Multi-Frequency Microwave Dielectric Characterization of Agricultural Soils for Precision Agriculture Applications

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Abstract
Soil quality plays a vital role in sustainable agriculture and crop productivity. This study evaluated the physical, chemical, and microwave dielectric properties of twenty agricultural soil samples collected from Mantha and Ghansawangi talukas of Jalna district, Maharashtra, India. Physical and chemical properties were determined using standard laboratory methods, while dielectric measurements were performed at C band (4.785 GHz), J band (7.60 GHz), and X band (9.685 GHz) using the two-point transcendental waveguide method. The soils were predominantly classified as clay loam, loam, and sandy loam with slightly alkaline pH (7.60–8.40) and non-saline conditions. The dielectric constant decreased with increasing frequency, ranging from 4.04–4.67 at C band to 2.70–3.15 at X band, while dielectric loss varied between 0.28 and 1.66 across the investigated bands. Correlation analysis revealed that moisture content, clay fraction, bulk density, and nutrient status significantly influenced the dielectric response. The findings demonstrate that microwave dielectric techniques provide a rapid, reliable, and non-destructive approach for soil quality assessment and have significant potential for precision agriculture and sustainable land management.

Keywords: Agricultural soils; Microwave dielectric characterization; Complex permittivity; Two-point transcendental waveguide method; Soil quality; Precision agriculture; Jalna district; Microwave sensing.

1. Introduction

Soil is a vital natural resource that supports agricultural productivity, environmental sustainability, and ecosystem functioning by supplying water, nutrients, and physical support for plant growth. The quality of soil directly influences crop yield, nutrient cycling, and long-term agricultural sustainability. However, continuous cultivation, excessive fertilizer use, climate variability, and inappropriate land management practices have gradually altered soil physical and chemical properties, resulting in declining fertility and productivity [1]. Consequently, rapid and reliable periodic assessment of soil quality has become essential for sustainable agriculture and precision farming.

Conventional soil quality assessment relies on laboratory determination of parameters such as soil texture, bulk density, moisture content, pH, electrical conductivity (EC), organic carbon, and available nutrients. Although these methods provide accurate information, they are time-consuming, labor-intensive, destructive, and unsuitable for rapid large-scale monitoring. Therefore, there is an increasing need for alternative techniques capable of providing fast, non-destructive, and reliable soil characterization.

Microwave dielectric techniques have emerged as a promising approach because the interaction of electromagnetic waves with soil is highly dependent on its dielectric properties. The complex dielectric constant consists of the real part (ε'), representing the ability of soil to store electromagnetic energy, and the imaginary part (ε''), representing energy dissipation due to dielectric relaxation and ionic conduction. These dielectric parameters are strongly influenced by soil moisture, texture, bulk density, porosity, organic matter, mineral composition, and soluble salts, making them effective indicators of soil quality. Since water possesses a much higher dielectric constant than soil minerals and air, even small changes in moisture significantly affect the microwave dielectric response.

Although numerous studies have investigated microwave dielectric properties for soil moisture estimation and remote sensing applications, relatively few have integrated dielectric measurements with conventional physical and chemical soil properties for comprehensive soil quality evaluation [2]. Moreover, information on the microwave dielectric behaviour of agricultural soils from Jalna district, Maharashtra, remains limited.

Therefore, the present study evaluates the physical, chemical, and microwave dielectric characteristics of twenty agricultural soil samples collected from Jalna district using measurements at C band (4.785 GHz), J band (7.60 GHz), and X band (9.685 GHz). Relationships among conventional soil properties and dielectric parameters were investigated using statistical analyses to establish the potential of microwave dielectric techniques as rapid, non-destructive tools for soil quality assessment and precision agriculture.

2. Materials and Methods

2.1 Study Area

The present investigation was conducted in Mantha and Georai tehsils of Jalna district, Maharashtra, India. Jalna district is located in the Marathwada region between approximately 19°01′–20°03′ N latitude and 75°04′–76°04′ E longitude. The selected tehsils represent one of the major agricultural regions of the district, where farming is the primary occupation and soils exhibit considerable variability in their physical and chemical characteristics. Twenty agricultural soil samples were collected from representative villages of both tehsils to investigate their physical, chemical, and microwave dielectric

properties.
The study area experiences a semi-arid tropical climate with three distinct seasons: summer (March–June), monsoon (June–September), and winter (November–February). Summer temperatures frequently reach 40–45°C, whereas winter temperatures range between 10 and 15°C. The average annual rainfall is approximately 650–750 mm, most of which is received during the southwest monsoon. Variability in rainfall and prolonged dry periods strongly influence soil moisture availability, crop growth, and agricultural productivity.
Geologically, the region forms part of the Deccan Volcanic Province, where soils have developed from weathered basaltic lava flows of the Deccan Traps. The parent material has produced predominantly deep black soils rich in clay minerals, particularly montmorillonite, which possess high water-holding capacity, moderate to high cation exchange capacity, and good nutrient retention. The landscape is generally characterized by gently undulating plains with favorable agricultural potential.
Agriculture is the dominant land-use system in both tehsils. The major crops cultivated include cotton, soybean, pigeon pea (tur), sorghum (jowar), wheat, chickpea (gram), maize, and oilseed crops, with cotton–soybean and soybean–wheat being the most common cropping systems. Irrigation is provided through wells, borewells, farm ponds, and seasonal reservoirs, although a substantial proportion of agriculture remains dependent on monsoon rainfall.
The predominance of Vertisols (black cotton soils) and clay loam soils, together with their varying moisture content, nutrient status, and mineral composition, makes the study area highly suitable for microwave dielectric investigations [3]. These characteristics provide an excellent opportunity to establish relationships between conventional soil quality parameters and dielectric properties measured at C band (4.785 GHz), J band (7.60 GHz), and X band (9.685 GHz), thereby supporting rapid soil quality assessment and precision agriculture applications.

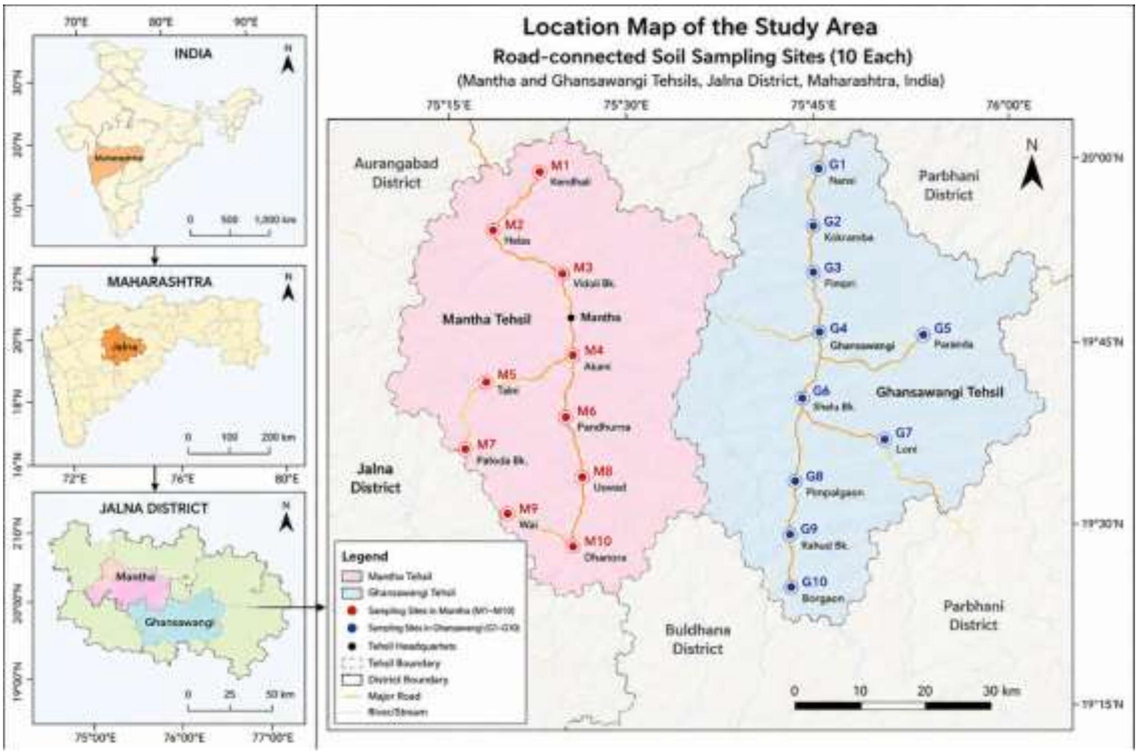

Figure 1. Location map of the study area showing all 20 sampling sites.

2.2 Soil Sampling

Twenty agricultural soil samples were collected from cultivated fields in Mantha (M1–M10) and Ghansawangi (G1–G10) talukas of Jalna district, Maharashtra, India. Sampling sites were selected to represent the dominant agricultural soils under different cropping systems and management practices. All samples were collected during the post-harvest season under relatively dry field conditions to minimize the influence of recent rainfall on the measured soil properties.
Surface soil samples were collected from the 0–15 cm depth, representing the active root zone. At each location, five subsamples were collected using a zigzag sampling pattern and combined to obtain a representative composite sample of approximately 1.5–2.0 kg. Stones, plant residues, and other foreign materials were removed during sampling. The geographical coordinates of each sampling site were recorded using GPS and verified through Google Maps. The collected samples were labeled as M1–M10 (Mantha) and G1–G10 (Ghansawangi) and transported to the laboratory in airtight polyethylene bags.
In the laboratory, the samples were air-dried at room temperature, gently crushed, and passed through a 2 mm sieve for the determination of physical and chemical properties. A portion of each sample was further ground and sieved through a 0.5 mm mesh for microwave dielectric measurements to ensure uniform packing within the rectangular waveguide sample holder. All prepared samples were stored in airtight containers until further analyses to maintain consistency throughout the experimental study.

2.3 Determination of Physical Properties

The physical properties of the collected agricultural soil samples were determined following standard soil analysis procedures to evaluate the structural and hydraulic characteristics of the soils. These parameters are important because they directly influence water movement, nutrient availability, root penetration, and the microwave dielectric behaviour of soils.

Soil texture was determined using the hydrometer method, in which the percentages of sand, silt, and clay were measured and the textural class was assigned according to the USDA textural triangle [4]. The collected soils were classified as loam, clay loam, and sandy loam, representing the dominant agricultural soil types of the study area.

Bulk density (Mg m⁻³) was determined by the core sampler method, in which the oven-dried mass of undisturbed soil was divided by the volume of the sampling core. Particle density was determined using the pycnometer method. Based on the measured bulk density and particle density, soil porosity (%) was calculated using

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

The measured physical properties of all twenty agricultural soil samples are presented in Table 1. The soils exhibited bulk density values ranging from 1.20 to 1.40 Mg m^{-3}, pH between 6.56 and 7.38, electrical conductivity (EC) from 0.14 to 0.78 dS m^{-1}, organic carbon between 0.80 and 1.50%, moisture content ranging from 7.82 to 14.88%, and porosity varying between 47 and 55%. Particle-size analysis showed that the sand fraction varied from 30 to 40%, silt from 21 to 30%, and clay from 36 to 47%, indicating the predominance of loam and clay loam soils. These physical characteristics are expected to influence the dielectric properties of the soils because moisture content, clay fraction, and pore distribution significantly affect microwave polarization and electromagnetic wave propagation.

Table 1. Physical properties of all agricultural soil samples.

Sample ID	Soil Texture	Bulk Density (Mg m^{-3})	pH	EC (dS m^{-1})	Organic Carbon (%)	Moisture Content (%)	Porosity (%)	Sand (%)	Silt (%)	Clay (%)
M1	Loam	1.22	7.24	0.27	0.85	7.82	53	31	29	40
M2	Clay loam	1.21	6.59	0.26	1.20	11.49	55	38	26	36
M3	Sandy loam	1.29	6.78	0.71	1.32	8.28	51	35	24	41
M4	Sandy loam	1.24	7.26	0.17	1.03	9.87	50	39	24	37
M5	Sandy loam	1.35	7.04	0.78	1.03	11.42	55	39	25	36
M6	Loam	1.24	6.57	0.56	1.33	14.88	48	31	26	43
M7	Clay loam	1.29	7.33	0.21	1.02	12.36	55	40	21	39
M8	Loam	1.33	7.03	0.27	1.10	9.16	55	38	23	39
M9	Loam	1.26	7.27	0.14	1.37	13.44	51	34	21	45
M10	Sandy loam	1.38	7.07	0.60	0.91	10.99	55	37	22	41
G1	Clay loam	1.23	7.24	0.48	1.31	10.43	54	36	25	39
G2	Sandy loam	1.40	6.64	0.45	1.32	13.89	47	40	22	38
G3	Loam	1.28	6.56	0.37	1.50	11.23	53	30	30	40
G4	Loam	1.22	7.38	0.63	1.33	9.72	49	36	22	42
G5	Clay loam	1.20	7.22	0.60	1.48	13.10	53	31	30	39
G6	Clay loam	1.37	7.01	0.24	1.03	8.29	53	30	29	41
G7	Clay loam	1.30	6.61	0.35	1.49	13.45	48	30	23	47
G8	Loam	1.39	6.59	0.44	0.80	13.08	47	32	30	38
G9	Clay loam	1.39	6.67	0.47	1.20	14.71	53	33	24	43
G10	Clay loam	1.40	7.15	0.41	1.14	7.97	48	31	25	44

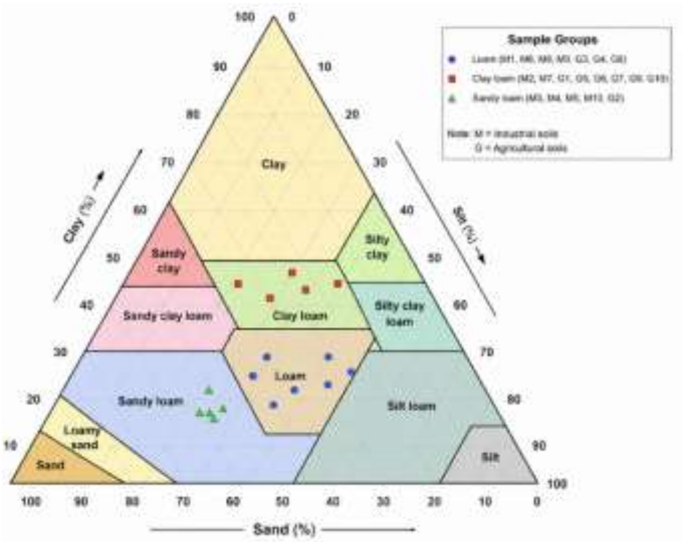

Figure 2. USDA soil texture triangle showing the classification of all samples.

2.4 Determination of Chemical Properties

The chemical properties of the collected agricultural soil samples were analysed at the Soil Testing Laboratory, Krishi Vigyan Kendra (KVK), Jalna, Maharashtra, India, following standard analytical procedures recommended by the Indian Council of Agricultural Research (ICAR) for soil fertility assessment. The selected chemical parameters were analysed because they significantly influence nutrient availability, soil fertility, ionic conductivity, and the microwave dielectric response of soils.

Soil pH was determined in a 1:2.5 (soil: distilled water) suspension using a calibrated digital pH meter. Soil reaction (pH) is an important indicator of nutrient availability and governs several physicochemical processes occurring in agricultural soils [5].

The electrical conductivity (EC) of the soil-water extract was measured using a digital conductivity meter and expressed in dS m^{-1}. Electrical conductivity provides an estimate of the concentration of soluble salts present in the soil and serves as an indicator of soil salinity.

Organic carbon (OC) content was determined using the Walkley and Black wet oxidation method. Organic carbon is a major indicator of soil organic matter and plays an important role in improving soil structure, water-holding capacity, nutrient retention, and microbial activity.

Available nitrogen (N) was estimated by the alkaline potassium permanganate method (Subbiah and Asija, 1956) and expressed in kg ha^{-1}. This method estimates the readily mineralizable fraction of nitrogen available for plant uptake [6].

Available phosphorus (P) was determined by the Olsen sodium bicarbonate extraction method, followed by colorimetric measurement using a spectrophotometer. The results were expressed in kg ha^{-1}. This method is suitable for neutral to alkaline soils and estimates the plant-available phosphorus fraction.

Available potassium (K) was extracted using neutral 1N ammonium acetate and measured with a flame photometer. The available potassium content was expressed in kg ha^{-1} and represents the exchangeable potassium available for crop growth.

The analysed chemical properties of the agricultural soil samples are presented in Table 2. These parameters were subsequently used to evaluate soil fertility status and to investigate their relationship with the measured microwave dielectric properties.

Table 2. Chemical properties of the agricultural soil samples.

Sample ID	Soil Type	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})	pH	EC (dS m^{-1})	Organic Carbon (%)
M1	Black Cotton Soil	158	20.56	418.88	8.3	0.78	0.31
M2	Black Cotton Soil	97	12.82	297.81	8.0	0.72	0.21
M3	Black Cotton Soil	174	16.45	352.80	8.4	0.30	0.31
M4	Black Cotton Soil	176	17.66	367.36	8.2	0.28	0.41
M5	Black Cotton Soil	146	22.50	482.83	8.1	0.77	0.29
M6	Black Soil	201	21.77	300.16	8.3	0.75	0.25
M7	Black Soil	115	15.24	629.44	7.6	0.63	0.20
M8	Black Cotton Soil	117	11.61	741.44	8.2	0.62	0.22
M9	Black Cotton Soil	142	21.77	433.44	7.9	0.32	0.34
M10	Black Cotton Soil	171	12.34	637.28	8.1	0.40	0.43
G1	Black Cotton Soil	138	24.43	435.68	7.9	0.28	0.27
G2	Black Cotton Soil	184	19.60	415.52	8.1	0.24	0.27
G3	Black Cotton Soil	107	22.98	405.44	8.2	0.62	0.38
G4	Black Soil	179	17.66	266.56	8.0	0.26	0.39
G5	Black Cotton Soil	206	15.72	277.76	8.1	0.22	0.39
G6	Black Cotton Soil	172	23.47	306.88	7.9	0.30	0.34

G7	Alluvial Soil	184	7.02	244.16	8.0	0.47	0.34
G8	Black Cotton Soil	178	24.68	585.52	8.2	0.38	0.21
G9	Black Cotton Soil	191	24.92	386.40	8.0	0.26	0.39
G10	Black Cotton Soil	187	18.39	250.88	8.2	0.50	0.22

2.5 Dielectric Measurements at Microwave frequencies

The microwave dielectric properties of the agricultural soil samples were measured using a rectangular waveguide transmission-line system based on the two-point transcendental waveguide method. The experimental setup (Figure 3) consisted of a microwave power supply, microwave signal generator, isolator, variable attenuator, automated slotted line, solid sample cell, and a personal computer for data acquisition and processing. Microwave signals propagated through the rectangular waveguide, and the standing-wave pattern generated by the soil sample was recorded using the automated slotted-line system.

A specially designed solid sample holder, mounted at a 90° orientation to the waveguide axis, was used to ensure uniform packing of the powdered soil and minimize errors caused by air gaps [7]. Before measurement, the soil samples were oven-dried, finely ground, and sieved to obtain homogeneous material. The prepared samples were packed uniformly inside the sample holder to maintain consistent bulk density during all measurements.

Measurements were performed in the dominant TE_{10} propagation mode at C band (4.785 GHz), J band (7.60 GHz), and X band (9.685 GHz). These frequency bands were selected to investigate the frequency-dependent dielectric behaviour of agricultural soils, as lower frequencies provide greater penetration depth, whereas higher frequencies are more sensitive to near-surface dielectric variations [9].

For each sample, dielectric measurements were carried out using three independently prepared sample lengths to improve measurement accuracy and reproducibility. Initially, the guide wavelength (λ_g) of the empty waveguide was determined from the spacing between successive voltage minima. After inserting the soil-filled sample holder into the waveguide, the new minimum position (D) and the voltage standing-wave ratio (VSWR) were measured. These waveguide parameters were used to determine the complex dielectric constant by applying the two-point waveguide method involving the solution of a transcendental equation, from which the real dielectric constant (ε′) and dielectric loss (ε″) were calculated. The measured dielectric parameters were subsequently processed using a custom-developed computational program to determine loss tangent, AC conductivity, phase angle, relaxation time, quality factor, reflection coefficient, and penetration depth. All measurements were performed under identical experimental conditions to ensure accuracy, repeatability, and consistency of the dielectric characterization

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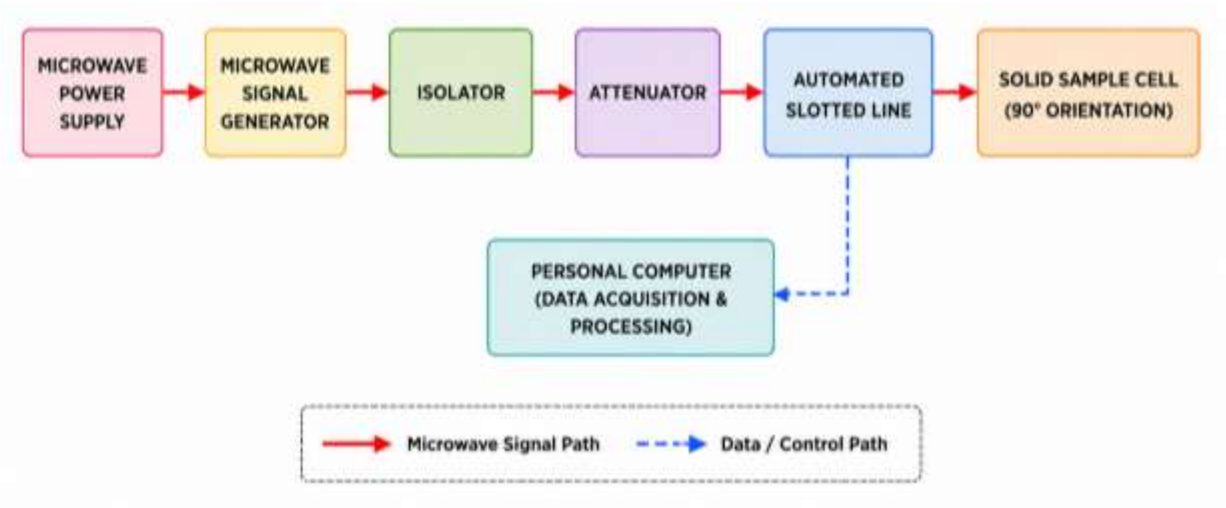


Figure 3: Block diagram of the microwave experimental setup

The dielectric behaviour at microwave frequencies of the twenty agricultural soil samples was evaluated at the C, J, and X band frequencies using the two-point transcendental waveguide method. In this method, the complex dielectric constant was determined from the measured guide wavelength (λ_g), sample length (l_e), power minimum positions (D_R and D), and voltage standing-wave ratio (VSWR).

The propagation constant of the empty waveguide was first calculated as

$$\kappa = \frac{2\pi}{\lambda_g}$$

Where κ is the propagation constant and λ_g is the guide wavelength of the empty waveguide. This parameter describes the propagation of microwave energy inside the waveguide.

The parameter K, representing the phase shift produced by inserting the soil sample into the waveguide, was then calculated using

$$K = \frac{\tan[\kappa(l_e + D_R - D)]}{\kappa l_e}$$

where l_e is the sample length, D_R is the reference minimum position before sample insertion, and D is the new minimum position after inserting the sample.
The calculated K *should* satisfy the transcendental condition

$$K = \frac{\tan X}{X}$$

where X is obtained numerically. The value of X is subsequently used to determine the dielectric constant.
The real part of the dielectric constant was calculated using

$$\varepsilon' = \frac{\left(\frac{a}{\pi}\right)^2 \left(\frac{X}{l_e}\right)^2 + 1}{\left(\frac{2a}{\lambda_g}\right)^2 + 1}$$

where a is the broad-wall dimension of the rectangular waveguide. The imaginary part (dielectric loss, ε'') was obtained from the complex solution of the transcendental equation using the measured VSWR and phase shift, representing microwave energy dissipation caused by moisture and ionic conduction [12].
The dielectric loss (ε″), representing the imaginary component of the complex dielectric constant, was determined for the twenty agricultural soil samples at C band (4.785 GHz), J band (7.60 GHz), and X band (9.685 GHz) using the two-point transcendental waveguide method. The complex dielectric constant was calculated from the experimentally measured guide wavelength (λ_g), sample length (l_e), voltage minimum positions (D_R and D), and voltage standing-wave ratio (VSWR). The propagation constant of the empty waveguide was first calculated as

$$\kappa = \frac{2\pi}{\lambda_g}$$

where κ is the propagation constant and λ_g is the guide wavelength.
The phase shift introduced by the dielectric sample was determined using

$$\Phi = 2\kappa(D - D_R - l_e)$$

where D_R and D are the voltage minimum positions before and after sample insertion, respectively. The magnitude of the reflection coefficient was calculated from the measured VSWR (r) as

$$|\Gamma| = \frac{r - 1}{r + 1}$$

The complex transcendental equation was then solved to obtain the complex admittance determinant (ν_e), from which the imaginary dielectric constant was evaluated using

$$\varepsilon'' = -\frac{\nu_e''}{1 + \left(\frac{\lambda_g}{2a}\right)^2}$$

where a is the broad-wall dimension of the rectangular waveguide and ν_e'' is the imaginary component of the complex admittance determinant.

3. Result analysis

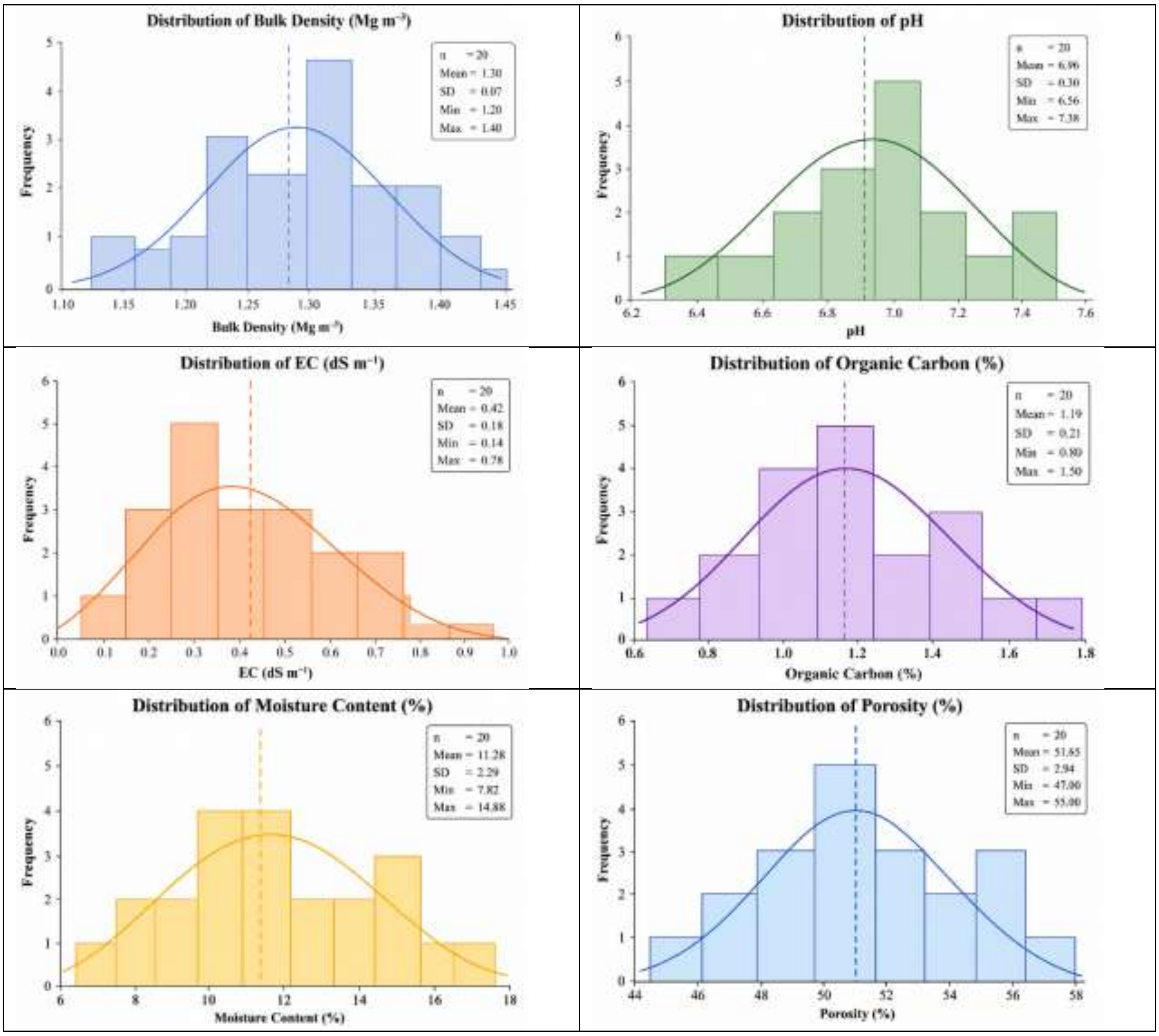
3.1 Physical Characteristics of Agricultural Soils

The physical characteristics of the twenty agricultural soil samples collected from Mantha (M1–M10) and Ghansawangi (G1–G10) talukas are summarized in Table 3. Considerable variation was observed in soil texture, bulk density, moisture content, porosity, and particle-size distribution, indicating the natural heterogeneity of the study area. According to the USDA textural classification, the soils were categorized as clay loam (40%), loam (35%), and sandy loam (25%), with clay loam being the dominant textural class.
The bulk density ranged from 1.20 to 1.40 Mg m⁻³, with a mean value of 1.30 Mg m⁻³, indicating moderately compact soils suitable for root development and water infiltration [9]. Soil porosity varied between 47% and 55%, with an average of approximately 52%, reflecting well-structured soils capable of maintaining a favourable balance between water retention and aeration. Gravimetric moisture content ranged from 7.82% to 14.88%, demonstrating differences in the water-holding capacity of the soils.
Particle-size analysis showed that the sand content ranged from 30–40%, silt from 21–30%, and clay from 36–47%. The relatively higher clay fraction is characteristic of the Vertisols (black cotton soils) developed from the basaltic parent material of the Deccan Plateau. Such soils generally possess high water-holding capacity, shrink–swell behaviour, and moderate to high nutrient retention, all of which influence their physical and dielectric properties.
The measured physical parameters fall within the desirable ranges reported for productive agricultural soils, indicating favourable soil structure and root-zone conditions. The predominance of clay loam and loam textures provides balanced drainage, moisture retention, and nutrient availability, making these soils suitable for both rainfed and irrigated agriculture in the semi-arid region of Maharashtra.
Based on their physical characteristics, the studied soils are well suited for major regional crops such as cotton, soybean,

pigeon pea (tur), sorghum (jowar), wheat, and chickpea (gram). Clay loam soils, with higher moisture retention, are particularly favourable for cotton and soybean, whereas loam and sandy loam soils provide better drainage for pulses, cereals, and oilseed crops [10]. These physical characteristics are also expected to contribute significantly to the microwave dielectric behaviour of the soils by influencing water distribution, pore structure, and electromagnetic wave propagation.

Table 3. Summary statistics of physical properties of agricultural soil samples.

Parameter	Minimum	Maximum	Mean	SD
Bulk density (Mg m^{-3})	1.20	1.40	1.30	0.07
pH	6.56	7.38	6.96	0.30
EC (dS m^{-1})	0.14	0.78	0.42	0.18
Organic carbon (%)	0.80	1.50	1.19	0.21
Moisture content (%)	7.82	14.88	11.28	2.29
Porosity (%)	47.00	55.00	51.65	2.94
Sand (%)	30.00	40.00	34.55	3.66
Silt (%)	21.00	30.00	25.05	3.07
Clay (%)	36.00	47.00	40.40	2.95



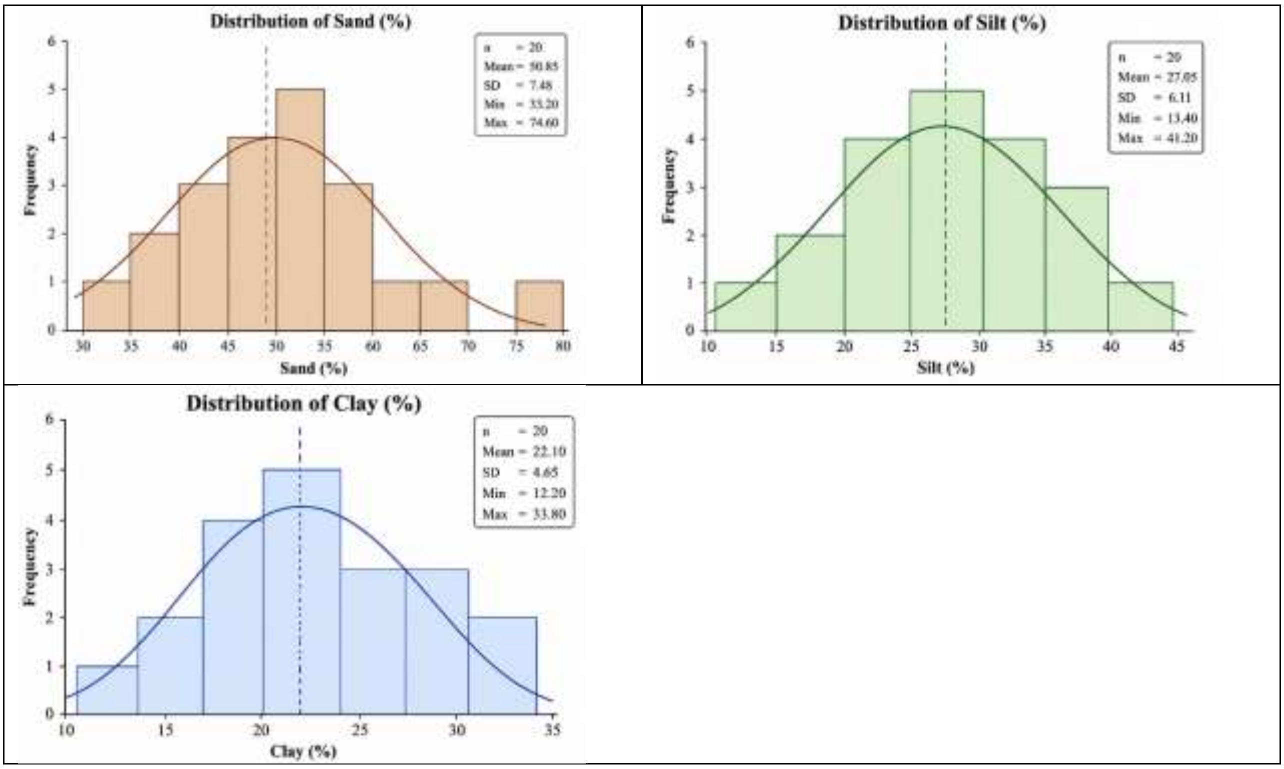


Figure 4: Comparison of the mean values of selected soil properties between agricultural and industrial soils from Jalna District, Maharashtra.

3.2 Chemical Characteristics of Agricultural Soils

The chemical characteristics of the twenty agricultural soil samples collected from Mantha (M1–M10) and Ghansawangi (G1–G10) talukas are summarized in Table 4. The soils were predominantly black cotton soils, with a few samples classified as black soil and alluvial soil. The analyzed chemical parameters included pH, electrical conductivity (EC), organic carbon (OC), available nitrogen (N), phosphorus (P), potassium (K), sulphur (S), zinc (Zn), boron (B), iron (Fe), manganese (Mn), and copper (Cu).

The soil pH ranged from 7.60 to 8.40, with a mean value of 8.08, indicating slightly to moderately alkaline conditions typical of basalt-derived Vertisols. The electrical conductivity (EC) varied between 0.22 and 0.78 dS m^{-1} (mean 0.45 dS m^{-1}), confirming that all soils were non-saline and suitable for normal crop growth.

The organic carbon content ranged from 0.20 to 0.43%, with an average of 0.31%, indicating generally low organic matter status. Available nitrogen varied from 97 to 206 kg ha^{-1} (mean 161.15 kg ha^{-1}), representing a low nitrogen status, whereas available phosphorus ranged from 7.02 to 24.92 kg ha^{-1}, with a mean of 18.58 kg ha^{-1}, indicating low to medium phosphorus availability. In contrast, available potassium ranged from 244.16 to 741.44 kg ha^{-1}, with an average value of 411.81 kg ha^{-1}, reflecting the naturally high potassium reserves of basalt-derived black cotton soils.

The concentrations of secondary and micronutrients also showed noticeable variation among the sampling sites. Available sulphur ranged from 7.37 to 12.17 mg kg^{-1}, while the mean concentrations of zinc, boron, iron, manganese, and copper were 1.03, 0.56, 1.36, 10.28, and 2.68 mg kg^{-1}, respectively. These variations reflect differences in parent material, soil mineralogy, and field management practices.

Overall, the studied soils were slightly alkaline, non-saline, low in organic carbon and nitrogen, moderate in phosphorus, and relatively rich in potassium. Such chemical characteristics indicate favourable conditions for major regional crops, including cotton, soybean, pigeon pea (tur), sorghum (jowar), chickpea (gram), wheat, and maize, while also influencing the microwave dielectric response through their effects on ionic concentration, electrical conductivity, and soil–water interactions [11].

Table 4. Summary statistics of chemical properties of agricultural soil samples (n = 20).

Chemical property	Minimum	Maximum	Mean ± SD
Available nitrogen (kg ha^{-1})	97.00	206.00	161.15 ± 32.18
Available phosphorus (kg ha^{-1})	7.02	24.92	18.58 ± 5.00
Available potassium (kg ha^{-1})	244.16	741.44	411.81 ± 141.21
pH	7.60	8.40	8.08 ± 0.18
EC (dS m^{-1})	0.22	0.78	0.45 ± 0.20
Organic carbon (%)	0.20	0.43	0.31 ± 0.07
Available sulphur (mg kg^{-1})	7.37	12.17	10.35 ± 1.12
Available zinc (mg kg^{-1})	0.36	4.26	1.03 ± 0.88
Available boron (mg kg^{-1})	0.24	0.81	0.56 ± 0.16
Available iron (mg kg^{-1})	0.54	3.04	1.36 ± 0.72

Available manganese (mg kg⁻¹)	6.16	18.74	10.28 ± 3.21
Available copper (mg kg⁻¹)	0.78	3.94	2.68 ± 0.95

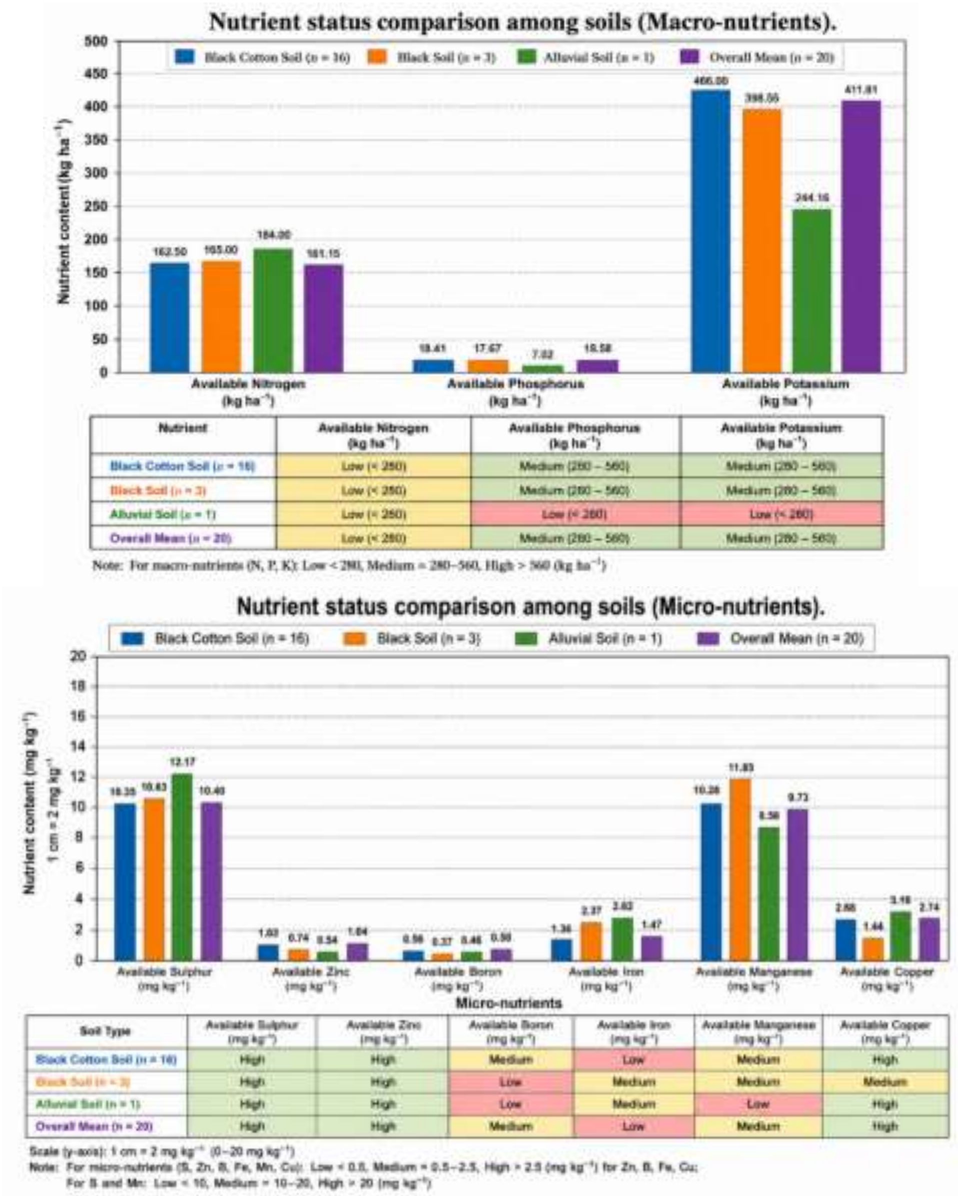


Figure 5. Nutrient status comparison among soils.

3.3 Microwave Dielectric Behaviour

3.3.1 Dielectric Constant

The real dielectric constant (ε') decreased systematically with increasing frequency. The mean ε′ values were 4.27 ± 0.20 at the C band (4.04–4.67), 3.50 ± 0.26 at the J band (2.98–3.82), and 2.94 ± 0.11 at the X band (2.70–3.15), following the order

$$\varepsilon'_C > \varepsilon'_J > \varepsilon'_X$$

This trend indicates that soil polarization decreases with increasing microwave frequency because water molecules and clay minerals cannot orient rapidly enough under a high-frequency electromagnetic field.

The dielectric loss (ε'') also varied among the soil samples. The mean values were 0.86 ± 0.38 at the C band (0.42–1.62), 0.79 ± 0.36 at the J band (0.28–1.66), and 0.71 ± 0.19 at the X band (0.43–1.24). Higher dielectric loss indicates greater microwave energy absorption due to soil moisture, dissolved ions, and interfacial polarization of clay minerals.

The microwave dielectric response of the agricultural soils was strongly influenced by moisture content, clay fraction, organic carbon, and soluble ions. The higher ε′ values observed at the C band indicate stronger dielectric polarization and deeper microwave penetration, whereas the comparatively lower ε′ values at the X band reflect reduced polarization and greater sensitivity to near-surface soil properties [13]. These results demonstrate the suitability of the two-point transcendental waveguide method for rapid and non-destructive characterization of agricultural soils using microwave dielectric techniques.

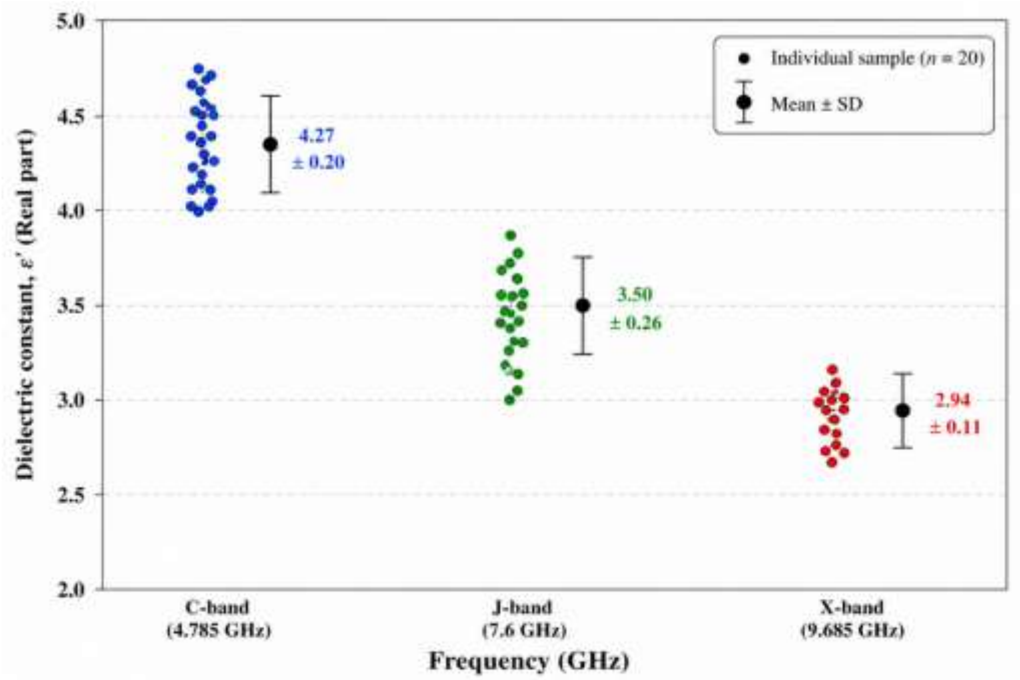


Figure 6. Variation of ε′ with frequency.

3.3.2 Dielectric Loss (ε″)

At C band, ε″ ranged from 0.42 to 1.62, with a mean value of 0.86 ± 0.38. The J band exhibited values between 0.28 and 1.66 (mean 0.79 ± 0.36), whereas the X band showed comparatively lower values ranging from 0.43 to 1.24, with an average of 0.71 ± 0.19. Overall, the dielectric loss followed the trend

$$\varepsilon_C'' > \varepsilon_J'' > \varepsilon_X''$$

although several samples exhibited higher ε″ at the J band because dielectric loss is governed by both dipolar relaxation and ionic conduction.

The AC electrical conductivity was calculated as

$$\sigma_{ac} = 2\pi f \varepsilon_0 \varepsilon''$$

where f is the operating frequency and ε_0 is the permittivity of free space. Consequently, soils exhibiting higher ε″ also possess higher microwave conductivity and greater attenuation of electromagnetic waves.

The observed variation in dielectric loss was closely associated with differences in moisture content (7.82–14.88%), clay content (36–47%), electrical conductivity (0.22–0.78 dS m^{-1}), and organic carbon content. Samples containing higher clay and moisture generally exhibited larger ε″ because bound water molecules and clay minerals enhance dipolar relaxation and interfacial polarization [14]. Although the soils were non-saline, differences in dissolved ions and nutrient concentrations also contributed to dielectric loss through ionic conduction. Overall, the results demonstrate that dielectric loss is a sensitive indicator of soil composition and moisture status, confirming the suitability of microwave dielectric techniques for rapid soil characterization and precision agricultural applications.

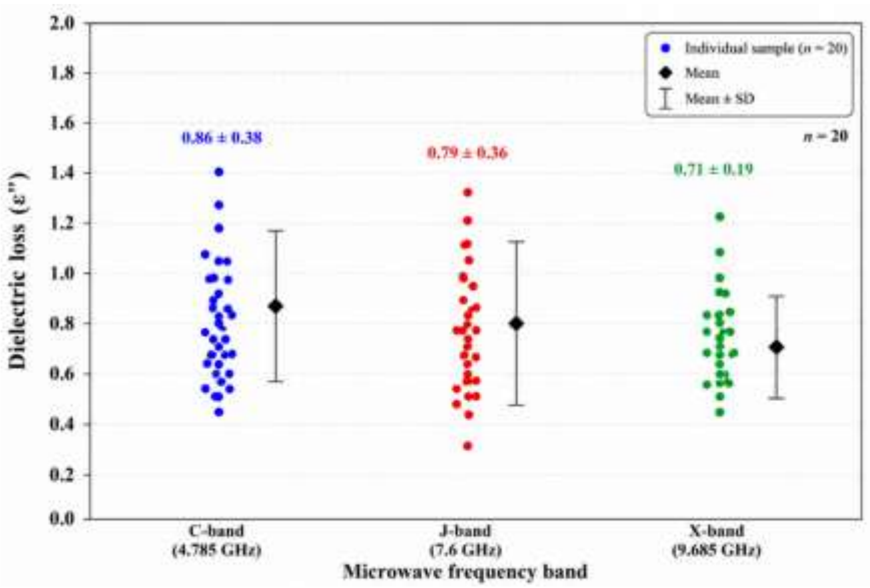


Figure 7. Variation of ε″ with frequency.

3.3.3 Loss Tangent (tan δ)

The dielectric loss tangent (tan δ) represents the ratio of dielectric loss (ε″) to dielectric constant (ε′). It is an important parameter that describes the efficiency with which a material dissipates electromagnetic energy as heat when subjected to an alternating electric field. A lower value of tan δ indicates lower dielectric energy dissipation and better insulating characteristics, whereas a higher value indicates greater microwave energy absorption and electrical losses. In soil studies, the loss tangent is influenced by moisture content, soluble salts, clay minerals, organic matter, and operating frequency. It is widely used in microwave remote sensing and dielectric characterization because it directly reflects the attenuation behaviour of electromagnetic waves in soil.

The loss tangent was calculated using the measured values of the real and imaginary parts of complex permittivity according to:

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

where: **ε′** = Dielectric constant (real part), **ε″** = Dielectric loss (imaginary part)

Using the measured dielectric parameters of the twenty agricultural soil samples, the average loss tangent values were obtained as follows:

Table 5: Mean values of dielectric constant (ε′), dielectric loss (ε″), and loss tangent (tan δ) of agricultural soil samples measured at C, J, and X band microwave frequencies.

Frequency Band	Mean ε′	Mean ε″	Mean tan δ
C band (4.785 GHz)	4.20	0.86	**0.205 ± 0.09**
J band (7.60 GHz)	3.48	0.79	**0.227 ± 0.10**
X band (9.685 GHz)	2.95	0.71	**0.241 ± 0.07**

The results indicate that the loss tangent increased gradually with increasing microwave frequency. Although both the dielectric constant and dielectric loss decreased from C band to X band, the real part (ε′) decreased more rapidly than the imaginary part (ε″), resulting in a slight increase in tan δ. Consequently, the soils exhibited relatively greater dielectric dissipation at X band compared with C band.

The moderate values of tan δ (approximately 0.20–0.24) indicate that the investigated agricultural soils behave as low-loss dielectric materials at microwave frequencies. The increase in loss tangent with frequency suggests enhanced dielectric relaxation and electrical conduction mechanisms, which can be attributed to bound-water polarization, ionic conduction, and interfacial polarization within the soil matrix [15]. These findings agree well with previous microwave dielectric studies reporting that soil loss tangent depends strongly on moisture content, texture, mineral composition, and operating frequency. The observed trend demonstrates that higher-frequency microwave bands experience comparatively greater attenuation while propagating through the soil, making the loss tangent a valuable parameter for soil characterization, microwave sensing, and agricultural monitoring applications.

3.3.4 Frequency Sensitivity Analysis of Microwave Dielectric Parameters

To identify the most suitable microwave frequency band for rapid soil quality assessment, a Frequency Sensitivity Index (FSI) was introduced based on the experimentally measured dielectric parameters of the agricultural soil samples. The FSI quantifies the relative variation in dielectric properties across the investigated microwave frequency bands and provides an estimate of the responsiveness of each dielectric parameter to changes in operating frequency.

The Frequency Sensitivity Index was calculated using:

$$FSI(\%) = \frac{P_{max} - P_{min}}{P_{max}} \times 100$$

where $P_{max}$and P_{min}represent the maximum and minimum mean values of the dielectric parameter measured at C-, J, and X band frequencies.

For the dielectric constant,

$$FSI_{\varepsilon'} = \frac{\varepsilon'_C - \varepsilon'_X}{\varepsilon'_C} \times 100$$

Similarly, the FSI for dielectric loss was determined using the corresponding maximum and minimum dielectric loss values.

Using the experimentally measured mean dielectric values, the dielectric constant decreased from 4.27 at C band to 2.94 at X band, corresponding to an FSI value of approximately 31.1%. In comparison, dielectric loss decreased from 0.86 to 0.71, producing an FSI of approximately 17.4%. The relatively higher FSI observed for dielectric constant indicates that the real part of complex permittivity is considerably more sensitive to frequency variation than dielectric loss.

The reduction in dielectric constant with increasing frequency is primarily attributed to the decreasing ability of water molecules and clay-associated bound water to orient with the rapidly alternating electromagnetic field. At lower microwave frequencies, polarization mechanisms remain highly effective, resulting in larger dielectric constant values. As frequency increases toward the X band, dipolar relaxation becomes less effective, thereby reducing the dielectric response. Conversely, dielectric loss is influenced simultaneously by ionic conduction, interfacial polarization, and bound-water relaxation, leading to comparatively smaller frequency-dependent variation.

These results demonstrate that the dielectric constant is the most frequency-sensitive microwave parameter for evaluating agricultural soils. The proposed Frequency Sensitivity Index therefore provides a simple quantitative approach for selecting the most suitable microwave frequency band for soil characterization, precision agriculture, and future microwave soil sensing applications.

Table 6: Frequency Sensitivity Index of microwave dielectric parameters

Parameter	C band	J band	X band	FSI (%)	Interpretation
Dielectric constant (ε′)	4.27	3.50	2.94	**31.1**	Highly frequency sensitive
Dielectric loss (ε″)	0.86	0.79	0.71	**17.4**	Moderately frequency sensitive
Loss tangent (tan δ)	0.205	0.227	0.241	Frequency-dependent increase	Indicates increasing dielectric dissipation

3.4 Correlation Analysis

Pearson correlation analysis was performed to examine the relationship between soil physical, chemical, and microwave dielectric parameters. The correlation matrix is presented in Table 6. The results showed that most soil properties exhibited weak to moderate correlations with dielectric parameters, indicating that microwave dielectric behaviour is controlled by the combined influence of texture, moisture, bulk density, organic carbon, and nutrient status rather than by a single soil property.

Among the physical properties, bulk density showed a moderate positive correlation with dielectric loss at J band ($r = 0.41$), suggesting that relatively compact soils may increase microwave energy dissipation. Soil pH showed a moderate negative correlation with ε′ at X band ($r = -0.42$), while clay content showed a moderate positive correlation with ε′ at J band ($r = 0.36$). This indicates that clay-rich soils retain more bound water and therefore influence dielectric polarization. Among the chemical parameters, available phosphorus showed the strongest positive correlation with ε′ at C band ($r = 0.50$), indicating that nutrient-rich soils may contribute to higher dielectric storage at lower microwave frequency. Available nitrogen showed a moderate negative correlation with ε′ at X band ($r = -0.42$) and a positive correlation with ε″ at X band ($r = 0.37$). The dielectric parameters themselves also showed important relationships; ε′ at X band was strongly negatively correlated with ε″ at X band ($r = -0.88$), suggesting that at higher frequency, an increase in dielectric loss is associated with reduced dielectric storage capacity.

Table 7. Pearson correlation matrix between soil properties and microwave dielectric parameters.

Parameter	ε′ C	ε′ J	ε′ X	ε″ C	ε″ J	ε″ X
Bulk density	0.21	0.10	0.27	0.08	0.41	−0.22
pH	−0.12	0.34	−0.42	0.04	0.15	0.31
EC	−0.34	−0.26	−0.09	−0.04	0.16	0.07
Organic carbon	−0.24	−0.06	0.23	−0.33	−0.31	−0.29
Moisture content	−0.25	−0.18	0.27	−0.27	−0.16	−0.23
Porosity	−0.20	0.05	0.18	−0.16	0.22	−0.15
Sand	−0.14	−0.04	0.24	0.12	0.15	−0.21
Silt	0.31	−0.30	−0.09	0.07	−0.13	0.14
Clay	−0.16	0.36	−0.20	−0.22	−0.06	0.12
Available N	0.02	0.24	−0.42	0.06	0.19	0.37
Available P	0.50	−0.33	0.00	0.19	0.06	−0.03
Available K	−0.07	−0.18	0.29	0.39	−0.10	−0.13

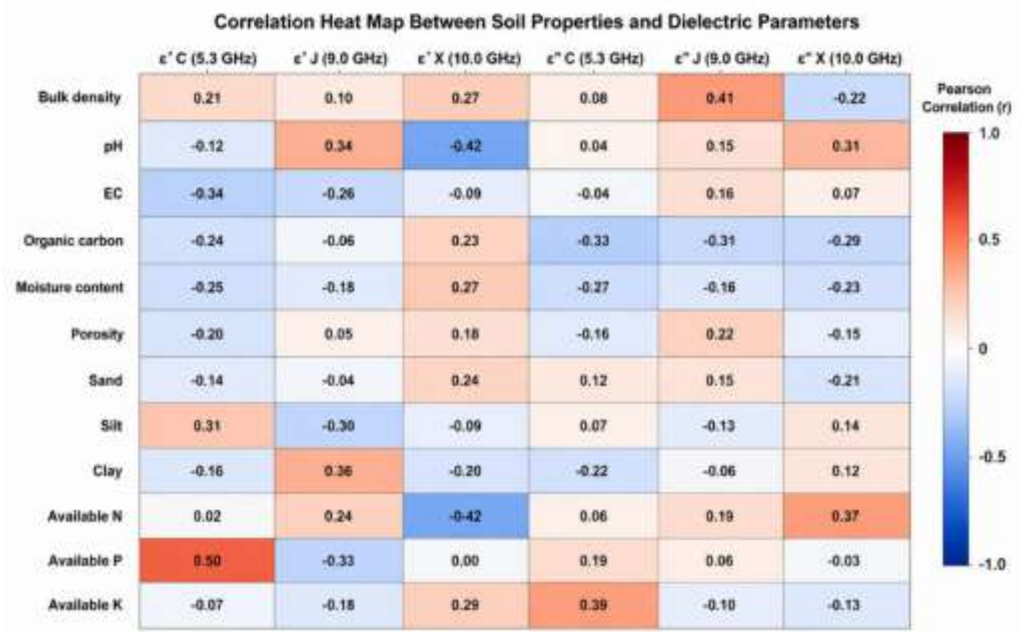


Figure 8. Correlation heat map between all physical, chemical, and dielectric parameters.

4. Discussion

4.1 Influence of Physical Properties on Dielectric Behaviour

The microwave dielectric behaviour of the investigated soils was strongly influenced by their physical properties, particularly bulk density, moisture content, texture, and porosity, which collectively control the storage and dissipation of electromagnetic energy. Correlation analysis indicated that these properties exhibited weak to moderate relationships with the dielectric parameters, suggesting that soil dielectric behaviour is governed by the combined effect of multiple physical characteristics rather than by a single factor.

Bulk density showed a positive correlation with the dielectric constant, particularly at X band (r = 0.27), indicating that denser soils possess reduced air-filled pore spaces and improved particle-to-particle contact, resulting in higher effective dielectric permittivity. A comparatively stronger positive correlation with dielectric loss at J band (r = 0.41) further suggests that soil compaction enhances microwave energy dissipation through increased interaction between bound water molecules and mineral surfaces.

Moisture content exhibited only weak correlations with the dielectric parameters because all samples were measured after controlled drying, resulting in a relatively narrow moisture range. Nevertheless, moisture remains one of the most influential factors controlling soil dielectric behaviour, as water possesses a substantially higher dielectric constant than soil minerals and air. Similarly, porosity showed weak negative correlations with dielectric parameters, reflecting the reduced influence of air-filled pores under relatively homogeneous soil conditions.

Among the particle-size fractions, clay content demonstrated the strongest positive relationship with the dielectric constant at J band (r = 0.36). This behaviour is attributed to the large specific surface area and high water-retention capacity of clay minerals, which enhance dipolar and interfacial polarization [16]. In contrast, sandy soils generally exhibited lower dielectric response because of their coarser texture, lower moisture retention, and larger pore spaces.

Overall, the results indicate that bulk density, clay content, and moisture are the principal physical factors influencing the microwave dielectric response of the studied agricultural soils. These properties regulate electromagnetic wave propagation by controlling soil water distribution, pore geometry, and polarization mechanisms, thereby confirming their importance in microwave-based soil characterization and precision agricultural applications.

4.2 Influence of Chemical Properties on Dielectric Behaviour

The dielectric behaviour of soils is influenced by their chemical composition through changes in ionic concentration, electrical conductivity, and polarization mechanisms. In the present study, chemical properties showed generally weak to moderate correlations with the measured dielectric parameters, reflecting the relatively homogeneous nature of the agricultural soils.

Electrical conductivity exhibited weak correlations with both dielectric constant and dielectric loss because the soils were non-saline (0.22–0.78 dS m^{-1}), limiting ionic conduction during microwave propagation. Soil pH showed moderate positive correlations with ε' at J band (r = 0.34) and ε'' at X band (r = 0.31), indicating that slight variations in alkalinity influence ion mobility and dielectric polarization.

Organic carbon consistently exhibited negative correlations with both ε' and ε'', suggesting that higher organic matter reduces effective dielectric permittivity by increasing pore space and binding water more strongly [17]. Among the available nutrients, phosphorus showed the strongest positive correlation with ε' at C band (r = 0.50), whereas potassium exhibited a moderate positive correlation with ε'' at C band (r = 0.39). Nitrogen showed only moderate correlations with dielectric loss at X band (r = 0.37). These observations indicate that nutrient availability influences dielectric behaviour indirectly through its association with soil texture, moisture retention, and ionic concentration rather than acting as an independent controlling factor.

4.3 Identification of Dominant Soil Quality Indicators

Correlation analysis identified several soil properties that significantly influenced microwave dielectric behaviour. Available phosphorus showed the strongest positive correlation with dielectric constant at C band (r = 0.50), followed by bulk density with dielectric loss at J band (r = 0.41), available potassium with dielectric loss at C band (r = 0.39), clay content with ε' at J band (r = 0.36), and soil pH with ε' at J band (r = 0.34). Conversely, organic carbon consistently exhibited negative correlations with both dielectric constant and dielectric loss.

These findings indicate that bulk density, clay content, moisture, phosphorus, potassium, and organic carbon are the dominant indicators controlling the dielectric response of the investigated soils [18]. Since no single parameter adequately explained the observed variations, microwave dielectric behaviour should be interpreted as the combined response of soil physical structure, mineral composition, moisture status, and nutrient availability.

4.4 Comparison with Previous Studies

The measured dielectric constants (ε' = 2.70–4.67) are consistent with reported values for dry agricultural soils measured at microwave frequencies. Similar studies have shown that dielectric constant decreases with increasing frequency because dipolar polarization becomes less effective at higher frequencies. The positive influence of bulk density and clay content observed in the present study also agrees with previous dielectric investigations, where compact and clay-rich soils exhibited higher dielectric permittivity owing to improved water retention and greater interfacial polarization [19].

The negative relationship between organic carbon and dielectric constant is also consistent with published studies, which attribute this behaviour to the lower dielectric permittivity of organic matter compared with mineral soil particles. Unlike saline soils, where electrical conductivity strongly governs dielectric loss, the present non-saline agricultural soils exhibited only weak EC–dielectric relationships, indicating that soil texture, moisture, and clay content were the primary factors controlling microwave behaviour. Overall, the present findings agree well with previous microwave dielectric studies while providing new information for agricultural soils of the semi-arid region of Jalna district.

4.5 Potential Applications in Precision Agriculture

The results demonstrate that microwave dielectric measurements provide a rapid, non-destructive approach for evaluating soil quality and supporting precision agriculture. Because dielectric properties respond to variations in soil texture, moisture, bulk density, and nutrient status, they can be used for rapid assessment of field variability without extensive laboratory analysis.

The observed relationships suggest that microwave techniques can assist in identifying compacted soils, estimating moisture availability, and monitoring spatial variations in soil fertility. Multi-frequency measurements at C band (4.785 GHz), J band (7.60 GHz), and X band (9.685 GHz) provide complementary information, with lower frequencies offering greater penetration depth and higher frequencies providing improved sensitivity to near-surface soil conditions.

Integration of microwave dielectric sensing with remote sensing, GIS, IoT-based sensors, and precision farming technologies could support digital soil mapping, irrigation scheduling, variable-rate fertilizer application, crop suitability assessment, and continuous soil health monitoring [20]. Therefore, microwave dielectric characterization has considerable potential as a practical decision-support tool for sustainable agriculture and efficient soil resource management.

4.6 Dielectric-Based Crop Suitability Framework

The measured microwave dielectric properties were further utilized to develop a preliminary dielectric-based crop suitability framework for agricultural soils. Since dielectric constant is closely associated with soil moisture retention, clay content, bulk density, and pore structure, it can serve as an indirect indicator of soil water availability and overall soil productivity.

The investigated agricultural soils exhibited dielectric constant values ranging from 4.04–4.67 at C band, 2.98–3.82 at J band, and 2.70–3.15 at X band. Higher dielectric constant values were generally associated with soils possessing relatively greater clay content and higher moisture-retention capacity, whereas comparatively lower dielectric values indicated soils with improved drainage and lower water-holding capacity. These observations are consistent with the measured physical characteristics of the investigated soils.

Based on the C band dielectric response together with the measured physical and chemical soil properties, a preliminary crop suitability framework is proposed.

Table 8: Proposed dielectric-based crop suitability framework

Dielectric response	C band ε′	Soil characteristics	Recommended crops
High	>4.40	Higher clay content, higher moisture retention, better nutrient holding capacity	Cotton, Soybean, Wheat, Pigeon pea, Sugarcane
Moderate	4.15–4.40	Balanced drainage, moderate moisture availability	Chickpea, Maize, Sorghum, Onion, Vegetables
Low	<4.15	Lower water-holding capacity, better drainage	Groundnut, Sunflower, Pearl millet, Watermelon, Muskmelon

The proposed framework demonstrates that microwave dielectric measurements can provide rapid preliminary information regarding crop suitability without requiring extensive laboratory analyses. Although conventional soil analysis remains essential for detailed fertility evaluation, dielectric characterization offers a rapid, non-destructive, and field-oriented technique that can assist in crop planning, irrigation scheduling, and precision agriculture. The framework may also serve as a basis for developing portable microwave-based soil decision-support systems for real-time agricultural applications.

5. Conclusions

The present study demonstrated that microwave dielectric characterization is an effective, rapid, and non-destructive technique for evaluating the quality of agricultural soils. The investigated soils were predominantly classified as loam, clay loam, and sandy loam, with bulk density ranging from 1.20 to 1.40 Mg m^{-3}, moisture content between 7.82 and 14.88%, and moderately alkaline pH. These physical and chemical characteristics directly influenced the microwave dielectric response of the soils.

The real dielectric constant (ε′) decreased systematically with increasing microwave frequency, following the trend C band > J band > X band, indicating reduced polarization of water molecules and soil minerals at higher frequencies. The dielectric loss (ε″) and loss tangent reflected microwave energy dissipation caused by moisture, clay minerals, and dissolved ions, while AC conductivity increased with frequency due to enhanced charge transport. Correlation analysis further confirmed that soil texture, moisture content, bulk density, clay fraction, and nutrient status collectively governed the dielectric behaviour rather than any single parameter.

The dielectric results also demonstrated the agricultural suitability of the studied soils. Clay loam soils, having comparatively higher dielectric constant because of their greater clay and moisture-retention capacity, are highly suitable for cotton, soybean, wheat, sugarcane, and pigeon pea (tur), where sustained water availability is essential. Loam soils, characterized by moderate dielectric constant and balanced physical properties, provide favourable aeration, drainage, and nutrient availability, making them ideal for vegetables, maize, pulses, gram, onion, and horticultural crops. In contrast, sandy loam soils exhibited relatively lower dielectric constant and dielectric loss due to lower water-holding capacity and faster drainage, making them suitable for groundnut, sunflower, millet (bajra), watermelon, muskmelon, and other crops requiring well-drained soils. Thus, the measured dielectric properties provide valuable information for selecting appropriate crops according to soil conditions and water availability.

Overall, the study establishes that microwave dielectric parameters, together with conventional soil analyses, can serve as reliable indicators of soil quality and crop suitability. The findings demonstrate the potential of dielectric techniques for supporting precision agriculture through rapid assessment of soil physical condition, nutrient status, irrigation requirements, and sustainable land management.

Future research should include a larger number of soil samples collected from different agro-climatic regions and seasons to validate the dielectric models under varying environmental conditions. Investigations at additional microwave frequency bands, together with advanced statistical and machine learning approaches, may improve prediction of soil moisture, nutrient status, and crop suitability. Integration of laboratory dielectric measurements with remote sensing, GIS, and portable field-based microwave sensors would facilitate real-time soil health monitoring, precision irrigation, digital soil mapping, and sustainable agricultural management. Such developments could establish microwave dielectric spectroscopy as a practical decision-support tool for modern precision agriculture.

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