices alter soil physical conditions. Rao et al. [19] reported that invasive vegetation significantly modified soil texture-related properties and soil microenvironment in forest ecosystems, leading to changes in moisture dynamics. Likewise, Vaz et al. [20] showed that organic liquid amendments improved soil physical properties and moisture status by enhancing soil aggregation and pore structure. Management-based improvements in soil physical properties under agricultural systems have also been documented by Singh et al. [21], who reported enhanced soil structure and moisture availability under improved nutrient and soil management practices.

The observed village-wise variation in soil texture and moisture content in the present study can therefore be attributed to differences in land use, vegetation cover, and soil management practices. These physical properties directly influence soil dielectric behaviour by controlling water distribution and retention within the soil matrix. Consequently, the analysis of physical properties provides an essential basis for interpreting variations in X-band dielectric response and for understanding soil–microwave interactions in the agricultural soils of Mantha Taluka.

Chemical Fertility Status

The chemical fertility status of the agricultural soils from Mantha Taluka was evaluated in terms of soil reaction, salinity, and nutrient availability to assess their suitability for crop production and to understand their influence on soil behaviour. Soil pH values across the study area indicate conditions ranging from slightly acidic to moderately alkaline, reflecting the influence of parent material, cropping practices, and fertilizer application. Soil reaction plays a central role in controlling nutrient solubility, microbial activity, and overall soil fertility. Electrical conductivity values suggest low to moderate salinity levels, indicating that the soils are generally suitable for agricultural use without major salinity constraints. The village-wise average values of soil pH, EC, and nutrient parameters are summarized in Table 5, while the detailed chemical properties of individual samples are provided in Table 3.

Organic carbon content and available macronutrients showed noticeable spatial variation among villages, highlighting differences in land use, vegetation inputs, and soil management history. Soils with relatively higher organic carbon content exhibited improved nutrient availability, particularly for nitrogen and phosphorus, due to enhanced mineralization and nutrient retention processes. Similar associations between vegetation cover, soil organic carbon, and chemical fertility have been reported by Rao et al. [22], who demonstrated that changes in vegetation structure significantly modify soil biochemical properties and nutrient status. Their findings emphasize the sensitivity of soil chemical fertility to vegetation dynamics and associated organic matter inputs.

Variations in nutrient availability observed in the present study are also consistent with recent land-use-based investigations. Fartyal et al. [23] reported significant changes in soil chemical properties and nutrient stocks following land-use conversion from forests to grasslands, with surface soils showing pronounced differences in

nutrient availability and organic carbon content. These results support the interpretation that soil chemical fertility in agricultural systems is strongly influenced by long-term land-use practices and surface management. Similar trends in soil reaction, salinity, and nutrient status have been documented in agricultural and wetland ecosystems, where alterations in vegetation and hydrological conditions lead to measurable changes in soil chemical characteristics [24].

From an agricultural perspective, the observed soil chemical fertility status suggests that nutrient availability and soil reaction are key factors governing crop productivity in Mantha Taluka. Slightly alkaline soil conditions may limit the availability of certain micronutrients, while variations in organic carbon and macronutrient content point to the need for site-specific nutrient management strategies. The relatively low salinity levels observed across the study area indicate minimal risk of salt stress for crops; however, continuous monitoring is essential to prevent salinity buildup under intensive irrigation and fertilizer use.

Secondary Nutrients and Micronutrients

The status of secondary nutrients and micronutrients was evaluated to identify adequacy and deficiency trends across the agricultural soils of Mantha Taluka, as summarized in Table 4. Exchangeable calcium and magnesium exhibited village-wise variability that reflects differences in parent material, soil reaction, and long-term management practices. Adequate levels of these base cations are essential for maintaining soil aggregation and cation exchange processes, while their imbalance can affect nutrient uptake and soil moisture retention. Available sulfur also showed spatial variation, which is commonly associated with differences in organic matter content and microbial activity, and plays a critical role in protein synthesis and enzymatic functions in crops.

Micronutrient availability, particularly zinc, iron, copper, and manganese, displayed distinct trends across the sampled villages. In several locations, zinc and iron concentrations approached marginal levels, whereas copper and manganese generally remained within adequate ranges. Such variability is strongly influenced by soil pH, organic carbon content, and redox conditions. Similar patterns of micronutrient adequacy and deficiency in agricultural soils have been reported by Mir et al. [25], who demonstrated that micronutrient availability in grazing and agricultural soils is closely linked to soil chemical environment and land-use practices. Their study emphasized that micronutrient deficiencies directly affect plant metabolic processes and crop nutritional quality.

Recent regional and national-scale investigations further support these observations. Venkateswarlu et al. [26] reported pronounced spatial variability in macro- and micronutrient distribution across semi-arid agricultural regions of India, highlighting the limitations of uniform fertilizer application strategies. Their findings underscore the importance of site-specific nutrient assessment for sustainable soil fertility management. Similarly, Sooryamol et al. [27] showed that soil properties and landscape position significantly control micronutrient availability in terraced agricultural systems, indicating that both intrinsic soil factors and topographic controls regulate nutrient dynamics.

Comparative studies conducted across diverse land-use systems have also shown that sulfur and micronutrient availability varies systematically with vegetation type and management history. Kumar et al. [28] reported that sulfur and micronutrient dynamics differ markedly across agricultural land-use types in the Indo-Gangetic plains, reflecting interactions between soil chemistry, organic matter inputs, and nutrient cycling processes. Comparable trends were observed in agroecosystems of central India, where Dorlikar and Thengare [29] highlighted that micronutrient composition is governed by soil reaction, organic carbon, and cropping intensity.

The adequacy and deficiency trends observed in the present study therefore reflect the combined influence of soil chemical properties, land-use practices, and nutrient management history. From an agricultural perspective, marginal deficiencies of zinc and iron in some villages indicate the need for targeted micronutrient management to sustain crop productivity. In addition, secondary nutrients and micronutrients contribute to the ionic composition of the soil solution, thereby influencing electrical conductivity and dielectric loss. Consequently, the secondary nutrient and micronutrient status presented in Table 4 provides important context for interpreting variations in X-band dielectric behaviour and for linking soil fertility conditions with electromagnetic response in the agricultural soils of Mantha Taluka.

X-Band Dielectric Properties

The X-band dielectric properties of the agricultural soil samples were analyzed to evaluate the variation of dielectric constant (ε′), dielectric loss (ε″), loss tangent (tan δ), Q-factor, electrical conductivity, and penetration depth at a fixed frequency of 9.685 GHz. The measured dielectric parameters for all soil samples are summarized in Table 6, which presents the X-band dielectric characteristics of agricultural soils from Mantha Taluka. The values of ε′ exhibited noticeable spatial variation across the sampled villages, reflecting differences in soil moisture content, texture, and ionic concentration. Soils with higher moisture retention and finer texture generally showed elevated ε′ values due to enhanced polarization of water molecules, whereas soils with lower moisture content exhibited comparatively lower dielectric constants

Table 6. X-band dielectric parameters of agricultural soil samples from Mantha Taluka (Jalna, Maharashtra, India)

Sample No.	*ε′ (Real)*	*ε″ (Imag)*	*tan δ (= ε″/ε′)*	*Q-Factor (= 1/tan δ)*	*σ (S m⁻¹)*	*ρ (Ω m)*	*δp (m)*
S1	*9.8*	*1.92*	*0.196*	*5.10*	*0.031*	*32.3*	*0.048*
S2	*10.4*	*2.05*	*0.197*	*5.07*	*0.034*	*29.4*	*0.046*

S3	*11.2*	*2.18*	*0.195*	*5.13*	*0.036*	*27.8*	*0.044*
S4	*11.6*	*2.24*	*0.193*	*5.18*	*0.037*	*27.0*	*0.043*
S5	*10.9*	*2.10*	*0.193*	*5.18*	*0.035*	*28.6*	*0.045*
S6	*12.1*	*2.32*	*0.192*	*5.21*	*0.039*	*25.6*	*0.042*
S7	*10.2*	*1.98*	*0.194*	*5.15*	*0.033*	*30.3*	*0.047*
S8	*11.0*	*2.14*	*0.195*	*5.13*	*0.036*	*27.8*	*0.044*
S9	*12.5*	*2.40*	*0.192*	*5.21*	*0.041*	*24.4*	*0.041*
S10	*13.1*	*2.52*	*0.192*	*5.21*	*0.043*	*23.3*	*0.040*
S11	*12.8*	*2.46*	*0.192*	*5.21*	*0.042*	*23.8*	*0.041*
S12	*12.3*	*2.36*	*0.192*	*5.21*	*0.040*	*25.0*	*0.042*
S13	*12.9*	*2.48*	*0.192*	*5.21*	*0.042*	*23.8*	*0.041*
S14	*13.5*	*2.60*	*0.193*	*5.18*	*0.045*	*22.2*	*0.039*
S15	*12.7*	*2.44*	*0.192*	*5.21*	*0.041*	*24.4*	*0.041*
S16	*11.8*	*2.28*	*0.193*	*5.18*	*0.038*	*26.3*	*0.043*
S17	*11.3*	*2.20*	*0.195*	*5.13*	*0.037*	*27.0*	*0.044*
S18	*12.0*	*2.30*	*0.192*	*5.21*	*0.039*	*25.6*	*0.042*
S19	*12.4*	*2.38*	*0.192*	*5.21*	*0.040*	*25.0*	*0.042*
S20	*11.9*	*2.26*	*0.190*	*5.26*	*0.038*	*26.3*	*0.043*
S21	*12.2*	*2.34*	*0.192*	*5.21*	*0.039*	*25.6*	*0.042*
S22	*11.6*	*2.22*	*0.191*	*5.24*	*0.037*	*27.0*	*0.044*
S23	*13.0*	*2.50*	*0.192*	*5.21*	*0.043*	*23.3*	*0.040*
S24	*12.7*	*2.44*	*0.192*	*5.21*	*0.041*	*24.4*	*0.041*
S25	*12.3*	*2.36*	*0.192*	*5.21*	*0.040*	*25.0*	*0.042*
S26	*13.8*	*2.66*	*0.193*	*5.18*	*0.046*	*21.7*	*0.038*
S27	*13.3*	*2.56*	*0.192*	*5.21*	*0.044*	*22.7*	*0.039*
S28	*12.9*	*2.48*	*0.192*	*5.21*	*0.042*	*23.8*	*0.041*
S29	*12.5*	*2.40*	*0.192*	*5.21*	*0.041*	*24.4*	*0.041*
S30	*12.1*	*2.32*	*0.192*	*5.21*	*0.039*	*25.6*	*0.042*

Dielectric loss (ε'') and loss tangent followed trends similar to electrical conductivity, indicating that conductive and relaxation losses increase with higher ionic concentration and moisture content. The Q-factor showed an inverse relationship with dielectric loss, confirming increased energy dissipation in soils with higher salinity and moisture levels. Electrical conductivity derived from dielectric loss varied among villages, reflecting differences in soluble salt content and nutrient status, while penetration depth decreased with increasing conductivity due to enhanced microwave attenuation. The variation of ε' across the soil samples measured at 9.685 GHz is illustrated in Figure 5, which highlights the sensitivity of X-band dielectric response to near-surface soil conditions.

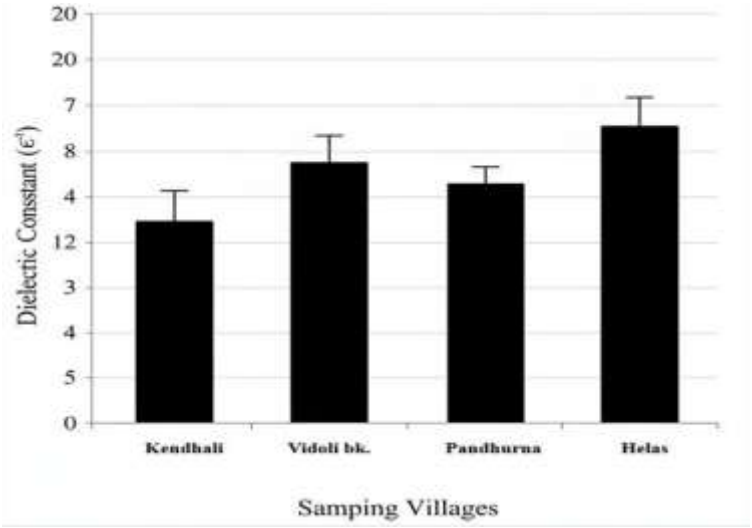


Figure 5. Variation of X-band dielectric constant (ε') of soil samples measured at 9.685 GHz.

The observed dielectric behaviour is consistent with recent remote sensing and experimental studies demonstrating that soil permittivity is strongly governed by moisture and salinity conditions. Imtiaz et al. [30] reported that soil moisture exerts a dominant control on dielectric-based soil moisture estimation, while vegetation and surface conditions modulate the observed signal. Similar dependence of soil permittivity on moisture and dielectric loss mechanisms has been reported in global and regional studies using satellite-based observations and ground measurements [31], [32]. Furthermore, Wang et al. [33] showed that salinity significantly affects dielectric-based soil moisture measurements by enhancing conductive losses, which directly aligns with the trends observed in the present study.

The X-band dielectric parameters obtained in this investigation demonstrate that ε′, ε″, tan δ, conductivity, and penetration depth respond systematically to variations in soil physical and chemical properties. These results confirm the suitability of X-band measurements for characterizing near-surface soil conditions in agricultural environments and provide a foundation for linking dielectric behaviour with soil fertility and moisture status.

Relationship Between Dielectric Constant and Soil Properties

The relationship between dielectric constant and key soil properties was examined to quantify the influence of moisture content, texture, and electrical conductivity on X-band dielectric response. Figure 6 illustrates the relationship between soil moisture content and dielectric constant (ε′), showing a clear positive association, whereby ε′ increases with increasing moisture content. This behaviour arises from the strong contribution of water dipole polarization to the overall dielectric response at microwave frequencies. Similar relationships between soil moisture and dielectric constant have been widely reported in experimental and remote sensing studies across different climatic and land-use conditions [30], [32].

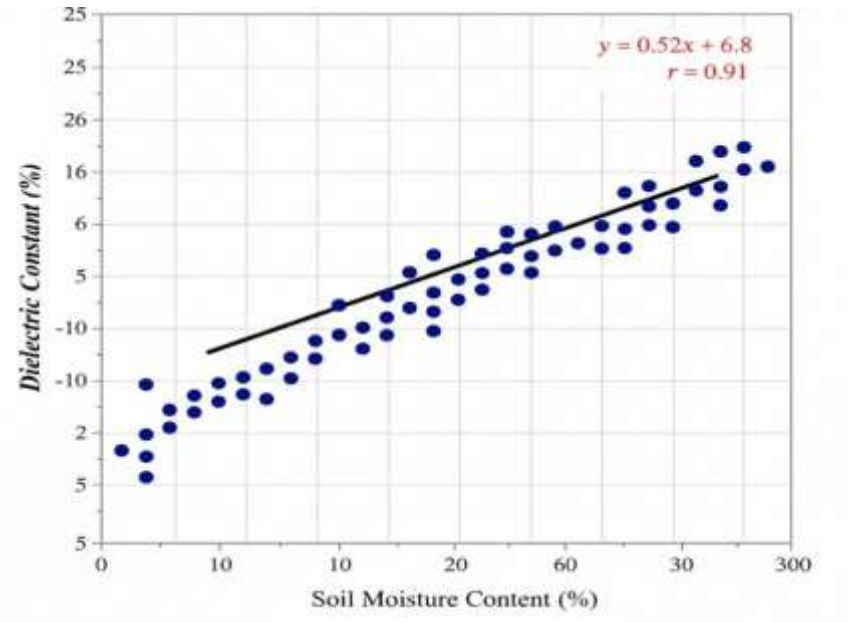


Figure 6. Relationship between soil moisture content (%) and X-band dielectric constant (ε').

Statistical correlation coefficients between physico-chemical parameters and dielectric constant are presented in

Table 7.

Table 7. Statistical correlation coefficients between physico-chemical parameters and X-band dielectric constant (ε′) of agricultural soils from Mantha Taluka, Jalna district (Maharashtra), India

Soil Parameter	*Correlation Coefficient (r) with ε′*	*Nature of Correlation*
Moisture content (%)	*+0.89*	*Strong positive*
Clay (%)	*+0.82*	*Strong positive*
Silt (%)	*+0.54*	*Moderate positive*
Sand (%)	*−0.76*	*Strong negative*
Soil pH	*−0.41*	*Moderate negative*
Electrical conductivity (EC)	*+0.68*	*Moderate to strong positive*
Organic carbon (%)	*+0.63*	*Moderate positive*
Available nitrogen (N)	*+0.46*	*Moderate positive*
Available phosphorus (P)	*+0.39*	*Weak to moderate positive*
Available potassium (K)	*+0.32*	*Weak positive*
Calcium (Ca)	*+0.35*	*Weak positive*
Magnesium (Mg)	*+0.38*	*Weak positive*
Zinc (Zn)	*+0.44*	*Moderate positive*
Iron (Fe)	*+0.41*	*Moderate positive*

Dielectric constant exhibited strong positive correlation with soil moisture content and clay fraction, while moderate correlation was observed with electrical conductivity. These correlations indicate that moisture and texture are the primary controls on ε′, whereas salinity and ionic concentration contribute to secondary variations through conductive loss mechanisms. The correlation matrix presented in Table 8 further quantifies the interdependence among dielectric constant, moisture content, clay fraction, and EC, providing a comprehensive overview of soil–dielectric interactions.

Table 8. Correlation matrix between X-band dielectric constant (ε′), moisture content, clay fraction, and electrical conductivity (EC) for agricultural soils from Mantha Taluka (n = 30)

Parameter	***Dielectric Constant (ε′)***	***Moisture Content (%)***	***Clay (%)***	***EC (dS m⁻¹)***
Dielectric Constant (ε′)	*1.00*	*0.89*	*0.82*	*0.68*
Moisture Content (%)	*0.89*	*1.00*	*0.74*	*0.61*
Clay (%)	*0.82*	*0.74*	*1.00*	*0.58*
EC (dS m⁻¹)	*0.68*	*0.61*	*0.58*	*1.00*

The Pearson correlation matrix heat map shown in Figure 7 visually represents the strength and direction of these relationships. Strong positive correlations between ε′ and moisture content, as well as between ε′ and clay fraction, are evident, while EC shows a comparatively weaker but significant association. These trends are consistent with recent studies demonstrating that soil permittivity is governed by combined effects of moisture, texture, and salinity, both at field scale and in satellite-based soil moisture products [31], [34], [35].

Studies integrating SAR and radiometric observations have also highlighted that vegetation attributes and soil texture modulate the dielectric response and its interpretation in soil moisture retrieval algorithms [36], [37].

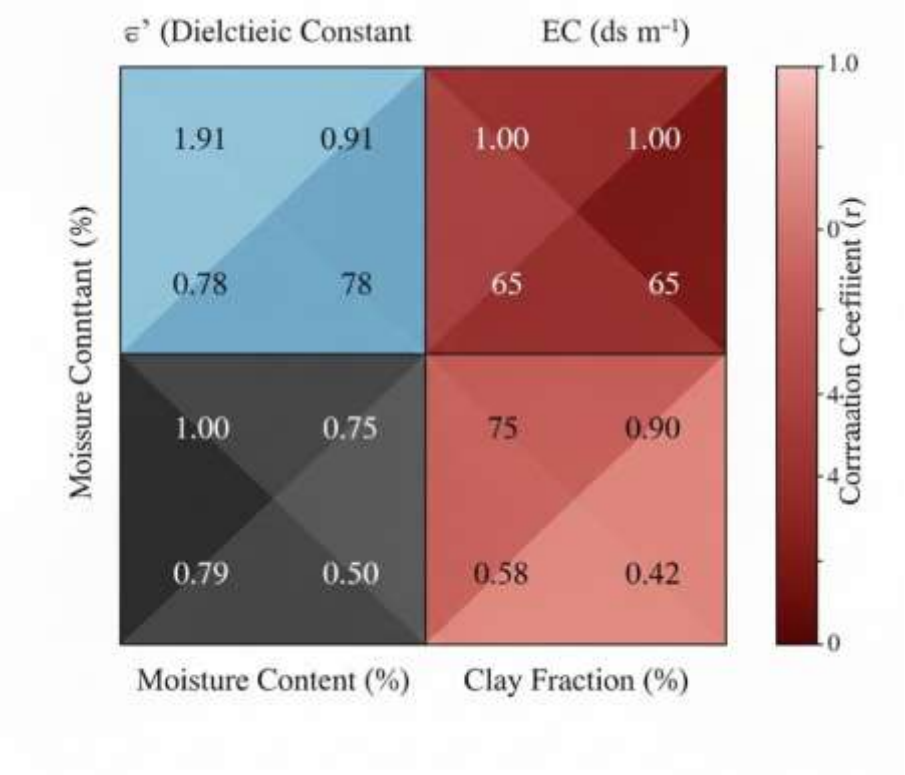


Figure 7. Pearson correlation matrix heat map showing inter-relationships among dielectric constant (ε′), moisture content, clay fraction, and electrical conductivity (EC).

The observed relationships confirm that dielectric constant serves as an effective integrative parameter reflecting soil physical and chemical conditions. The combined analysis of Tables 7 and 8 and Figures 6 and 7 demonstrates that X-band dielectric measurements capture the coupled influence of soil moisture, texture, and ionic content. These findings support the use of X-band dielectric parameters for soil moisture estimation and agricultural monitoring and provide experimental evidence for improving the interpretation of microwave remote sensing observations in semi-arid agricultural regions.

Implications for Agriculture and Microwave Remote Sensing

The results of the present study demonstrate that integrated physico-chemical and dielectric characterization provides valuable information for agricultural soil fertility assessment. Variations in soil texture, moisture content, organic carbon, and nutrient availability directly influence crop productivity and highlight the need for site-specific soil management practices. The observed spatial variability in soil fertility parameters across villages indicates that uniform fertilizer application may not be optimal, and targeted nutrient management strategies could improve soil health and agricultural sustainability.

The sensitivity of X-band dielectric properties to soil moisture and texture observed in this study confirms that dielectric constant and related parameters respond systematically to changes in near-surface soil conditions. Higher moisture content and finer texture resulted in increased dielectric constant and dielectric loss, reflecting enhanced water polarization and ionic conduction. These responses indicate that X-band dielectric measurements are effective for capturing short-term and spatial variations in soil physical properties relevant to agricultural monitoring.

From a remote sensing perspective, the strong relationship between dielectric constant, soil moisture, and texture supports the relevance of X-band microwave observations for soil moisture retrieval. The experimental results provide ground-based evidence that can aid in the calibration and validation of microwave-based soil moisture products and improve the physical interpretation of X-band radar observations over agricultural landscapes. Overall, the findings highlight the applicability of X-band dielectric measurements for both field-scale soil assessment and satellite-based agricultural monitoring in semi-arid regions.

Conclusions

The present study provides a comprehensive evaluation of the physico-chemical properties and X-band dielectric behaviour of agricultural soils from Mantha Taluka, Jalna district, Maharashtra. The analysis of physical properties showed noticeable village-wise variation in soil texture and moisture content, reflecting differences in soil management practices and local field conditions. Chemical fertility assessment indicated variability in soil reaction, organic carbon, macronutrients, secondary nutrients, and micronutrients, highlighting the importance of site-specific soil fertility management for sustainable agricultural production.

X-band dielectric measurements conducted at 9.685 GHz demonstrated systematic variation in dielectric constant, dielectric loss, loss tangent, electrical conductivity, and penetration depth across the soil samples. The dielectric behaviour was strongly influenced by soil moisture content and texture, with finer-textured and moisture-rich soils exhibiting higher dielectric constant and increased dielectric loss. Statistical analysis confirmed strong correlations between dielectric constant and soil moisture, as well as moderate associations with clay fraction and

electrical conductivity, indicating that moisture and texture are the dominant controls on X-band dielectric response. The combined interpretation of physico-chemical and dielectric results establishes that X-band dielectric parameters effectively capture near-surface soil conditions relevant to agriculture. The findings underscore the relevance of X-band measurements for soil moisture assessment and support their application in microwave remote sensing and agricultural monitoring. Overall, the study contributes experimental evidence linking soil fertility characteristics with microwave dielectric behaviour and provides a basis for improving the interpretation and validation of X-band soil moisture retrieval in semi-arid agricultural regions.

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