



RESEARCH ARTICLE

Investigation of dielectric response of soil with varying physicochemical properties

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Received: 11 July 2025; Accepted: 07 January 2026; Available online: Version 1.0: 08 April 2026

Cite this article: Mahesh SD, Sushant BD, Ashish BI, Shailendra BK. Investigation of dielectric response of soil with varying physicochemical properties. *Plant Science Today*. 2026; 13(sp1): 1-13. <https://doi.org/10.14719/pst.10596>

Abstract

Soil dielectric properties are essential for understanding electric response, which is an indicator for soil sensing. The relationship between soil dielectrics and the physicochemical property of soil is a useful link for remote sensing, widely used for agriculture applications. This investigation examines how soil dielectric response varies with fundamental physicochemical properties namely acidity/alkalinity levels (pH), electrical conductivity (EC), organic carbon (OC) content and particle size distribution (texture). The measurements are carried out for the complex dielectric constant of different coloured soils, viz. black, dark red, very pale green, pale green and reddish brown collected from location India (20.5292° N, 76.1842° E). The validation and investigation of dielectric response for different physicochemical changes in the soil is a significant information for active and passive remote sensing. The measurements were performed for the complex dielectric constant of distinct soil samples representing different physicochemical profiles, collected using standardized protocol. The short waveguide method is used to perform these measurements using a precision automated waveguide-based measurement system, at X-, J-, C- microwave frequency bands. The results demonstrate variation of dielectric properties for different frequency bands as a function of colour, pH, EC, OC and texture of the soil. These trends provide unique frequency dependent signatures that are useful to build interrelationship between electromagnetic behaviour and characteristics of soil. This will help to enhance the capability of satellite-based soil monitoring and to establish models in this concern.

Keywords: electric conductivity; microwave; remote sensing; soil dielectric properties; texture

Introduction

Soil forms the foundation of agricultural systems, yet intensive farming practices must lead to widespread soil degradation. Excessive use of chemical fertilisers disrupted natural nutrient cycles while creating imbalance in soil chemistry. Inefficient irrigation methods have led to threaten both ecosystem health and agricultural productivity (1). Addressing challenges demand better understanding of how fundamental soil properties interact fertility and function (2). This complex challenge requires a deeper understanding of soil nutrient dynamics and their relationship with physicochemical properties that govern soil health (3).

The systematic study of soil gives an overview to understand soil health to accelerate land-use planning in interest. In this context, soil pH, electrical conductivity (EC) and organic carbon (OC) play an important role in helping plant growth (4). The pH of soil is used as an indicator of the acidity or alkalinity availability in soil, which controls the mobility and presence of nutrients (5). The pH also affects many soil processes like breaking down organic matter, the activity of microbes and how bacteria work (6). When soil is too acidic, nutrients like nitrogen, phosphorus and potassium give the lesser quantity. If soil is too alkaline then nutrients like iron, manganese and phosphorus are difficult for plant to absorb (7).

Soil EC serves as a fundamental for assessing soil health, with well-established salinity and nutrient availability (8). It gives rapid, cost-effective measures for assessing soil properties; however, it is limited by its sensitivity to multiple interacting factors, including soil moisture, clay content, organic matter, soluble salt and nutrients such as nitrogen (N) and potassium (K) which directly affect the EC extracted soil solution (9). But the moisture has a significant effect on soil EC. When the water content in soil increases, then soil EC increases because of the increased solubility of ions in soil (10). Organic matter can affect EC due to the presence of nutrients and salt; however, it was not fully understood. To ensure accurate EC measurement, the deployment of soil EC sensors must incorporate variations in soil texture and organic matter as key influencing factors (11).

Microwave technology gives powerful solutions for both soil measurements and large-scale remote sensing applications due to its ability to interact with soil dielectric properties (12). Laboratory and field microwave techniques, including time domain reflectometry and waveguide spectroscopy, enable precise measurement of soil dielectric constant (ϵ') and loss factor (ϵ''), which is directly linked to critical soil parameters such as moisture content, texture and organic matter, etc. (13). To effectively use

microwave energy for soil, it must absorb microwave frequency and convert it into heat. This is called as complex permittivity. The ability to store energy is called dielectric constant (ϵ') and energy conversion to heat is called as dielectric loss (ϵ'') (14)

The dielectric principles underlie microwave remote sensing systems like synthetic aperture radar (SAR) on satellites, which measure surface soil moisture at the regional to global scale. Recent advances combine multi-frequency (L/C/X-band) and multi-polarisation data with dielectric mixing models to simultaneously estimate soil moisture, surface roughness and texture (15).

Dielectric parameters are influenced by soil texture, which is the size and distribution of soil particles. Finer soil, which has a high clay content, generally exhibits a higher dielectric constant, whereas sandy soils tend to have a lower dielectric constant. Quantitative research shows that soil with a texture chart distribution dominated by fine particles has a dielectric constant ranging from 3–7, while coarser soil, such as sandy loams, demonstrates as low as 2–4 at low moisture levels (16). Recent advances in soil dielectric constant have shown the necessity of both texture and mineral composition to achieve accurate characterisation. The recent literature for dielectric investigation is limited at a restricted frequency band and with varying very few properties of soil (17).

This study aims to fill this gap by systematically examining the dielectric properties of different soil samples with different soil parameters. Our research focused on setting an interpretation of how the dielectric properties correlate with soil parameters such as pH, EC and OC and how external factors affect this correlation. By integrating these factors, future research can offer more accurate predictions of soil behaviour under varying environmental conditions, improving both theoretical models and practical applications.

Materials and Methods

Sample collection and preparation

Soil sample collection defines a systematic approach to ensure that it covers all experimental areas. Soil samples were collected from agricultural fields representing diverse global textures such as loamy sand, sandy loam, clay loam as per United States Department of Agricultural (USDA) classification. It followed a randomized zig-zag sampling method across the field, with 4–5 sampling site. Approximately 0.5 kg of soil sample was taken from the 0–20 cm depth using steel auger. To obtain a representative sample, sub-samples were intermixed using the quartering method, where collected sample was repeatedly mixed and

divided. The collected soil samples were dried at room temperature 25–30 °C to prevent thermal degradation of organic matter. Aggregates were gently broken down using an agate mortar and pestle to avoid contamination. The soil was then passed through of a series of stainless-steel sieves: first through a 300 μm sieve to isolate the sand fraction, then through a 150 μm sieve for the silt fraction and finally through a 75 μm sieve for the clay fraction. Each fraction was combined in predetermined ratios based on the USDA particle size classification to create a representative sample.

Laboratory analysis for pH, electrical conductivity and organic carbon of the soil sample

The prepared soil samples were examined for chemical parameters of soil pH, EC and OC. pH was determined using a potentiometric pH meter (Harvest digital soil testing kit, W. S. Telematics Private Limited) as shown in Fig. 1 (18). The value of pH greater than 7 then it is alkaline in nature or pH value is less than 6 then it is acidic in nature, in-between this soil is normal. All samples show pH values from 7.75–9.95 which is natural or alkaline in nature shows in Table 1. Electrical conductivity was measured by using digital conductivity meter (Harvest digital soil testing kit, W. S. Telematics Private Limited) as shown in Fig. 1; during this process exchange of cation of soil and salt solution is known as cation exchange. The conductivity values can be varied with chemical properties (19). The value less than 0.4 dSm^{-1} shows normal soil type, above that it shows slightly saline which is given in Table 1. Organic Carbon was determined by wet oxidation method (Harvest digital soil testing kit, W. S. Telematics Private Limited) as shown in Fig. 2 giving values in the



Fig. 1. Laboratory setup for calculating the values of pH and electrical conductivity.

Table 1. Soil samples for different texture with percentage of sand, silt and clay

| Soil color | Soil type | Sand % | Silt % | Clay % |
|-----------------|------------|--------|--------|--------|
| Black | Loamy sand | 70 | 20 | 10 |
| | Sandy loam | 50 | 30 | 20 |
| | Clay loam | 30 | 40 | 30 |
| Dark red | Loamy sand | 70 | 20 | 10 |
| | Sandy loam | 50 | 30 | 20 |
| | Clay loam | 30 | 40 | 30 |
| Very pale green | Loamy sand | 70 | 20 | 10 |
| | Sandy loam | 50 | 30 | 20 |
| | Clay loam | 30 | 40 | 30 |
| Pale green | Loamy sand | 70 | 20 | 10 |
| | Sandy loam | 50 | 30 | 20 |
| | Clay loam | 30 | 40 | 30 |
| Reddish brown | Loamy sand | 70 | 20 | 10 |
| | Sandy loam | 50 | 30 | 20 |
| | Clay loam | 30 | 40 | 30 |

Table 2. Observed values of pH, EC and OC by the harvest soil testing kit

| Sample | Color | Latitude | Longitude | pH | EC | OC |
|--------|-----------------|-------------|-------------|------|-------|--------|
| 1 | Black | 21°02'54.5" | 76°30'18.4" | 9.1 | 0.535 | 0.0766 |
| 2 | Dark red | 20°43'38.0" | 76°35'12.4" | 8.48 | 0.59 | 0.0865 |
| 3 | Very pale green | 20°39'26.4" | 76°29'57.5" | 9.15 | 0.494 | 0.1008 |
| 4 | Pale green | 20°39'10.9" | 76°28'43.8" | 9.17 | 0.514 | 0.1053 |
| 5 | Reddish brown | 20°34'25.0" | 76°11'12.2" | 7.71 | 0.599 | 0.0937 |

**Fig. 2.** Harvest soil testing kit setup for electrical conductivity.

range 0.05–0.107 that defines low proportion of OC as shown in Table 2 (20).

Experimental methodology for dielectric measurement of soil

Several methods are available for the dielectric measurement of soil. The selection of the waveguide method with an automated band microwave bench was based on a dual rationale of technical merit and economical (Table 3). The setup is significantly more cost-effective than high-end alternatives like Vector Network Analysers' (VNA). It also presents a lower total cost of ownership compared to probe technology and Time-Domain Reflectometry (TDR) in a dedicated laboratory setting, making it a scalable and commercially attractive option.

The measurement of dielectric properties impacts on monitoring the specific parameters of materials undergoing physical and chemical changes. The complex permittivity of soil samples was characterised using a two-point method chosen for its established reliability in determining both the relative dielectric constant (ϵ') and loss factor (ϵ'') of heterogeneous materials.

Measurements were conducted across X-band, J-band and C-band frequencies using a computer-controlled microwave bench system. The microwave bench setup is made with a Reflex klystron source (Vidyut Yantra Udyog, India beam voltage 250 V, current 17 mA, Repeller 77 V), isolator, using automated waveguide slotted section, all are interconnected to PC-based system as shown in Fig. 3. A custom designed in an automated slotted line measurement system in which a tunable detector probe is precisely positioned by step motor, recorded power at programmed intervals along with waveguide. To convert radio frequency (RF) signals into proportional dc voltages by the high sensitivity detector circuit which was digitised in real-time through a 16-bit analog-to-digital converter (ADC) interface as shown in Fig. 3. This helps to synchronised probe positioning with data acquisition, getting both position coordinates and corresponding power values direct into the spreadsheet. The microwave bench setup utilised a Reflex klystron as the microwave source which was optimised at a beam voltage at 250 V, beam current 17 mA and Repeller voltage is 77 V to generate stable microwave signal. Each soil sample was placed in sample holder with consistent thickness of soil 1, 2 and 3 cm and ensure proper alignment to avoid air gaps that could affect measurement. The empty sample holder was also measured to account for its insertion loss. For each soil sample inserted into sample holder, the detector probe moves by using step motor along with slotted line, stopping at precise intervals to record power level at each probe position. This forms a standing wave pattern which gives the position of minima and maxima and the distance between two minima is used to calculate the guided wavelength (λ_g).

$$\beta = 2\pi / \lambda_g$$

β = phase factor

The free space wavelength is determined using the relation

$$1/\lambda_0^2 = 1/\lambda_g^2 + 1/\lambda_c^2$$

Where $\lambda_c = 2a$ and 'a' is the inner broader side rectangular

Table 3. The experimental results of waveguide microwave bench at different bands

| Soil colour | Soil type | X band | | J band | | C band | |
|-----------------|------------|-------------|--------------|-------------|--------------|-------------|--------------|
| | | ϵ' | ϵ'' | ϵ' | ϵ'' | ϵ' | ϵ'' |
| Black | Loamy sand | 2.7 | 0.5 | 3.5 | 1.01 | 3.9 | 1.6 |
| | Sandy loam | 3.3 | 0.7 | 3.8 | 1.2 | 4.2 | 1.8 |
| | Clay loam | 3.8 | 0.9 | 4.1 | 1.3 | 4.5 | 2.1 |
| Dark red | Loamy sand | 2.6 | 0.5 | 3.4 | 0.4 | 4.5 | 1.5 |
| | Sandy loam | 3.1 | 0.8 | 3.7 | 0.6 | 4.9 | 2.1 |
| | Clay loam | 3.5 | 1.1 | 4.1 | 1.3 | 5.1 | 2.4 |
| Very pale green | Loamy sand | 2.5 | 0.4 | 3.2 | 0.8 | 3.8 | 1.3 |
| | Sandy loam | 2.3 | 0.8 | 3.9 | 1.1 | 4.5 | 1.6 |
| | Clay loam | 2.6 | 0.9 | 4.1 | 1.3 | 4.3 | 1.9 |
| Pale green | Loamy sand | 2.5 | 0.3 | 3.5 | 1.4 | 4.2 | 1.5 |
| | Sandy loam | 2.4 | 0.7 | 3.8 | 1.6 | 4.4 | 1.7 |
| | Clay loam | 2.3 | 0.9 | 4.1 | 1.9 | 4.7 | 1.9 |
| Reddish brown | Loamy sand | 2.8 | 0.6 | 3.2 | 1.2 | 4.1 | 1.4 |
| | Sandy loam | 3.05 | 0.9 | 3.4 | 1.4 | 4.3 | 1.6 |
| | Clay loam | 3.2 | 1.1 | 3.9 | 1.8 | 4.9 | 1.9 |

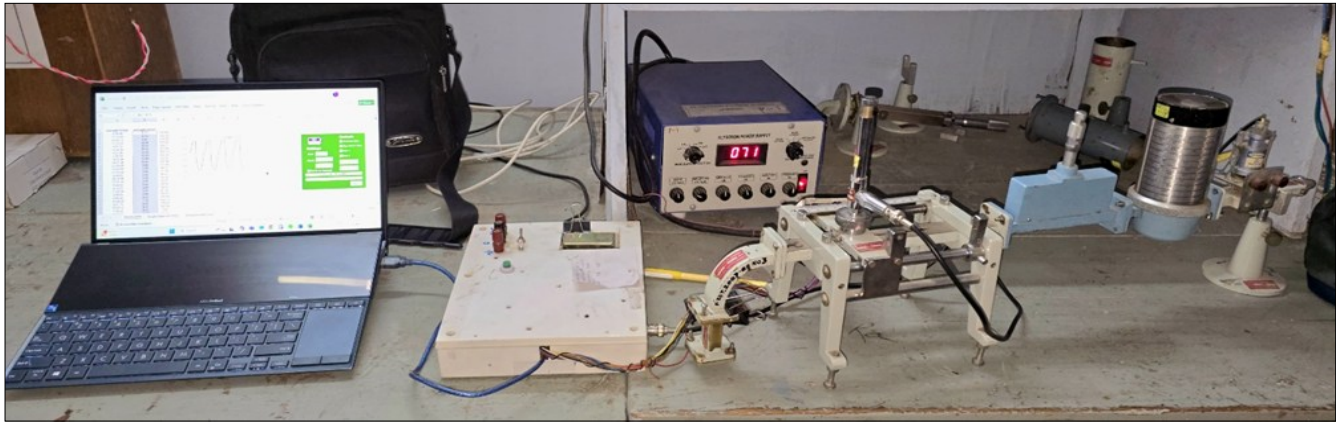


Fig. 3. Automated microwave X band bench experimental setup.

waveguide.

The real and imaginary parts of the complex dielectric constant are calculated using relation

$$\epsilon' = \lambda_0^2 \{1/\lambda_c^2 + (\alpha^2 - \beta^2) / 4\pi^2\}$$

$$\epsilon'' = \lambda_0^2 \alpha \beta / 2\pi^2$$

ϵ' : real part

ϵ'' : imaginary part

α : attenuation factor

A program was developed for processing an input file to compute the dielectric properties of soil sample by combining data obtained from different thicknesses of sample. The program converted experimental results for 1, 2 and 3 cm into a single structured input file. Then this inputs file merging algorithm that combined data from different thickness pairs such as 1–2, 2–3 and 1–3 cm. It is important for the verification of measurement consistency across thickness and to generate a unified data structure. The final output of this file computed gives dielectric constant and dielectric loss of the soil sample.

Results and Discussion

The experimental data provides a structure to outline the 5 soil samples investigating their dielectric properties and fundamentals of soil parameters. The outputs show a significant bond between soil composition, colour and electromagnetic response. The dielectric study shows well-defined frequency-dependent behaviour.

Frequency-dependent dielectric response of different coloured soils

This study presents a comprehensive analysis of the dielectric properties for soils across different soil colours (black, dark red, very pale green, pale green, reddish brown) classifications measured at three distinct frequency bands (X band, J band, C band). In the X band, reddish brown soil exhibits the highest dielectric constant–2.8, while very pale green shows the lowest–2.49 and for dielectric loss, black soil shows the highest loss–0.54, while pale green demonstrates the lowest–0.41. This pattern undergoes a notable transition in the J band where pale green and very pale green soils display the highest dielectric constant values 3.71 and 3.70 while dielectric loss ordering reverses. The C band measurement shows the most pronounced dielectric response with dark red soil having the highest value of 4.33, indicating that lower frequency may be

more sensitive to specific soil components such as clay or iron oxide. For dielectric loss, the C band shows the greatest magnitude with black soil 1.67, potentially indicating a significant dipole relaxation process at these frequencies as shown in Fig. 4 and 5. The X band appears particularly suitable for organic-rich soils, while the C band shows enhanced sensitivity to mineral composition and moisture content. The shifted dielectric behavior in J band suggests this frequency range may be optimal for indicating specific soil properties.

Variation of dielectric properties as a function of electrical conductivity, pH, organic carbon and soil textures

The soils studied exhibit pH values ranging from moderately alkaline (7.71 for reddish brown) to strongly alkaline (up to 9.17 for pale green). This pH range influences dielectric responses due to its effects on chemistry and moisture of soil. The lowest dielectric constant values, ranging from 2.48–2.82, which suggests relatively lower energy storage within the soil matrix at these higher frequencies as shown in Fig. 6. Loss values increase from X-band (0.32–0.61), J-band (0.81–1.16), to C-band (1.38–1.67), showing stronger microwave energy absorption at lower frequencies as shown in Fig. 7.

The results show connection between soil EC and dielectric properties across different frequency bands for various soil type. Soil with higher EC values such as dark red 0.599 dS m⁻¹, exhibit evaluated dielectric constant in the C band (4.33) along with significant dielectric loss across all frequency bands. In contrast, lower EC soils like very pale green display show reduced dielectric constant 3.98 and loss factor 0.475 maintaining a more stable frequency response as shown in Fig. 8 and 9. Similar results were reported in previous studies which showed that the EC of Sawai Madhopir soils range between 0.33–0.90 dS m⁻¹ (21). The result indicated that all the soils are normal in nature, similar to results reported by previous researchers (22). The results support enhanced dielectric models for ground penetrating radar and better moisture-content correlation in SAR data.

This investigation examines X band, J band and C band measurements for soils with OC content ranging from 0.0766–0.1053 %, revealing frequency-dependent patterns in electromagnetic response to organic matter. Higher OC soils such as pale green 0.1053 % exhibit reduced dielectric constant in the X band at 2.49 compared to low soils like black at 2.77 which shows organic matter content, bulk soil properties and polarisation mechanisms. In the J band, a positive correlation emerges between OC content and dielectric constant 3.71 for high OC soils, indicating specific polarisation effects associated with organic functional

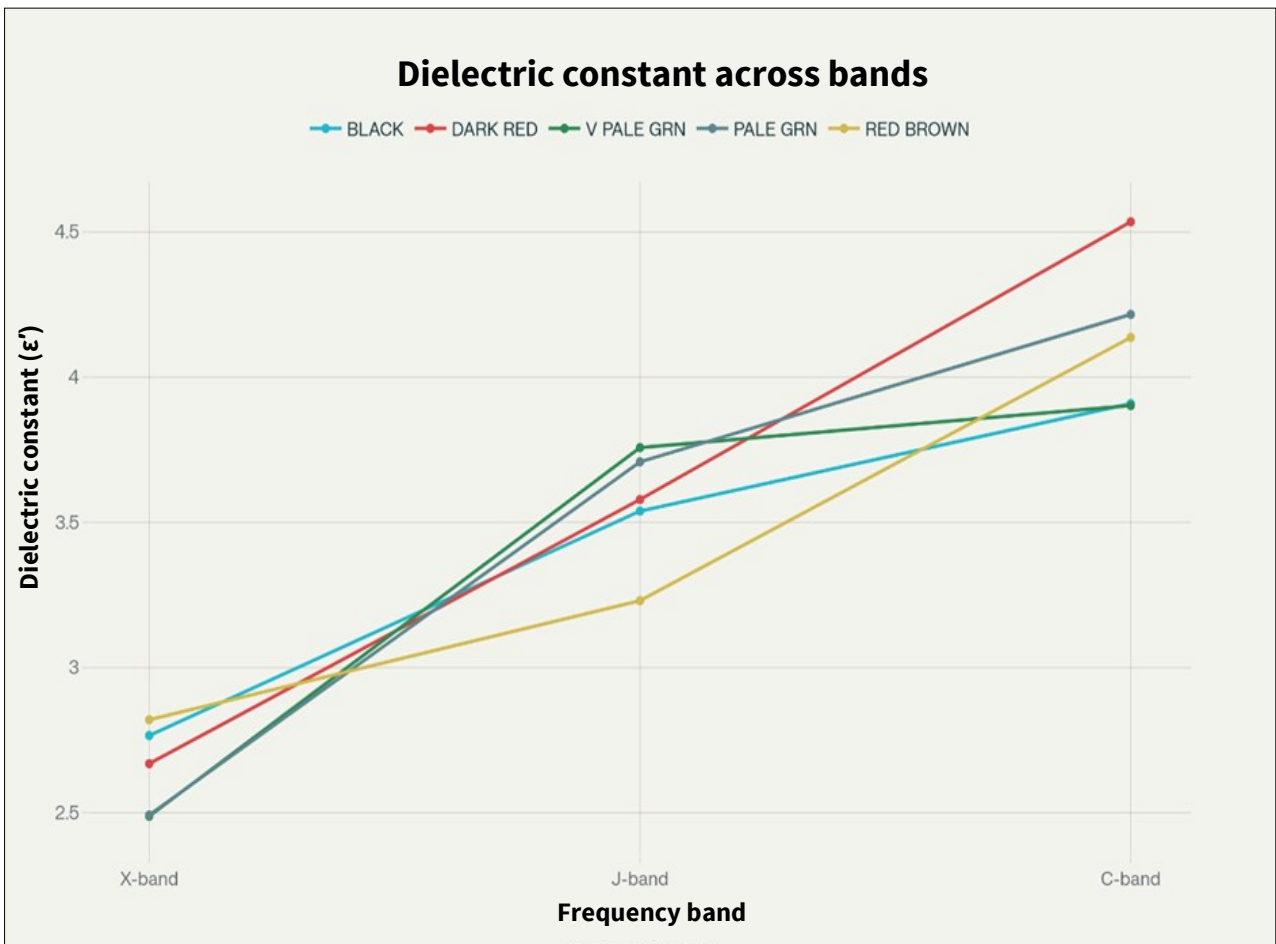


Fig. 4. Comparison of dielectric constant across frequency bands for different soil types.

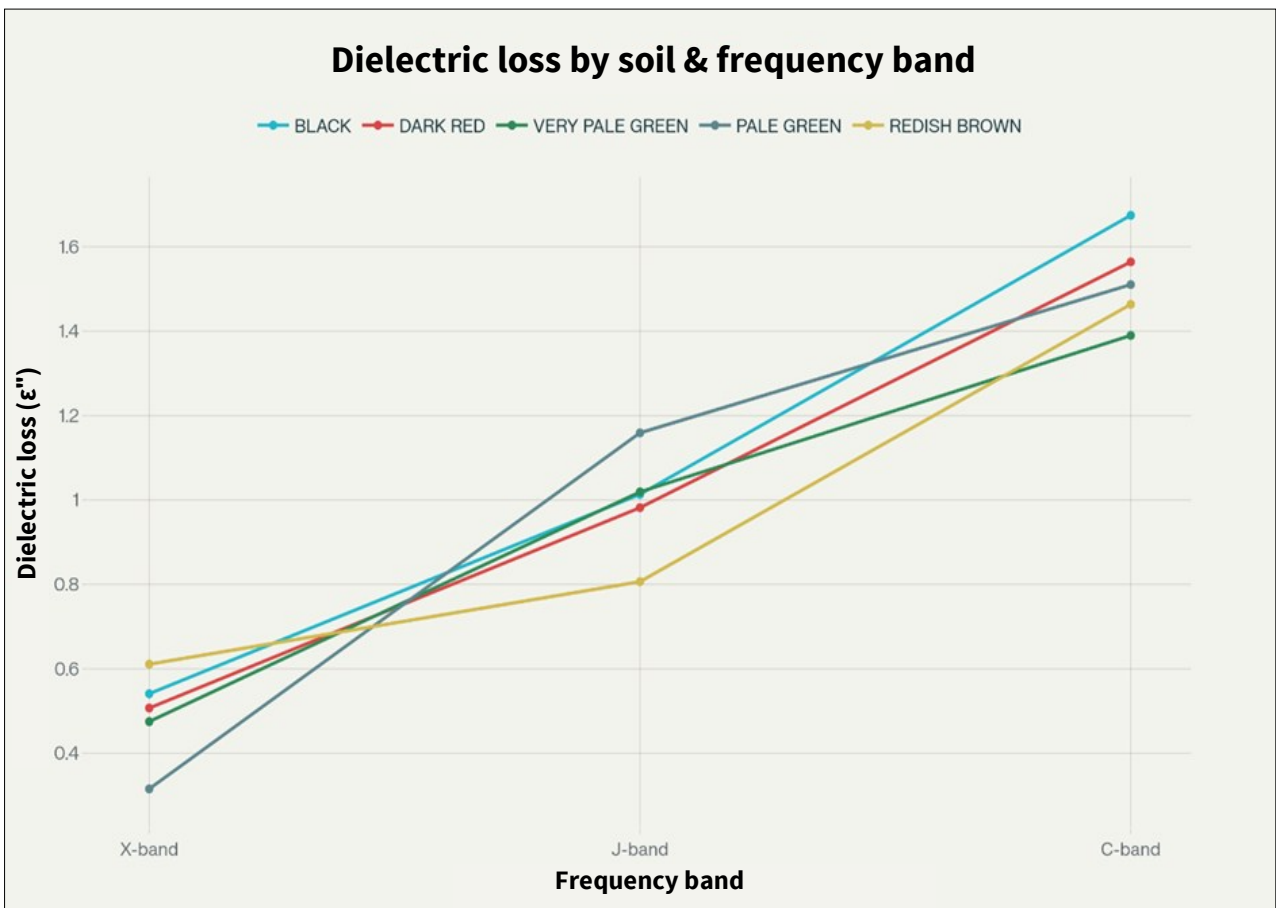


Fig. 5. Comparison of dielectric loss across frequency bands for different soil types.

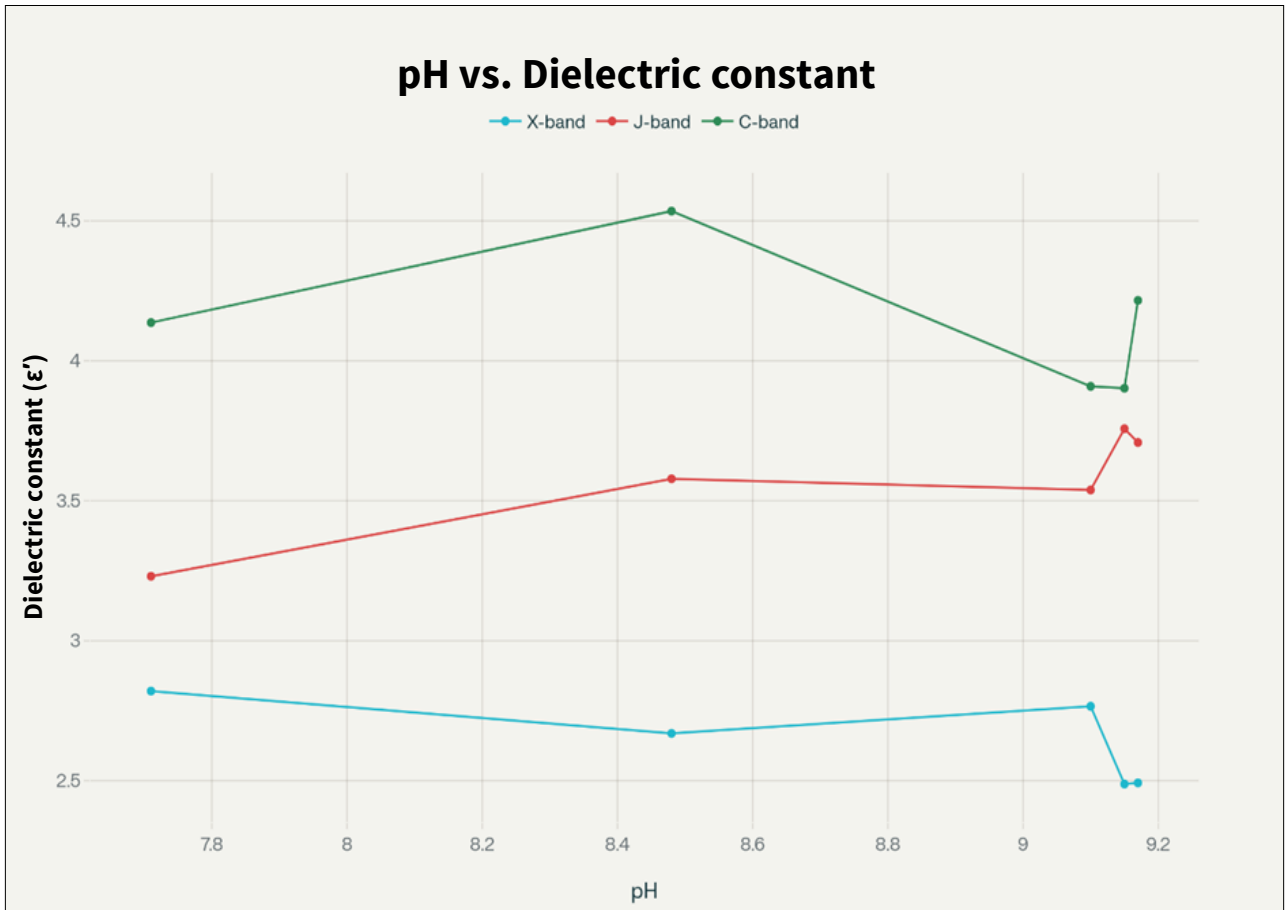


Fig. 6. Trend of dielectric constant vs pH across X, J and C frequency bands.

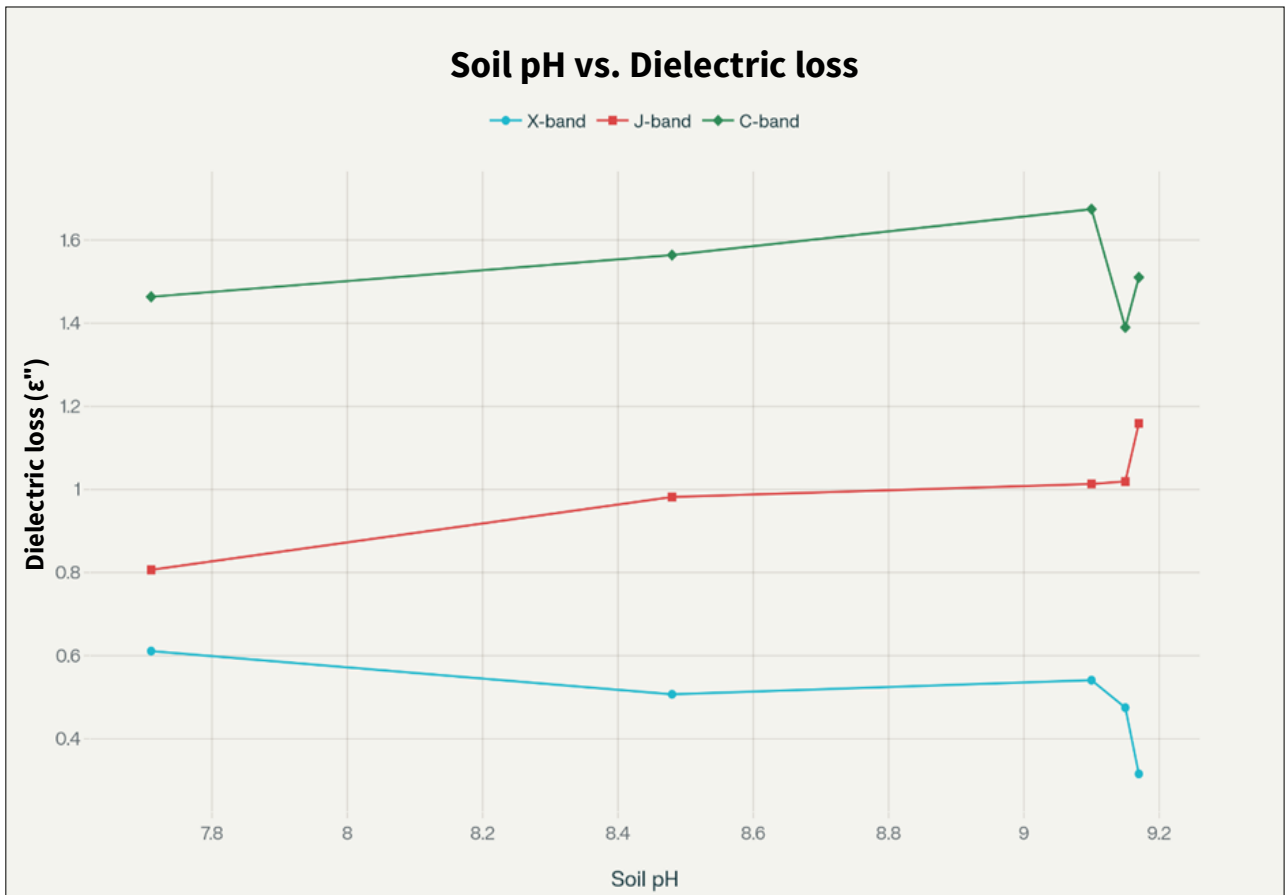


Fig. 7. Trend of dielectric loss vs pH across X, J and C frequency bands.

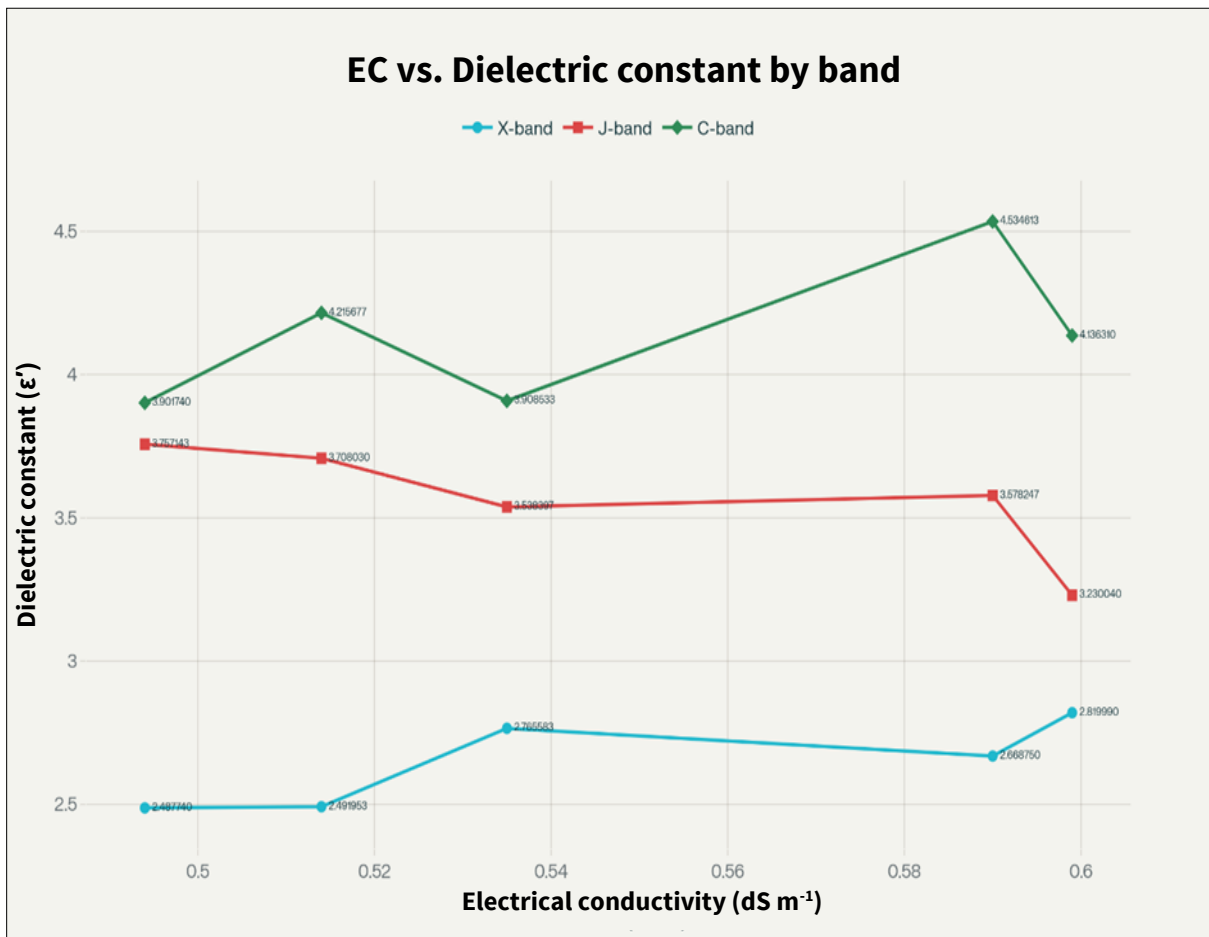


Fig. 8. Trend of dielectric constant vs electrical conductivity across X, J and C frequency bands.

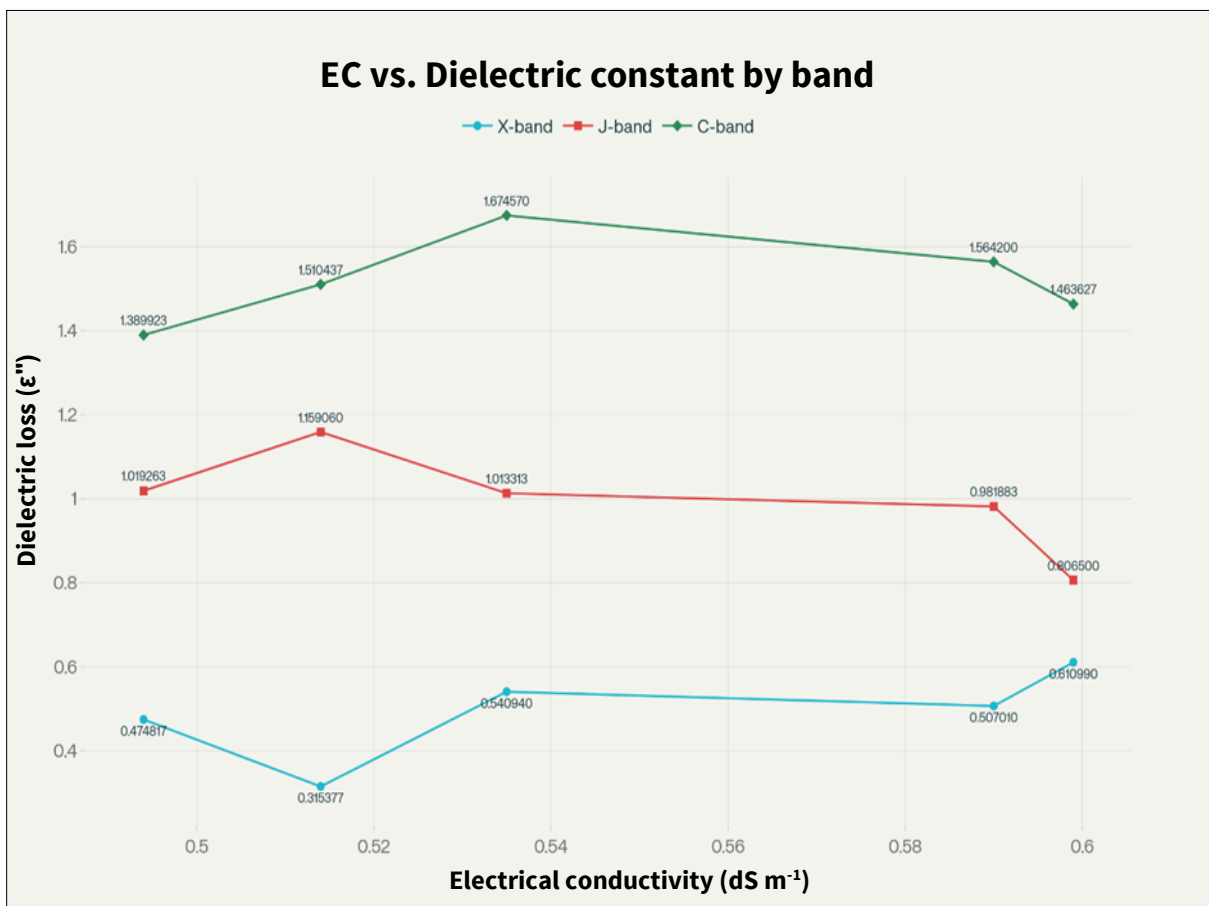
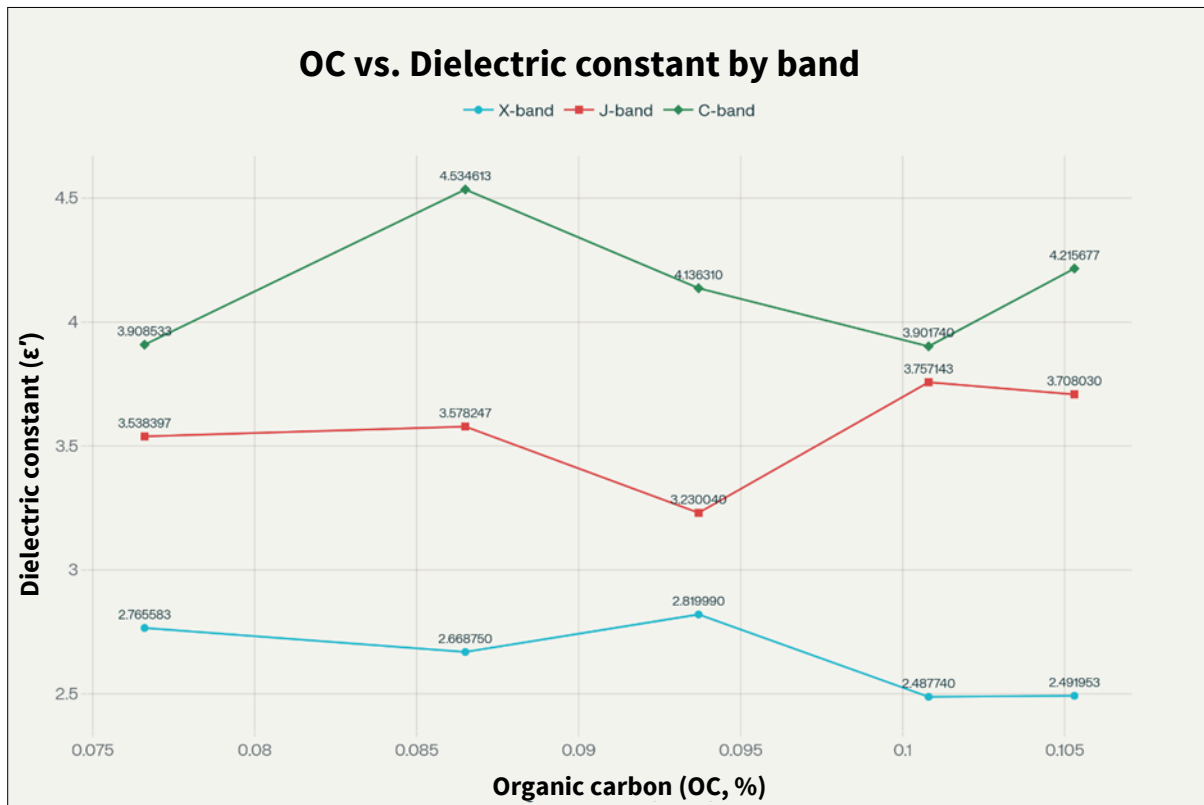


Fig. 9. Trend of dielectric loss vs electrical conductivity across X, J and C frequency bands.



cation

Fig. 10. Trend of dielectric constant vs organic carbon across X, J and C frequency bands.

groups. The C band indicates both dielectric constant and loss components respond to OC variation in a non-linear fashion shows in Fig. 10 and 11. As a result, these soils have higher levels of organic residue and consequently, more OC in the soil (23). The maximum OC level was found at the surface (24).

The investigation of soil texture influence on dielectric constant and loss defined several key findings that advance understanding for soil electromagnetic behavior. Three primary soil types are defined by loamy sandy having high sand content of 70 %, sandy Loam with balanced composition and clay loam with higher clay contain 30 % which is shown in Table 1. Loamy sandy soils, with their high sand content, consistently show the lowest dielectric constant and loss values across all colors (25). In black soil, the X band values is 2.7, while the clay loam reaches 3.8; it shows sandy soils are less electrically active due to sand's low conductivity and dielectric absorption as shown in Fig. 12. In dark red soil the C-band real value for clay loam is 5.1, significantly higher than loamy sandy's 4.5. This is attributed to clay's high surface area and ion exchange capacity, which enhance conductivity and energy absorption as shown in Fig. 13 (26). Very pale green and pale green soils exhibit the lowest X- band values, with loamy sandy as low as 2.5 dielectric constant, it defined leached minerals and low Clay or iron content, resulting in reduced conductivity as shown in Fig. 14 and 15 (27). Reddish brown soils, which often contain mix of organic materials and iron, show moderate conductivity but strong dielectric losses, particularly in J and C band as shown in Fig. 16.

The experimental results indicate that texture-dependent gradient in both dielectric constant (ϵ') and dielectric loss (ϵ''), with finer-textured clay loam soils consistently exhibiting higher values compared to coarser loamy sand samples across all frequency bands. The response of dielectric constant in clay rich soils can be reliant on many parameters such as greater specific surface area if clay particles provide more sites for water molecule absorption and

accumulation (28). The presence of exchangeable cations in clay minerals contributes to ionic conduction losses, particularly evident in the dielectric constant values.

Conclusion

This study shows dielectric behaviour of soils under multi-frequency microwave bands which reveals fundamental details about physicochemical properties of soil. These findings open new ways to check soil health quickly using remote tools, with direct implications for large-scale agricultural and geotechnical applications. Soil texture emerges as the dominant control on both dielectric constant and dielectric loss across X, J and C bands, due to interfacial polarisation at clay-water and mineral-water boundaries. Organic carbon and electrical conductivity modulate dielectric response in a frequency-dependent manner, offering complementary indicators for soil fertility and salinity mapping. More organic matter boosts energy storage at medium frequencies, while higher salt levels increase energy loss at low frequencies. These patterns support smarter fertiliser application and more efficient irrigation.

This work establishes a broad and flexible framework for understanding soil electromagnetic signatures. It creates new opportunities for developing advanced soil-assessment systems that combine machine learning techniques with data collected from multiple microwave frequencies bands. By utilising frequency-diverse microwave datasets, this approach enhances the accuracy and depth of soil analysis, allowing for better monitoring of soil properties and health. Such integrated platforms have the potential to revolutionise precision agriculture, environmental monitoring and land management by providing quicker, more precise.

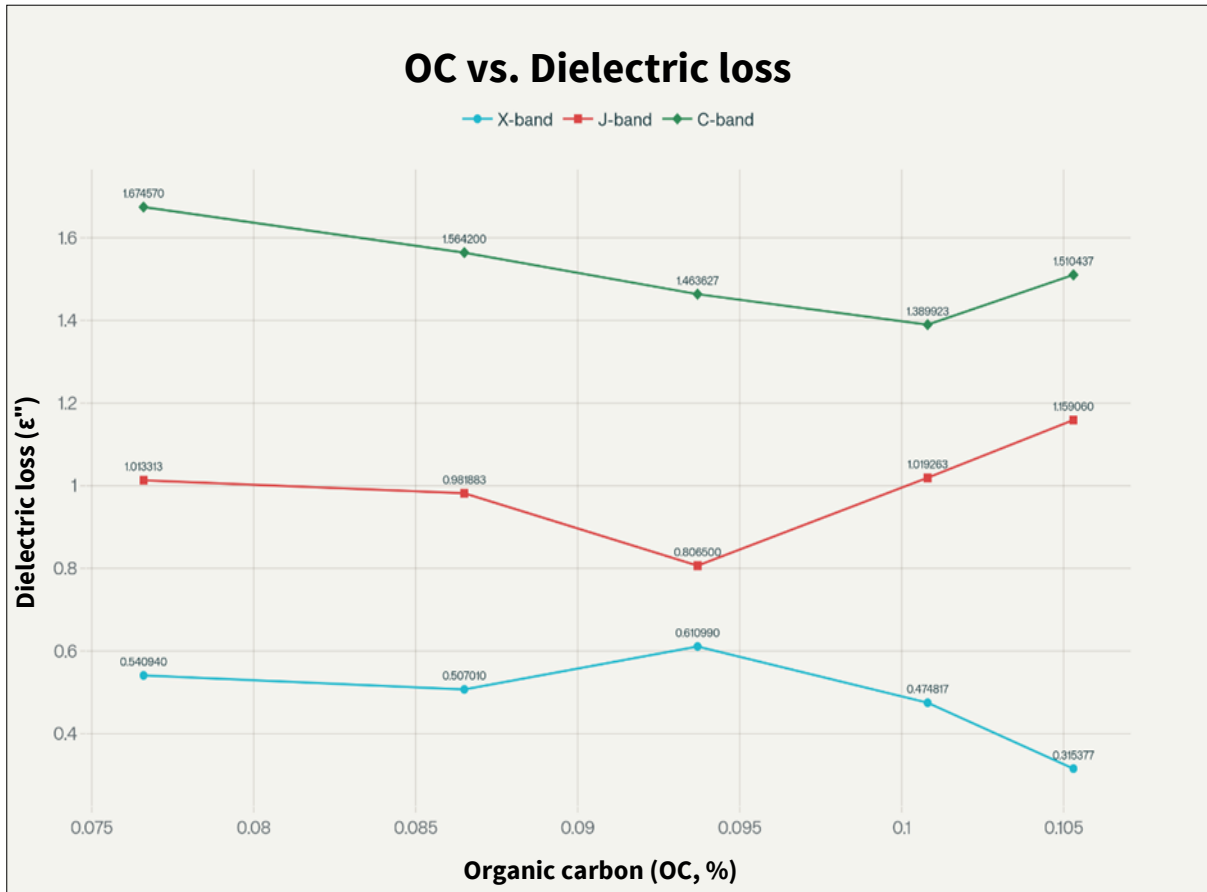


Fig. 11. Trend of dielectric loss vs organic carbon across X, J and C frequency bands.

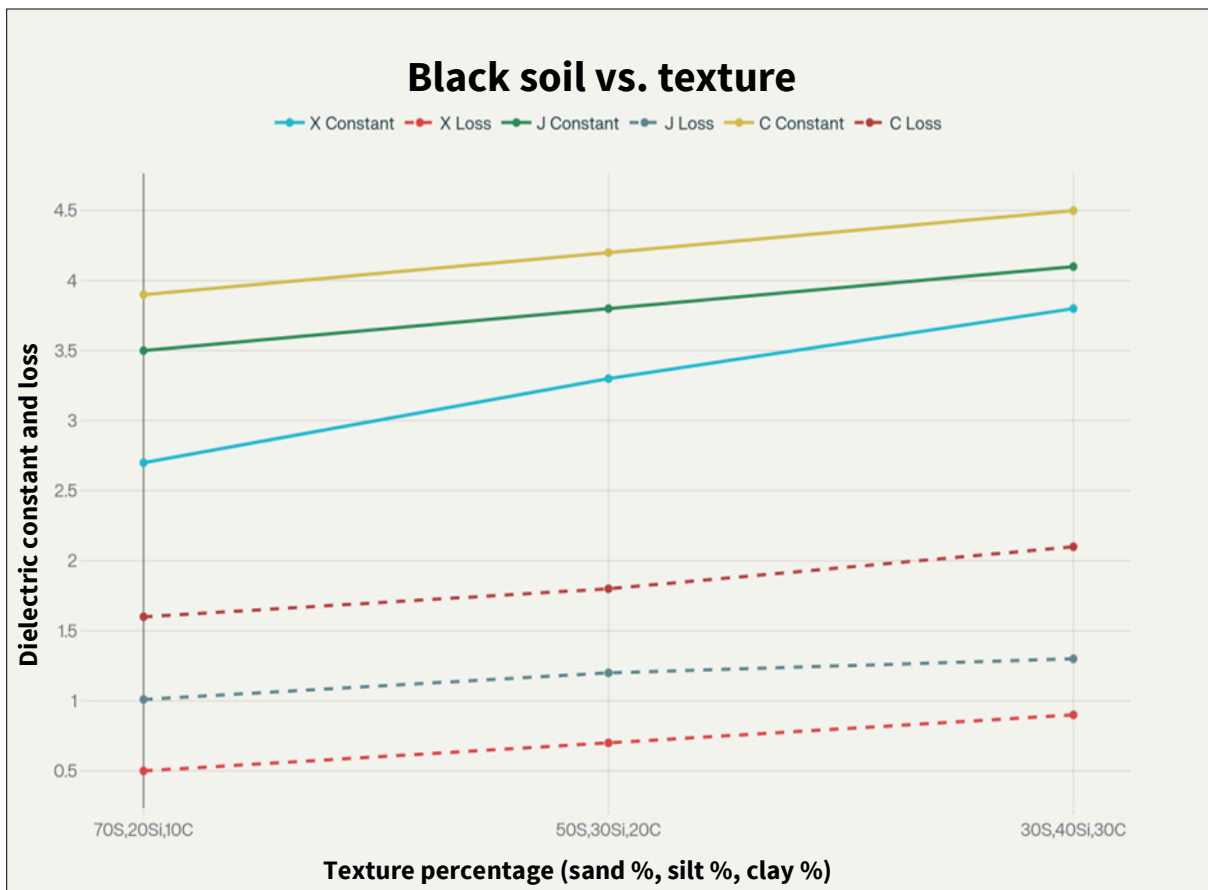


Fig. 12. Variation of dielectric constant and loss with texture composition for black soil.

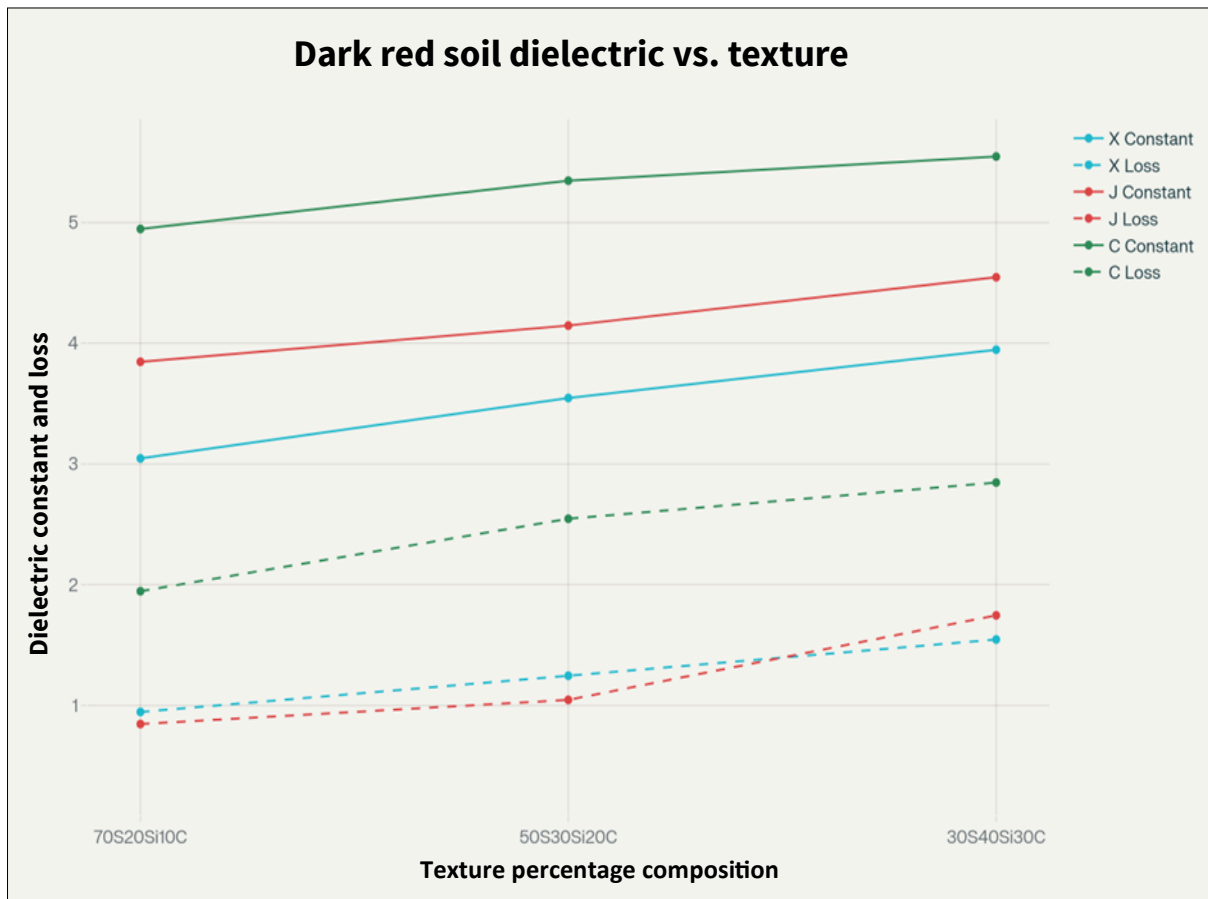


Fig. 13. Variation of dielectric constant and loss with texture composition for dark red soil.

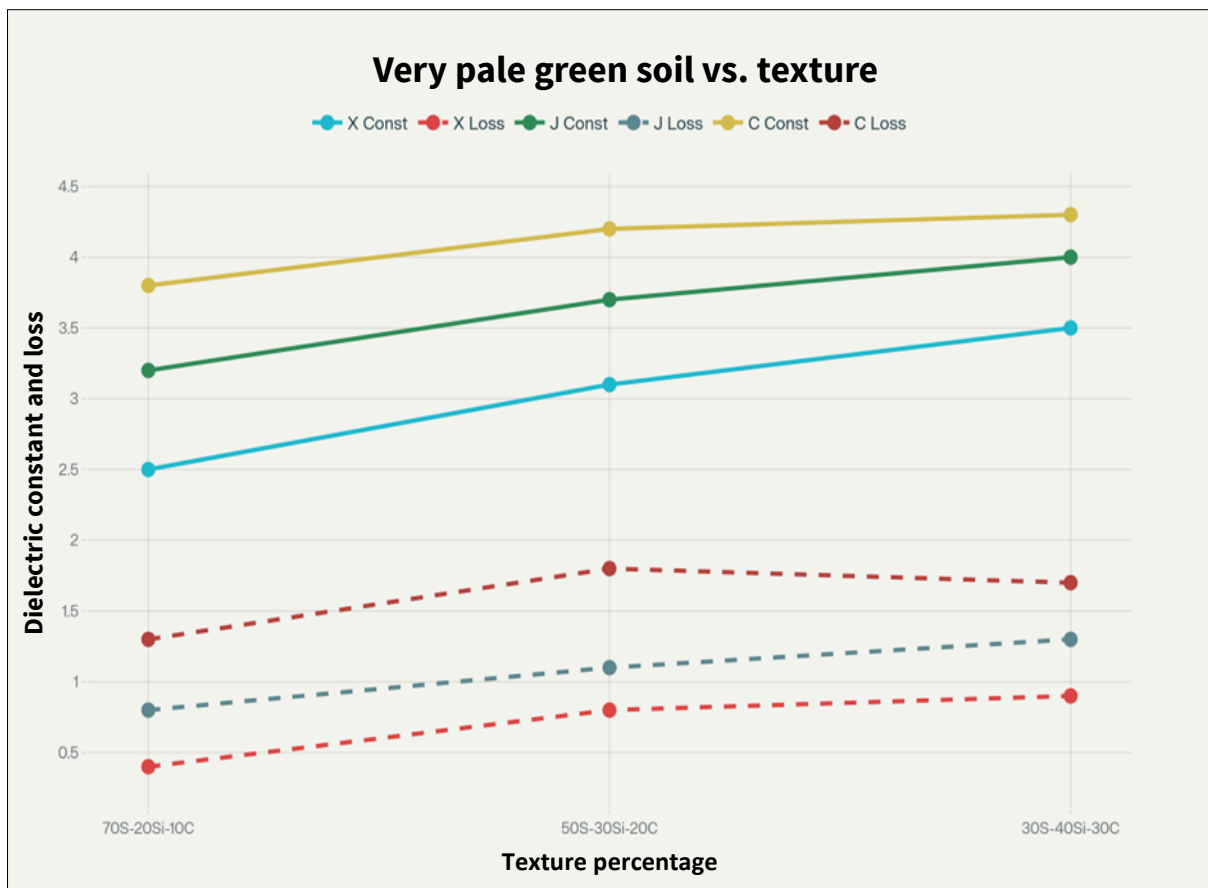


Fig. 14. Variation of dielectric constant and loss with texture composition for very pale green soil.

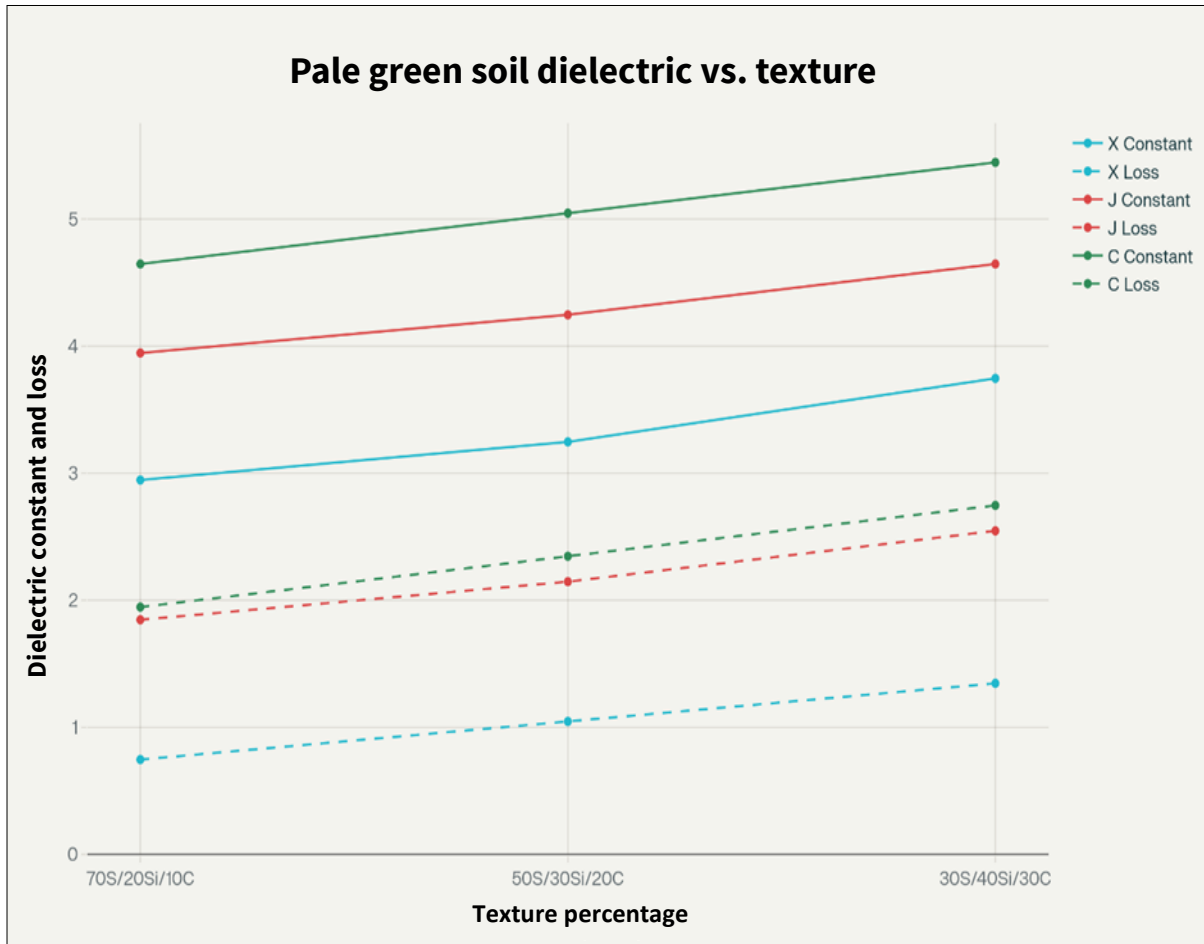


Fig. 15. Variation of dielectric constant and loss with texture composition for pale green soil.

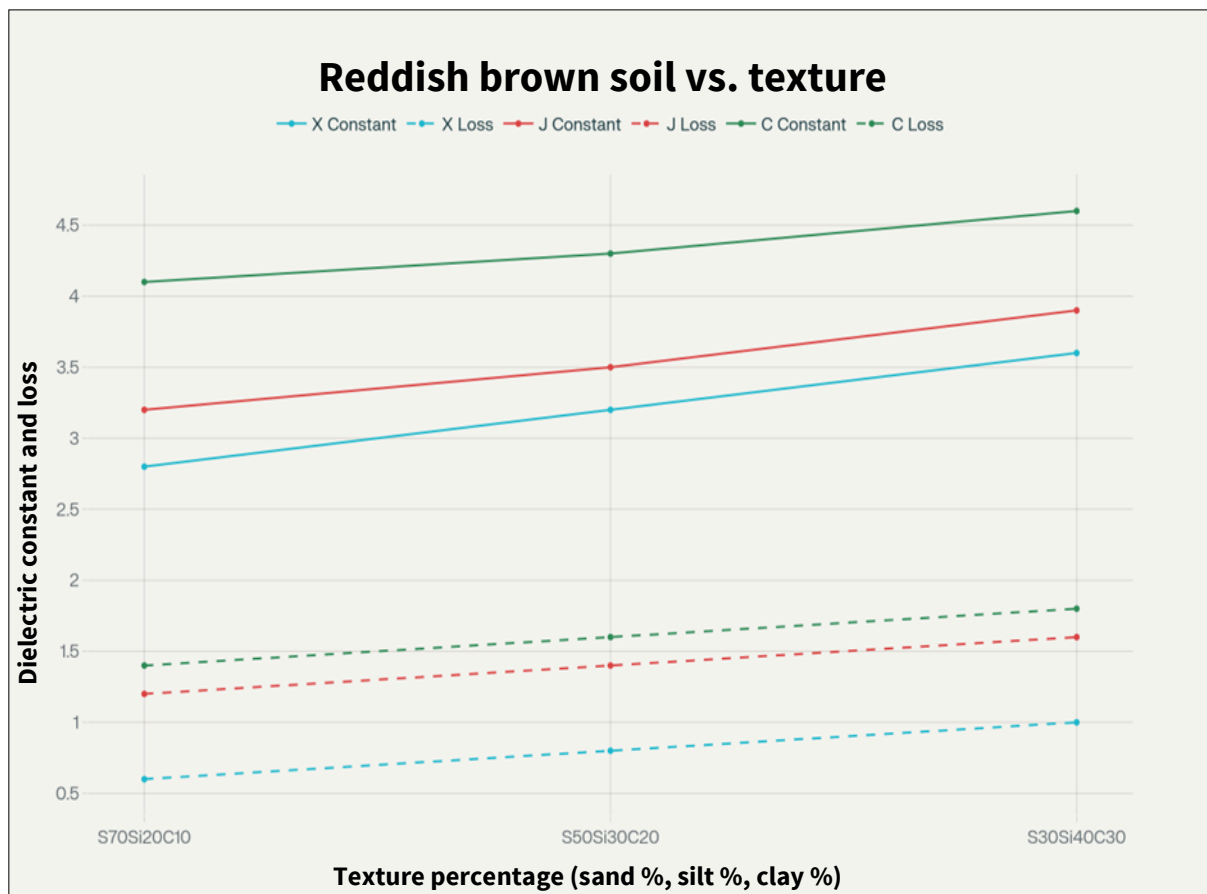


Fig. 16. Variation of dielectric constant and loss with texture composition for reddish brown soil.

Acknowledgements

Authors are thankful to the Janata Education Society College of Jalna for providing all research facilities.

Authors' contributions

MSD conceptualized and coordinated the study, performed the literature review, designed the research, selected samples, carried out measurements and calculations, analyzed the data and contributed to manuscript writing. SBD provided access to experimental facilities and developed the program to compute dielectric constant and dielectric loss values from raw data. ABI supervised and mentored the overall research. SBK supervised the research. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used DeepSeek to improve understanding of the subject matter. After using this tool, the authors reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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