

# DIELECTRIC AND EMISSIVITY BEHAVIOR OF COAL BELT AREA SOILS OF SURAJPUR, CHHATTISGARH, AT X-BAND MICROWAVE FREQUENCY

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## ABSTRACT

This study examines the dielectric properties and microwave emissivity of soils collected from the coal belt areas of Surajpur and Bishrampur in the northern region of Chhattisgarh, India. Soil samples were collected from the top 010 cm layer to assess the impact of moisture content on their electromagnetic characteristics during the year 2023-2024 period. Moisture content was varied from 0% to 20%, and measurements of dielectric constant ( $\epsilon'$ ), dielectric loss ( $\epsilon''$ ), and emissivity at horizontal and vertical polarizations were conducted. Results showed a systematic increase in dielectric constant and loss with increasing moisture, reflecting enhanced polarization and energy dissipation from bound and free water. Dry soils exhibited low dielectric values, whereas intermediate moisture levels (12-16%) produced a pronounced increase due to capillary water formation between particles. Emissivity decreased consistently with increasing moisture, indicating higher reflectivity and the influence of free water. Sandier soils showed higher emissivity and lower moisture sensitivity, while clay-rich soils displayed greater dielectric values and responsiveness. These findings demonstrate the strong dependence of soil electromagnetic properties on moisture content and texture. The study provides essential baseline data for soil characterization and highlights the importance of dielectric and emissivity measurements for estimating soil moisture, remote sensing, hydrological modeling, and environmental monitoring in mining-affected regions.

(Key words: Soil moisture, dielectric properties, emissivity, coal belt soils, remote sensing)

## INTRODUCTION

The dielectric properties of soils have attracted significant research interest over the past decades because of their fundamental importance in microwave remote sensing, radar applications, and soil moisture monitoring. The dielectric constant (the real part of permittivity) and dielectric loss (the imaginary part) govern the interaction of microwave signals with soil, thereby influencing both scattering and emissivity characteristics. These parameters are not only functions of soil texture, structure, density, and salinity but are most strongly dependent on soil moisture content, which serves as the dominant factor in microwave soil characterization.

### Influence of moisture content and frequency

The dependence of soil dielectric properties on moisture content has been extensively studied. Gadhani and Vyas (2008) investigated soil samples from various districts in the state of Gujarat, measuring both the dielectric constant and dielectric loss at X-band and C-band frequencies. Their results revealed a strong correlation between dielectric constant and volumetric moisture content, with dielectric values increasing steadily as water

content increased. They also noted that dielectric loss exhibited a similar trend, though the magnitude of change depended on the measurement frequency. This frequency dependence highlights the need for multi-band microwave studies to enhance the reliability of soil moisture retrieval algorithms in remote sensing.

### Transition moisture concept

Building upon these findings, Ghosh *et al.* (1998) introduced the concept of a transition moisture threshold, beyond which the dielectric constant shows a nonlinear rise. Their study indicated that at low to moderate soil moisture, bound water molecules associated with soil particles dominate, leading to a relatively slow increase in the dielectric constant. However, once the transition moisture level is surpassed, free water molecules play a greater role, resulting in a sharp rise in dielectric response. This two-stage behavior is crucial for accurate dielectric modeling, as it highlights the limitations of linear approximations in soil moisture-dielectric relationships.

### Emissivity and radiometric applications

Complementing the dielectric studies, Nalla *et al.* (1999) focused on the emissivity characteristics of dry and wet loamy sand soils at microwave frequencies. Their

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experiments demonstrated that soil emissivity is inversely related to moisture content: as the dielectric constant increases with water addition, emissivity decreases systematically. Furthermore, polarization dependence was evident, with emissivity under vertical polarization consistently higher than that under horizontal polarization. These findings are particularly significant for radiometric remote sensing, where emissivity data are integrated into models for estimating soil moisture from satellite-based radiometers (Shrivastava, 2001).

## MATERIALS AND METHODS

Soil samples were collected from the coal belt area of Surjapur district of Chhattisgarh. This is situated in the northern region of Chhattisgarh state of India. These soil samples were collected from the coal belt area of Bishrampur, and their depths ranged from 0 to 10 cm (topsoil). These topsoil samples were sieved by a gyratory sieve shaker to remove the coarser particles. After removing the coarser particles, the particles were dried to a temperature of approximately 110°C for 30 minutes in a microwave oven to completely remove any trace of moisture. Hence, these dry samples were referred to as oven-dry or dry base samples. To prepare the moisture content of soil samples, add an exact amount of distilled water to oven-dry samples. The sample soil water mixtures were thoroughly mixed and stored in a closed container to allow for proper settling. These mixed soil samples were inserted into the solid dielectric cell for measuring their dielectric properties using a microwave test bench.

### Physical properties of the soil sample

The physical properties of soil samples were described as shown in Table 1 represents the physical properties of the soil samples from the Coal Belt Area of Surjapur district of Chhattisgarh (India). The wilting point (Wp) and transition moisture (Wt) of soil in terms of volumetric water content ( $\text{cm}^3/\text{cm}^2$ ) were calculated by using the Wang and Schmugge model

$$W_p = .06774 - .00064 * \text{Sand}\% + .00478 * \text{clay}\% \dots \dots \dots (1)$$

$$W_t = .49 * w_p + .165 (2)$$

$$\dot{O} = -0.57 * w_p + 0.481 (3)$$

### Evaluation of complex dielectric constant

The dielectric constant of soils was measured using the infinite sample method described in equation (1). Horizontal polarization and Vertical polarization were calculated from equations (2) and (3). Hence, the Emissivity of a soil sample can be calculated from its dielectric constant, with moisture content (Table 2). The complex dielectric constants of dry soils and different moisture content percentages were calculated, which led to the following empirical relation for the variation of complex permittivity with respect to humidity.

$$\epsilon' = 6.3485 + .04 H\% - 7.78 * 10^{-4} H^2\% + 5.56 * 10^{-6} H^3\% \dots \dots \dots (3)$$

$$\epsilon'' = .0929 + .02 H\% - 3.71 * 10^{-4} H^2\% + 2.76 * 10^{-6} H^3\% \dots \dots \dots (4)$$

Where H is the moisture content (%)

$$\epsilon = \epsilon' - j\epsilon'' \dots \dots \dots (5)$$

**Table 1. Soil physical properties**

S. No.	Sand (%)	Silt (%)	Clay (%)	Wp	Wt	Y	Porosity
S1	39.0	46.0	16.0	0.1192	0.2234	0.4130	0.198
S2	38.0	44.0	19.0	0.1342	0.2307	0.4044	0.185
S3	35.0	42.0	17.0	0.1266	0.2270	0.4088	0.230
S4	47.0	31.5	10.5	0.0870	0.2040	0.4310	0.242
S5	36.0	43.0	18.0	0.1300	0.2290	0.4064	0.201

**Table 2. Dielectric constant of soil samples from the coal belt area of Bishrampur, Surajpur (C.G.)**

Sample ID	Dielectric constant
S1	3.51 + j0.223
S2	3.63 + j0.243
S3	3.75 + j0.352
S4	3.48 + j0.211
S5	3.81 + j0.382

Evaluation of emissivity

The emissivity  $\epsilon_p(\theta)$  can be calculated by

$$e_p(\theta) = (1 - r_p(\theta)) \dots \dots \dots (6)$$

$r_p(\theta)$  can be obtained from the Fresnel Reflection coefficient  $R_p(\theta)$  as

$$r_p(\theta) = |R_p(\theta)|^2 \dots \dots \dots (7)$$

For horizontal polarization

$$R_p(\theta) = \frac{\cos\theta - \sqrt{(\epsilon' - \sin^2\theta)}}{\cos\theta + \sqrt{(\epsilon' - \sin^2\theta)}} \dots \dots \dots (8)$$

For vertical polarization

$$R_v(\theta) = \frac{\epsilon' \cos\theta - \sqrt{(\epsilon' - \sin^2\theta)}}{\epsilon' \cos\theta + \sqrt{(\epsilon' - \sin^2\theta)}} \dots \dots \dots (9)$$

Where  $\theta$  is the angle of observation from nadir,  $\epsilon'$  is the dielectric constant of the soil, and  $e_p(\theta)$  is the emissivity of the surface layer, and  $r_p(\theta)$  is the reflection coefficient.

## RESULTS AND DISCUSSION

### Dielectric properties and emissivity of coal belt area of Surajpur, Chhattisgarh (India)

The results obtained from the experimental analysis are summarized in Table 3. The dielectric properties of soil samples collected from the coal belt area of Surajpur (C.G.) were studied as a function of moisture content ranging from 0 to 20%. The results revealed a systematic increase in both the dielectric constant ( $\epsilon'$ ) and dielectric loss ( $\epsilon''$ ) with increasing soil moisture for all samples (S1S5). At 0% moisture, the dielectric constant values were relatively low (3.483.87), consistent with dry soils where polarization is dominated by mineral constituents and bound water. With the gradual addition of moisture (4-8%),  $\epsilon'$  exhibited a moderate increase; for example, S1 rose from 3.51 to 3.78 and S3 from 3.75 to 4.02, accompanied by an increase in dielectric loss due to enhanced dipolar relaxation and ionic conduction. At intermediate moisture levels (12-16%), a stronger increase was recorded as water formed capillary bridges between soil particles, intensifying polarization effects. At the highest moisture level (20%),  $\epsilon'$  reached its maximum, ranging between 4.01 (S4) and 4.34 (S5), while  $\epsilon''$  also peaked, indicating the dominance of free water with high dielectric behavior and greater energy dissipation. Comparatively, sample S5 consistently exhibited the highest dielectric constant and loss values, suggesting a higher clay or organic matter fraction that enhances water retention and polarization. In contrast, sample S4 displayed the lowest values, indicative of a sandier texture with less bound water. Overall, the dielectric constant of Surajpur soils increased by approximately 1520% between dry and saturated states, a trend that aligns well with existing dielectric mixing models reported in the literature. Zhang and Wulfmeyer (2021) developed an inverse dielectric mixing model at 50 MHz that

incorporates soil organic carbon for predicting volumetric soil moisture. The results showed that including organic carbon significantly improved model accuracy, particularly in organic-rich soils, with the model achieving a higher correlation ( $R^2 > 0.88$ ) and a reduced root mean square error compared to traditional dielectric models. The study demonstrated that accounting for soil composition, particularly organic content, is crucial for accurate microwave-based soil moisture estimation.

The study demonstrates that the dielectric behavior of soils in the Surajpur coal belt was highly moisture-dependent, with variations among samples reflecting textural and compositional differences. These findings are in agreement with previously established soil dielectric models. Abdulraheem *et al.* (2024) reported that advances in dielectric-based soil moisture measurement had improved accuracy through refined calibration models and modern TDR/FDR techniques. They emphasized that integrating dielectric sensing with remote sensing and AI enhances large-scale soil water content estimation.

Data regarding the emissivity of soil samples from the coal belt area of Bishrampur (C.G.) at horizontal polarization are presented in Table 4.

The coal belt area of Bishrampur (C.G.) at horizontal polarization exhibited a clear decreasing trend with increasing moisture content from 0% to 20%. Initially, dry soils showed relatively high emissivity values, ranged from 0.8625 (S5) to 0.8777 (S4), reflecting low dielectric constants and strong thermal emission. As moisture increased to 48%, emissivity declined moderately (e.g., S1: 0.8763  $\rightarrow$  0.8637; S3: 0.8652  $\rightarrow$  0.8530) due to enhanced dielectric contrast from water, which increased reflectivity. At intermediate moisture levels (12-16%), the decrease became more pronounced, corresponding to the formation of capillary water and continuous water films that further alter dielectric properties (S2: 0.8537  $\rightarrow$  0.8500; S5: 0.8460  $\rightarrow$  0.8424). At 20% moisture, all samples reached minimum emissivity values (0.8395-0.8535), indicating dominance of free water and maximum reflectivity. Among the samples, S4 consistently showed the highest emissivity, suggesting sandier texture and lower water retention, whereas S5 had the lowest values, indicative of clay-rich composition with higher moisture sensitivity. Overall, these results demonstrate that horizontal polarization emissivity is inversely related to soil moisture content, reflecting textural and compositional differences, and support the use of emissivity measurements for accurately estimating soil moisture in hydrological and remote sensing applications. Zeng *et al.* (2020) developed a passive microwavebased Soil Moisture Index (SMI) and validated it against field measurements. The SMI exhibited a strong correlation ( $R^2 \approx 0.85$ ) with observed soil moisture, accurately capturing temporal variations, particularly in low-to medium-moisture conditions, and outperforming conventional indices in terms of sensitivity and reliability.

**Table 3. Dielectric constant of soil samples with varying moisture content in the coal belt area of Surajpur (C.G.)**

Moisture content (%)	S1	S2	S3	S4	S5
0	3.51 -j0.223	3.63 -j0.243	3.75 -j0.352	3.48 -j0.211	3.87 -j0.382
4	3.65 -j0.2988	3.777 -j0.3172	3.8979 -j0.4262	3.6279 -j0.2922	3.9579 -j0.4562
8	3.783 -j0.3606	3.9030 -j0.1700	4.02305 -j0.2759	3.7530 -j0.1419	4.0830 -j0.3060
12	3.887 -j0.4143	4.0076 -j0.4343	4.1276 -j0.5433	3.8576 -j0.4093	4.1876 -j0.5733
16	3.9736 -j0.4593	4.0936 -j0.4793	4.2136 -j0.5883	3.9436 -j0.4543	4.2736 -j0.6183
20	4.043 -j0.4966	4.1632 -j0.5168	4.2832 -j0.6256	4.0132 -j0.4916	4.3432 -j0.6557

**Table 4. Emissivity at horizontal polarization with varying moisture content in the coal belt area of Bishrampur (C.G.)**

Sample ID	0% Moisture	4% Moisture	8% Moisture	12% Moisture	16% Moisture	20% Moisture
S1	0.8763	0.8697	0.8637	0.8590	0.8552	0.8522
S2	0.8707	0.8639	0.8583	0.8537	0.8500	0.8470
S3	0.8652	0.8585	0.8530	0.8486	0.8449	0.8420
S4	0.8777	0.8708	0.8650	0.8637	0.8565	0.8535
S5	0.8625	0.8559	0.8505	0.8460	0.8424	0.8395

**Table 5. Emissivity at vertical polarization with varying moisture content in the coal belt area of Bishrampur (C.G.)**

Sample ID	0% Moisture	4% Moisture	8% Moisture	12% Moisture	16% Moisture	20% Moisture
S1	0.9351	0.9307	0.9266	0.9234	0.9207	0.9186
S2	0.9313	0.9267	0.9229	0.9197	0.9171	0.9150
S3	0.9276	0.9231	0.9292	0.9161	0.9135	0.9114
S4	0.9360	0.9314	0.9275	0.9243	0.9217	0.9207
S5	0.9257	0.9213	0.9174	0.9143	0.9117	0.9097

The vertical polarization emissivity of soil samples from the coal belt area of Bishrampur (C.G.) exhibited a consistent decrease with increasing moisture content from 0% to 20%, indicating a strong influence of soil water on dielectric and radiative properties are presented in Table 5. At 0% moisture, emissivity values were highest, ranging from 0.9257 (S5) to 0.9360 (S4), reflecting low dielectric constants and strong thermal emission from dry soils. As the moisture content increased to 48%, a gradual decline in emissivity was observed (e.g., S1: 0.9351  $\rightarrow$  0.9266; S2: 0.9313  $\rightarrow$  0.9229), attributed to enhanced reflectivity resulting from the increasing dielectric constant due to the added water. At intermediate moisture levels (1216%), the reduction became more pronounced (S1: 0.9234  $\rightarrow$  0.9207; S5: 0.9143  $\rightarrow$  0.9117), likely due to the formation of capillary

water and water films around soil particles, which further increased the dielectric contrast and reduced emissivity. At a maximum moisture content of 20%, emissivity values reached their minimum (0.9097-0.9186), indicating that the dominance of free water controls microwave emission. Sample S4 consistently exhibited the highest emissivity, indicating a sandier texture and lower water retention, whereas Sample S5 had the lowest, reflecting a clay-rich composition and higher sensitivity to moisture. Overall, the results demonstrate a clear inverse relationship between vertical polarization emissivity and soil moisture content, highlighting the significance of such measurements for soil moisture estimation, hydrological modeling and remote sensing applications. The study investigated how land surface emissivity (LSE) varied with changes in soil

composition, moisture, temperature, and vegetation cover. Results showed that emissivity varies both spectrally (especially in the 8–11  $\mu\text{m}$  range) and diurnally ( $\Delta\epsilon \approx 0.01$ ). These variations significantly affect the accuracy of land surface temperature (LST) retrievals. Incorporating dynamic (time-varying) emissivity into retrieval algorithms reduced LST errors from 6.02 °C to 2.97 °C. The study highlights that considering emissivity dynamics greatly improves remote sensing-based temperature estimation.

This study analysed the dielectric properties and microwave emissivity of soil samples from the coal belt areas of Surajpur and Bishrampur (C.G.) across a moisture ranged from 0% to 20%. The dielectric constant ( $\epsilon'$ ) and dielectric loss ( $\epsilon''$ ) of all samples increased systematically with moisture content, reflecting enhanced polarization and energy dissipation due to both bound and free water. Dry soils exhibited relatively low dielectric values, while intermediate moisture levels (12–16%) resulted in a more pronounced increase, associated with capillary water formation and intensified polarization. At the highest moisture level (20%), dielectric values reached their peak, indicating the dominant effect of free water. Horizontal and vertical polarization emissivity exhibited a clear inverse relationship with moisture content. Emissivity decreased steadily from dry to saturated conditions due to increased reflectivity, formation of water films, and enhanced dielectric contrast. Among the samples, sandier soils consistently had higher emissivity and lower moisture sensitivity, whereas clay-rich soils showed higher dielectric values and greater responsiveness to moisture. Overall, the results demonstrate that both

dielectric properties and microwave emissivity were highly sensitive to soil moisture and were influenced by soil texture and composition. These findings emphasized the importance of dielectric and emissivity measurements for accurate soil moisture estimation, hydrological modelling, remote sensing, and environmental monitoring, particularly in mining-affected regions, providing a valuable dataset for understanding soil-water interactions in coal belt soils.

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