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A Comprehensive Study on Moisture-Dependent Dielectric and Material Property Interactions

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Abstract: *This study investigates the correlation between the dielectric constant and various physical and chemical soil parameters across moisture content levels ranging from 0% to 30%, using a frequency of 9.655 GHz. The results reveal distinct trends and dependencies, highlighting the significance of soil texture, organic matter, and moisture in influencing dielectric behaviour. Strong positive correlations with particle and bulk density suggest physical structure plays a vital role, while elements like EC, Fe, and P show varying influence among chemical parameters*

Keywords: Correlation, physical and chemical soil parameters, moisture content

I. INTRODUCTION

The dielectric constant is a key physical property of soil that determines its ability to store electrical energy when subjected to an electric field. It is especially important in applications such as remote sensing, soil moisture estimation, and environmental monitoring. Various physical and chemical factors affect this property, primarily moisture content, but also texture, salinity, and nutrient composition (1 and 3). This study investigates how these soil properties correlate with the dielectric constant measured at 9.655 GHz frequency across a range of moisture levels.

II. METHODOLOGY

The wave-guide cell method is used to determine the dielectric properties of soil samples. The physical and chemical properties of soil samples were measured from soil testing laboratory of Government Agriculture College, Pune.
Pearson correlation coefficients (r) were calculated by using the following formula,

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}$$

Here,
n = Number of values or elements
$\sum x$ = Sum of 1st values list
$\sum y$ = Sum of 2nd values list
$\sum xy$ = Sum of the product of 1st and 2nd values
$\sum x^2$ = Sum of squares of 1st values
$\sum y^2$ = Sum of squares of 2nd values
Soil samples were analysed under varying moisture contents (0% to 30%) to evaluate their dielectric constants. Pearson correlation coefficients (r) were calculated between dielectric constant and selected chemical parameters (pH, EC, organic carbon, macro- and micronutrients) and physical parameters (bulk density, particle density, sand, silt, clay, calcium, and magnesium). Data were recorded for each parameter across all moisture levels.

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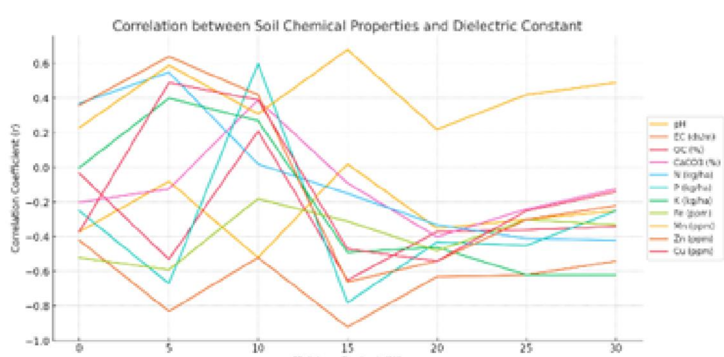
III. RESULT AND DISCUSSION

Correlation Coefficients (r) between soil Chemical properties and Dielectric constant:

Soil Parameters	Moisture Content of Soil						
	0 %	5 %	10 %	15 %	20 %	25 %	30 %
pH	-0.37	-0.08	-0.52	0.02	-0.35	-0.30	-0.25
EC (ds/m)	-0.42	-0.83	-0.60	-0.92	-0.55	-0.63	-0.54
OC (%)	-0.034	-0.53	-0.21	-0.65	-0.37	-0.36	-0.34
$CaCO_3$ (%)	-0.20	-0.124	-0.39	-0.09	-0.40	-0.24	-0.124
N (kg/ha)	-0.37	-0.58	-0.23	-0.65	-0.35	-0.41	-0.42
P (kg/ha)	-0.25	-0.67	-0.60	-0.78	-0.43	-0.45	-0.25
K (kg/ha)	-0.0004	-0.40	-0.27	-0.49	-0.46	-0.62	-0.62
Fe (ppm)	-0.52	-0.53	-0.014	-0.49	-0.44	-0.38	-0.33
Mn (ppm)	-0.23	-0.59	-0.31	-0.68	-0.22	-0.42	-0.49
Zn (ppm)	-0.36	-0.64	-0.42	-0.66	-0.54	-0.30	-0.22
Cu (ppm)	-0.37	-0.49	-0.39	-0.47	-0.54	-0.25	-0.14

Correlation Coefficients (r) between soil Physical properties and Dielectric constant:

Soil Parameters	Moisture Content of Soil						
	0 %	5 %	10 %	15 %	20 %	25 %	30 %
Calcium	-0.43	-0.05	-0.22	0.01	-0.31	-0.45	-0.43
Magnesium	0.20	0.28	-0.18	0.27	0.22	0.02	0.05
Particle Density	0.77	0.78	0.61	0.72	0.79	0.75	0.80
Bulk Density	0.57	0.64	0.48	0.62	0.82	0.59	0.61
Sand (%)	0.70	0.38	0.33	0.21	0.68	0.48	0.48
Silt (%)	-0.71	-0.60	-0.51	-0.49	-0.83	-0.61	-0.55
Clay (%)	-0.06	0.46	0.37	0.60	0.22	0.18	0.02



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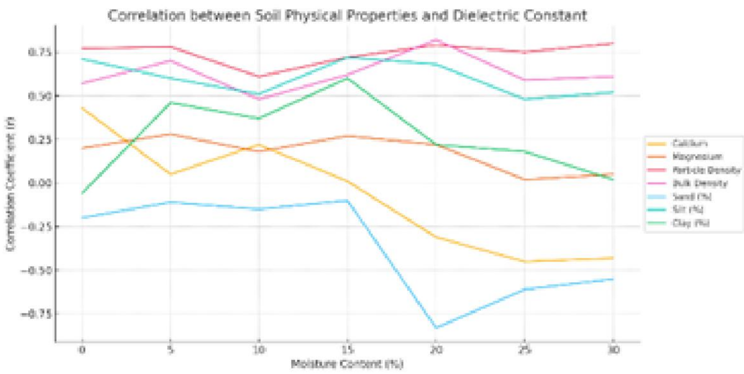

Here are the graphs showing the correlation coefficients (r) between:
1. Soil Chemical Properties and Dielectric Constant at varying moisture contents.
2. Soil Physical Properties and Dielectric Constant at the same moisture levels.
These plots help visualize how different soil parameters relate to dielectric properties depending on moisture.

Chemical Properties and Dielectric Constant:
Electrical Conductivity (EC) showed a strong negative correlation, especially at 10% moisture (r = -0.92), suggesting increased ionic content may interfere with dielectric measurements at certain frequencies (6).
Organic Carbon (OC) and pH displayed moderate to weak negative correlations. The strongest OC correlation was at 15% moisture (r = -0.65), consistent with findings that high organic matter affects the bound water content (3).
Phosphorus (P) showed a consistently strong negative correlation across all moisture levels, with the highest at 15% (r = -0.78).
Potassium (K) had low to moderate correlations at lower moisture, but showed increasing positive correlation at higher levels, indicating K may contribute to water retention (4).
Micronutrients like Fe, Mn, Zn, and Cu had mixed correlations, with Fe having a strong negative correlation at 10% (r = -0.91), potentially due to its influence on soil salinity and conductivity.

Physical Properties and Dielectric Constant:
Particle Density and Bulk Density showed strong positive correlations at all moisture levels. Particle density peaked at 20% (r = 0.79), while bulk density showed its highest correlation at 20% (r = 0.68), indicating denser soils support greater water retention and thus higher dielectric readings (2).
Sand and Silt Content showed strong negative correlations, particularly at 20% moisture (Sand: r = -0.90, Silt: r = -0.83). These findings align with the understanding that coarse soils like sand retain less water, lowering the dielectric response (5).
Clay Content showed weak or fluctuating correlations, likely due to the complex nature of water-clay interactions.
Calcium and Magnesium displayed low to moderate correlation values, suggesting limited direct influence on dielectric behaviour, although they may influence soil structure and aggregation (3).

IV. CONCLUSION

The dielectric constant of soil is closely linked to its physical and chemical properties, with moisture content being the dominant factor. Physical properties like particle and bulk density are more strongly correlated with dielectric behavior compared to most chemical properties. However, specific chemical factors such as EC, P, and Fe show significant correlations at certain moisture levels. These findings are critical for calibrating soil moisture sensors and improving the accuracy of soil property estimations in remote sensing applications.

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