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Study and Analysis of Dielectric Behavior of Fertilized Soil at Microwave Frequency

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ABSTRACT

This paper reports the experimental results of the dielectric behaviour of mixture of different types of fertilizers and soil at L, S and C frequency bands. A simple and rapid measurement method using microwave free-space transmission technique is used for measuring the dielectric constant. The variations in dielectric constant of soil with different concentration of various fertilizers like Boric Acid, NPK, Potash and Urea are studied extensively. Measurement has been performed using Vector Network Analyzer (VNA) and antenna/soil sample holder. The sample-mixtures are prepared by mixing different fertilizers in soil according to the statistics provided by the Department of Agriculture.

Key words: Dielectric constant, microstrip patch antenna, free-space transmission technique, soil

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INTRODUCTION

Soil is the unconsolidated material on the immediate surface of the earth that serves as a natural medium for the growth of land plants and has been subjected to and influenced by genetic and environmental factors of parent material, climate (including moisture and temperature effects), macro and micro organisms and topography, all acting over a period of time and producing a product that differs from the material from which it has derived all the properties and characteristics [1].

The pH of a soil refers to how acidic or alkaline the soil is. Thirteen elements, called nutrients, are essential for plant growth. They are classified as macro- and micro-nutrients, based on the quantity required. As they grow, plants extract nutrients they need from the soil. Unless these nutrients are replenished, plants will eventually cease to grow. In nature, nutrients are returned to the soil when plants die and decay. When cultivated plants are harvested, nutrients that the plants extracted from the soil are taken away. To keep the soil productive, it is necessary to replace these nutrients artificially. This is done by applying to the soil substances that contain these nutrients. Nitrogen, phosphorus, and potassium are the major macro-nutrients. Iron, Boron and Zinc are the main micro-nutrients. Many commercial fertilizers supply these thirteen essential elements. It has experimentally been proved that soil interacts with incident electromagnetic (EM) waves and exhibits EM properties that can be determined [2].

Dielectric materials behave differently in the presence of an electromagnetic field. When microwaves are directed towards a material, energy gets reflected or transmitted through the surface or absorbed by it. The proportions of above energy vary with the material properties. Permittivity ε and permeability μ are the key parameters describing the interaction of materials with electromagnetic fields [3].

Permittivity is not only frequency dependent but also dependent on density, water content, profile, mineral composition and concentration, granular size distribution, porosity etc.; some of these parameters, especially the last few, are typical in the case of Soil. Dielectric profiles of materials are investigated in different parts of the frequency spectrum. Since recent research applications are concentrated at microwave frequencies, the work focuses in this range. At microwave frequencies, various non-resonant and resonant techniques are available for the measurement of dielectric constant of materials, which include transmission line, free-space, coaxial probe and cavity techniques [4].

Water has a strong influence on the dielectric properties of soil at microwave frequencies. For agricultural purposes, the spatial and temporal variation in the concentration of fertilizers is considered as important as moisture content. Different levels of fertilizers give rise to a large variation in the dielectric constant. Thus, knowledge of the variation of the dielectric constant of soil with fertilizers is necessary for their efficient use in soil. Systematic study of the microwave sensing of soil properties in the presence of moisture and fertilizers has evolved as a major need of the hour. Moreover, soil testing as a tool for judicious fertilizer recommendation has assumed great relevance [5].

The effect of moisture content on soil has been extensively studied. Experimental results carried out on 62 different samples (31 samples acidic and 31 alkaline, with varying Total Soluble Salt (TSS) and organic contents) of 20 ml each of soil under two different cases - (i) all dry samples and (ii) all samples individually mixed with 5ml, 6ml and 8ml of water to study the effect of extra-added moisture in soil have been reported [6]. The following sections discuss the experimental setup and methodology used for the measurement of dielectric constant of the soil-fertilizer mixture and results.

EXPERIMENTAL SETUP AND METHODOLOGY

Application of an electric field changes the electric charge distribution of a material. Dielectric permittivity is a measure of this change. It is commonly expressed in relation to that of free space and is therefore termed as complex relative permittivity, ε_r. ε_r, given in equation (1), describes the material behaviour in the electric field. The real part, ε_r' is called the dielectric constant and the imaginary part, ε_r'' is called the loss factor.

$$\varepsilon_r = \varepsilon_r' - j\,\varepsilon_r'' \qquad (1)$$

Dielectric constant represents the ability of a material to store electric energy, while the loss factor represents the loss of electric-field energy in the material. Another parameter frequently employed is the loss tangent, defined as the ratio of the loss factor to the dielectric constant, as defined in equation (2).

$$\tan\delta = \varepsilon_r'' / \varepsilon_r' \qquad (2)$$

The objective of this work is to measure ε_r' of soil samples mixed with common fertilizers using microwave free-space transmission technique. Proper extractants are used to ensure that elements such as phosphorus, potassium, sodium, magnesium, calcium, sulphur, manganese, copper, zinc etc, which are the essential constituents of common fertilizers, are chemically removed from the soil samples.

ε_r' of most of the commonly used fertilizers is in the range 1.5 to 12. ε_r' of the mixture will vary between the ε_r' of dry soil and that of the added material. The measurement of attenuation and phase shift of microwaves traversing a layer of the soil sample gives ε_r' and ε_r'' [7]. The experimental setup used for the present study is shown in Fig. 1.

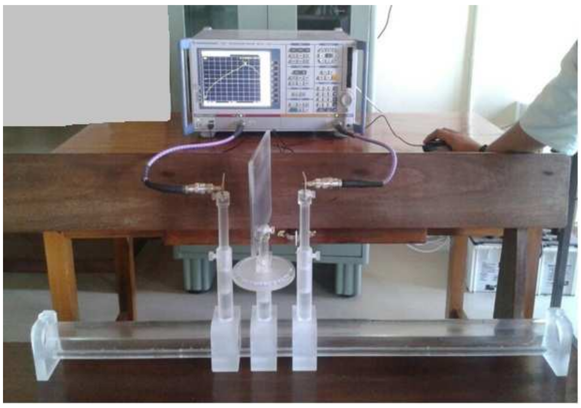

Fig. 1 Setup of free-space transmission method

A pair of identical coaxial probe-fed microstrip patch antennas (MPA) fabricated on a substrate (with ε_r' = 4.4, tan δ = 0.02 and thickness = 1.6 mm) are used as transmit/receive antennas. A sample-holder containing the soil samples whose, dielectric properties are to be determined, is placed in between the antennas. The study is conducted at three frequencies, viz. 1.88 GHz, 2.45 GHz and 5.44 GHz, in the L, S and C bands. Rohde & Schwarz ZVB8 Vector Network Analyzer (VNA) is used for measurement. The antennas are connected to the VNA. The VNA is calibrated in transmission mode (response-type calibration) with a bandwidth of 300MHz, centred on the respective resonant frequency, with the empty sample holder between the two antennas. The sample holder is a box of rectangular cross-section made of acrylic, a material with an ε_r' = 4.2 at 2.45 GHz, having dimensions 10cm x 10cm x 0.3cm. After calibrating the VNA, each soil sample is inserted into the sample holder. Measurements of magnitude and phase of transmission coefficient ($|S_{21}|$ and Φ), give the attenuation A and phase shift Φ according to equations (3) and (4), where n is an integer to be determined.

$$A = 20 \log |S_{21}| \text{ dB} \qquad (3)$$

$$\Phi = \Phi o - 2\pi n \text{ rad} \qquad (4)$$

The dielectric constant of each sample is computed using equation (5).

$$\varepsilon_r' = [(\Phi\, c/2\pi df)+1]^2 \quad (5)$$

where c is the velocity of light (m/s), f is the frequency (Hz) and d is the thickness of the layer of the soil (m).

Typical antenna geometry is shown in Fig. 2; dimensions of the antenna for the three frequencies are given in Table 1.

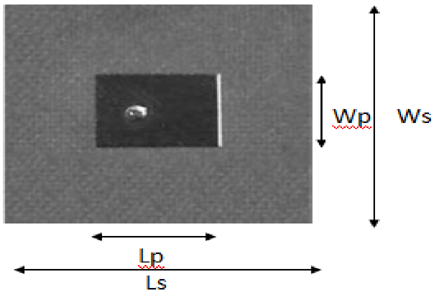

Fig. 2 Probe-fed MPA

Table -1 Dimensions of MPA

Dimensions (in cm)		Frequency, f_r (GHz)		
		1.88	2.45	5.44
Patch	L_p	4.71	2.8	1.6
	W_p	3.73	2.4	1.16
Substrate	L_s	8.4	6	3.75
	W_s	6.7	5	3.48

Two different cases are taken up for study:

a) 62 different samples of 20 ml each of soil are tested; of these, 31 samples are acidic in nature (pH below 7.0), while the rest are alkaline (pH above 7.0). All the samples are dry, powdered and fertilizer-extracted; the samples are the 'Udayamperoor' series from Ernakulam district which are moderately acidic in nature (pH between 4.7 and 6.4) and 'Anuppur'/'Agali' series from Palakkad district, which are moderately alkaline (pH between 7.0 and 7.5) [8].

b) All these samples are individually mixed with 1ml, 2ml and 5ml of four different types of commonly used fertilizers. The sample-mixtures are prepared by mixing different fertilizers in soil according to the statistics provided by the Department of Agriculture, Kerala.

RESULTS AND DISCUSSION

Values of ε_r' are found for four different cases : (a) all 9 soil samples, (b) soil mixed with all 4 fertilizers, (c) soil mixed with 3 levels of concentrations of all fertilizers - viz; 1/21 = 4.8%, 2/22 = 9.1% and 5/25 = 20% and (d) all 3 frequencies. Among these, the most relevant result which can be projected, is the variation of ε_r' at a particular frequency, for a distinct soil sample at the three fertilizer concentration levels, the four fertilizers mixed being the running parameter; a mixture ratio of 1/21 = 4.8% means 1ml fertilizer in 20ml soil. All discussions pertaining to the experiment are based on Table 2 (a to d). Results of the experiments carried out are classified into three categories. For simplicity of explanation, only 9 out of the 62 cases are taken up for discussion. Category 1 discusses the variation of ε_r' with frequency of the 9 plain soil samples with varying pH values. In category 2, the variation of ε_r' with frequency of plain soil and soil mixed with the 4 fertilizers is discussed. Category 3 discusses the variation of ε_r' values of soil-fertilizer mixture at different concentrations of the 4 fertilizers.

Table-2a ε_r' Values of Plain Soil Mixed with varying Concentrations of Powdered Boric Acid (PBA) at 3 Different Frequencies

Frequency															
1.88 GHz					2.45 GHz					5.44 GHz					
Plain Soil (20 ml)		Soil mixed with PBA			Plain Soil (20 ml)		Soil mixed with PBA			Plain Soil (20 ml)		Soil mixed with PBA			
		1ml	2ml	5ml			1ml	2ml	5ml			1ml	2ml	5ml	
pH	ε_r'	ε_r'	ε_r'	ε_r'	pH	ε_r'	ε_r'	ε_r'	ε_r'	pH	ε_r'	ε_r'	ε_r'	ε_r'	
4.7	3.98	9.15	9.26	9.34	4.7	3.90	7.79	7.93	8.05	4.7	3.84	5.59	5.67	5.74	
4.9	3.62	7.41	7.50	7.57	4.9	3.43	6.46	6.58	6.67	4.9	3.32	4.90	4.97	5.03	
5.0	3.79	7.63	7.72	7.79	5.0	3.53	6.81	6.93	7.03	5.0	3.27	5.19	5.26	5.32	
5.2	3.83	8.23	8.33	8.40	5.2	3.75	7.28	7.41	7.52	5.2	3.52	5.29	5.36	5.43	
5.8	3.76	8.72	8.82	8.90	5.8	3.68	7.48	7.61	7.73	5.8	3.45	4.91	4.98	5.04	
6.1	3.64	7.30	7.39	7.45	6.1	3.47	6.64	6.76	6.86	6.1	3.14	4.98	5.05	5.11	
6.3	3.55	7.65	7.74	7.81	6.3	3.48	6.93	7.05	7.16	6.3	3.21	4.85	4.92	4.98	
7.0	3.72	8.10	8.20	8.27	7.0	3.52	7.11	7.24	7.34	7.0	3.32	4.64	4.70	4.76	
7.4	3.80	8.26	8.36	8.43	7.4	3.58	7.62	7.76	7.87	7.4	3.3	5.33	5.40	5.47	

Table -2b $\varepsilon_r{}'$ Values of Plain Soil Mixed with varying Concentrations of Powdered NPK at 3 Different Frequencies

Frequency																		
1.88 GHz						2.45 GHz						5.44 GHz						
Plain Soil (20 ml)		Soil mixed with NPK			Plain Soil (20 ml)		Soil mixed with NPK			Plain Soil (20 ml)		Soil mixed with NPK						
		1ml	2ml	5ml			1ml	2ml	5ml			1ml	2ml	5ml				
pH	ε_r'	ε_r'	ε_r'	ε_r'	pH	ε_r'	ε_r'	ε_r'	ε_r'	pH	ε_r'	ε_r'	ε_r'	ε_r'				
4.7	3.98	3.94	4.05	4.19	4.7	3.90	4.02	4.15	4.84	4.7	3.84	3.92	3.95	4.30				
4.9	3.62	2.80	2.83	2.86	4.9	3.43	2.76	3.07	3.42	4.9	3.32	3.45	3.47	3.91				
5.0	3.79	3.68	3.87	3.90	5.0	3.53	3.18	3.24	3.58	5.0	3.27	3.03	3.68	3.99				
5.2	3.83	3.69	3.79	3.94	5.2	3.75	3.45	3.51	3.76	5.2	3.52	3.82	4.24	4.79				
5.8	3.76	3.89	3.93	4.26	5.8	3.68	3.54	3.60	3.86	5.8	3.45	3.86	4.21	4.75				
6.1	3.64	2.69	2.72	2.85	6.1	3.47	2.50	3.16	3.80	6.1	3.14	3.40	3.52	3.96				
6.3	3.55	3.47	3.59	3.93	6.3	3.48	3.27	3.33	3.98	6.3	3.21	3.85	4.01	4.44				
7.0	3.72	3.70	3.84	4.17	7.0	3.52	3.36	3.42	3.77	7.0	3.32	3.86	4.20	4.54				
7.4	3.80	3.90	4.14	4.77	7.4	3.58	3.64	3.71	4.11	7.4	3.30	3.41	3.76	3.98				

Table-2c $\varepsilon_r{}'$ Values of Plain Soil Mixed with varying Concentrations of Powdered Potash at 3 Different Frequencies

Frequency														
1.88 GHz					2.45 GHz					5.44 GHz				
Plain Soil (20 ml)		Soil mixed with Potash			Plain Soil (20 ml)		Soil mixed with Potash			Plain Soil (20 ml)		Soil mixed with Potash		
		1ml	2ml	5ml			1ml	2ml	5ml			1ml	2ml	5ml
pH	ε_r'	ε_r'	ε_r'	ε_r'	pH	ε_r'	ε_r'	ε_r'	ε_r'	pH	ε_r'	ε_r'	ε_r'	ε_r'
4.7	3.98	4.26	4.31	4.35	4.7	3.90	4.22	4.30	4.36	4.7	3.84	4.13	4.19	4.24
4.9	3.62	3.47	3.51	3.84	4.9	3.43	3.37	3.53	3.58	4.9	3.32	3.22	3.68	3.72
5.0	3.79	3.64	3.75	4.08	5.0	3.53	3.41	3.71	3.76	5.0	3.27	3.50	3.89	3.94
5.2	3.83	3.99	4.12	4.65	5.2	3.75	3.95	4.02	4.08	5.2	3.52	3.92	3.97	4.02
5.8	3.76	4.18	4.48	4.81	5.8	3.68	4.04	4.11	4.17	5.8	3.45	3.57	3.62	3.66
6.1	3.64	3.88	4.08	4.31	6.1	3.47	3.68	3.61	3.67	6.1	3.14	3.55	3.73	3.78
6.3	3.55	3.98	4.18	4.49	6.3	3.48	3.74	3.81	3.86	6.3	3.21	3.56	3.61	3.65
7.0	3.72	3.90	3.98	4.28	7.0	3.52	3.83	3.90	3.96	7.0	3.32	3.37	3.42	3.46
7.4	3.80	4.28	4.49	4.67	7.4	3.58	4.12	4.19	4.26	7.4	3.30	3.92	3.97	4.02

Table-2d $\varepsilon_r{}'$ Values of Plain Soil Mixed with varying Concentrations of Powdered Urea at 3 Different Frequencies

Frequency														
1.88 GHz					2.45 GHz					5.44 GHz				
Plain Soil (20 ml)		Soil mixed with Urea			Plain Soil (20 ml)		Soil mixed with Urea			Plain Soil (20 ml)		Soil mixed with Urea		
		1ml	2ml	5ml			1ml	2ml	5ml			1ml	2ml	5ml
pH	ε_r'	ε_r'	ε_r'	ε_r'	pH	ε_r'	ε_r'	ε_r'	ε_r'	pH	ε_r'	ε_r'	ε_r'	ε_r'
4.7	3.98	4.28	4.35	4.69	4.7	3.90	3.98	4.05	4.34	4.7	3.84	3.88	4.06	4.29
4.9	3.62	3.86	3.97	4.16	4.9	3.43	3.84	3.94	4.20	4.9	3.32	3.69	3.74	4.11
5.0	3.79	3.89	3.97	4.22	5.0	3.53	3.67	3.86	4.16	5.0	3.27	3.38	3.61	3.86
5.2	3.83	4.17	4.21	4.84	5.2	3.75	3.97	4.13	4.38	5.2	3.52	3.77	3.85	4.11
5.8	3.76	3.96	4.04	4.47	5.8	3.68	3.85	3.99	4.27	5.8	3.45	3.62	3.79	4.19
6.1	3.64	3.81	3.98	4.24	6.1	3.47	3.57	3.73	4.14	6.1	3.14	3.48	3.56	3.94
6.3	3.55	3.77	3.97	4.29	6.3	3.48	3.62	3.88	4.08	6.3	3.21	3.43	3.52	3.86
7.0	3.72	3.94	4.09	4.62	7.0	3.52	3.98	4.13	4.31	7.0	3.32	3.55	3.72	3.98
7.4	3.80	3.91	4.15	4.48	7.4	3.58	3.66	3.71	3.99	7.4	3.30	3.51	3.76	3.89

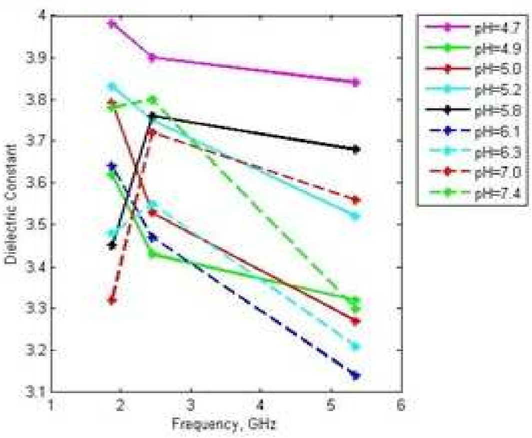

Fig. 3 Plot of $\varepsilon_r{}'$ of soil samples at 1.88, 2.45 and 5.44 GHz

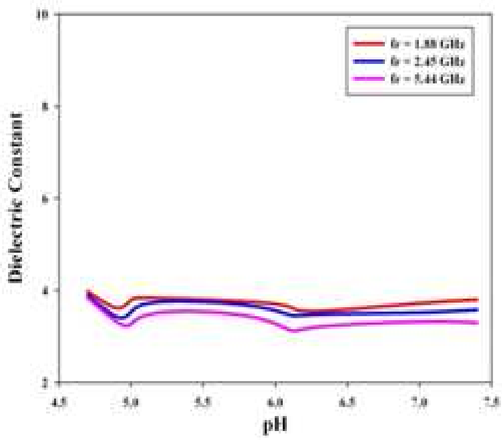

Fig. 4a $\varepsilon_r{}'$ vs pH of all plain soil samples

The variation of ε_r' with frequency of the 9 plain soil samples with varying pH values is plotted in Fig. 3. It is seen that there is a variation in ε_r' with frequency for all samples. All soil samples are mixed with 1ml of all the four fertilizers. Variation of ε_r' with frequency of the soil-fertilizer mixture at the three frequencies is plotted as in Figs. 4(a to e). As f_r increases from 1.88 GHz to 5.44 GHz, ε_r' of soil-boric sample decreases from 9.15 to 5.59 for the pH = 4.7 soil sample. For all the soil samples, ε_r' decreases. This trend of decrease in ε_r' value for increase in frequency is shown by all the other soil-fertilizer combinations also.

Before the analysis of these results is made, it is important to know the ε_r' values of the constituents of the fertilizers used. Values are given in Table 3 [9]. Since all the fertilizers are powdered and dry - with no trace of moisture - the mixtures are expected to display dielectric properties that are present in the constituent materials. For the four different cases of soil mixed with the powdered fertilizers, it can be seen that the variation is in accordance with the mixing rule [10]. The variation is maximum for powdered boric acid and minimum for NPK for most of the cases. This is to be expected as powdered boric acid has the highest ε_r' value and NPK, the lowest.

Table-3 ε_r' values of some common fertilizers

Fertilizer	ε_r'
Boric Acid Powder	11.8
Nitrogen, N	1.5
Phosphorus, P	4.1
Potassium, K	5.0
Urea	3.5

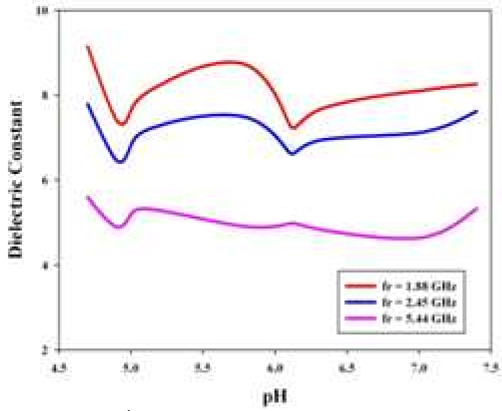

Fig. 4b ε_r' vs pH of Soil-Boric powder mixture

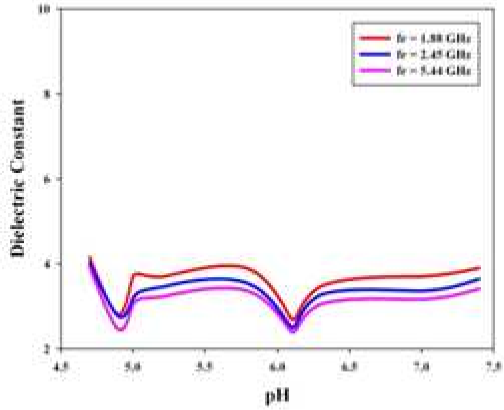

Fig. 4c ε_r' vs pH of Soil-NPK mixture

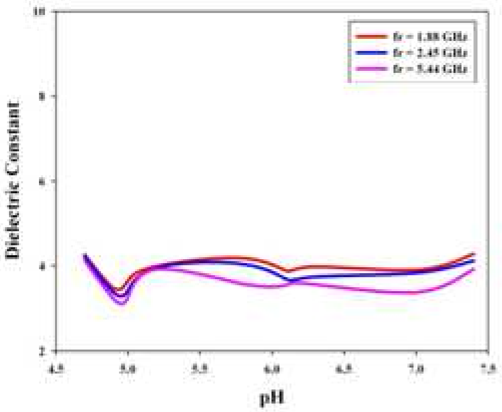

Fig. 4d ε_r' vs pH of Soil-Potash mixture

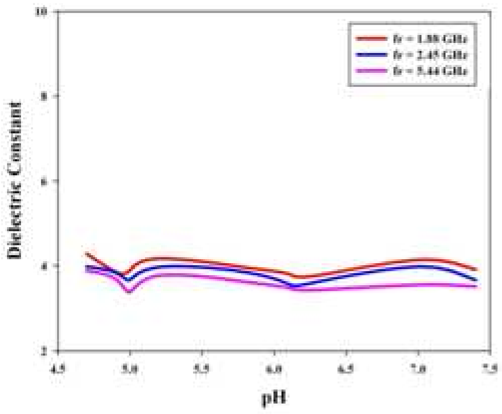

Fig. 4e ε_r' vs pH of Soil-Urea mixture

Finally, the variations in values of ε_r' with percentage variation of concentration levels of fertilizer content are plotted in Figures 5 (a to i), for each soil sample at f_r = 1.88GHz. A notable feature is that higher fertilizer contents have higher ε_r' as compared to that of lower fertilizer contents at this frequency. This is exhibited at the other frequencies too. Fertilizers increase the pore space of the soil. Due to more pore space, ε_r' increases and the fertility of soil is also increased. The different types of fertilizers have different organic components. Soil is also affected by these different organic components.

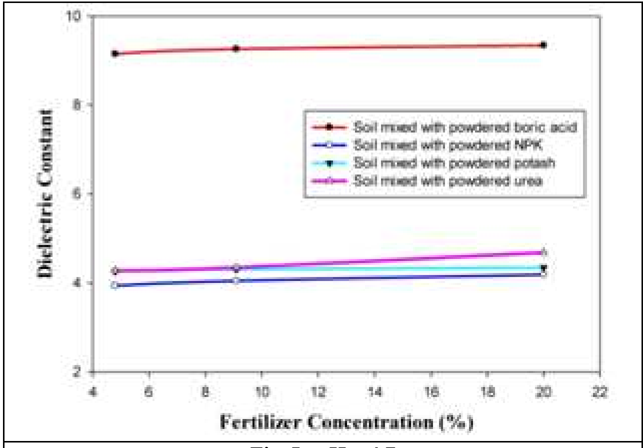

Fig. 5a pH = 4.7

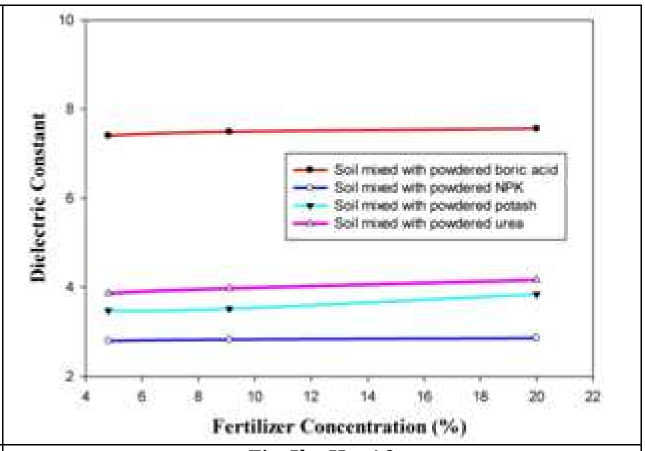

Fig. 5b pH = 4.9

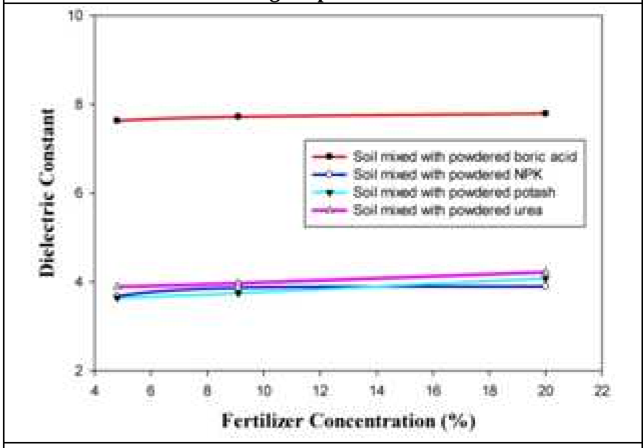

Fig. 5c pH = 5.0

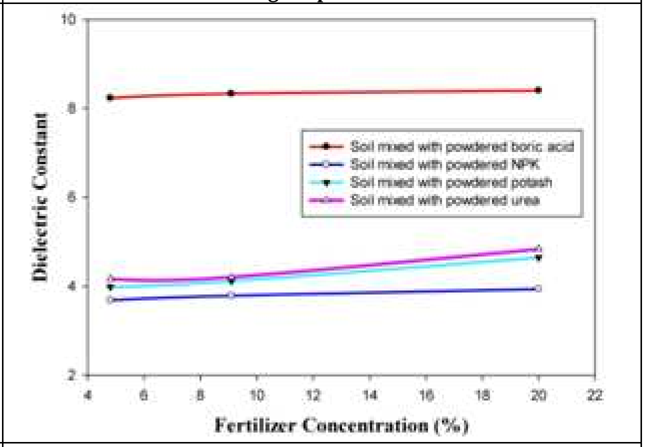

Fig. 5d pH = 5.2

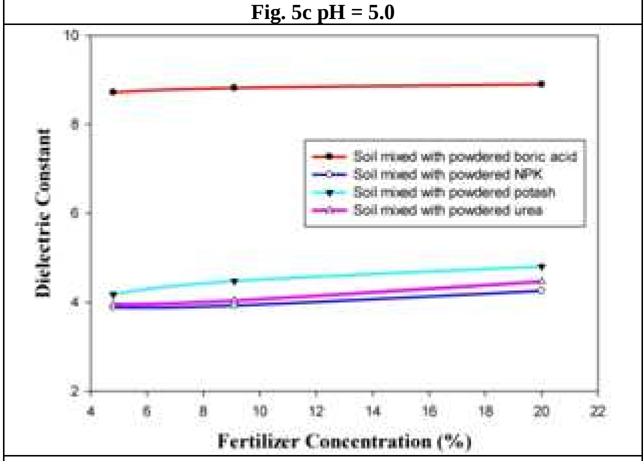

Fig. 5e pH = 5.8

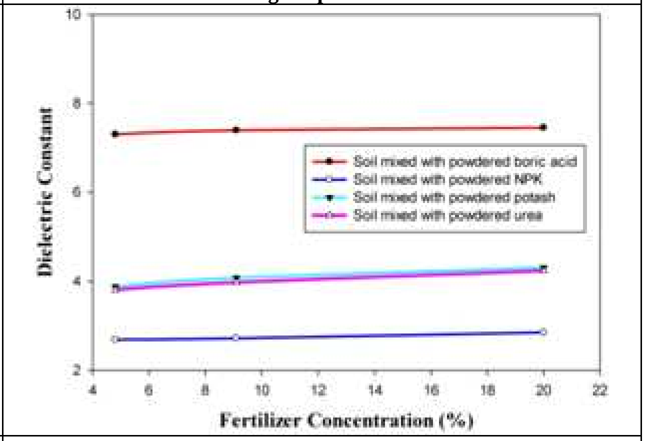

Fig. 5f pH = 6.1

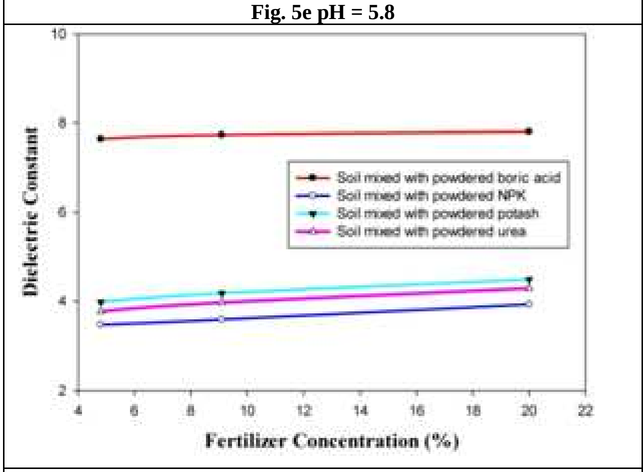

Fig. 5g pH = 6.3

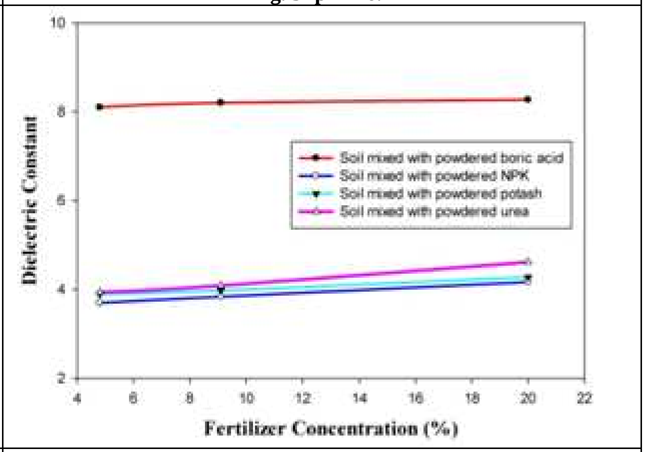

Fig. 5h pH = 7.0

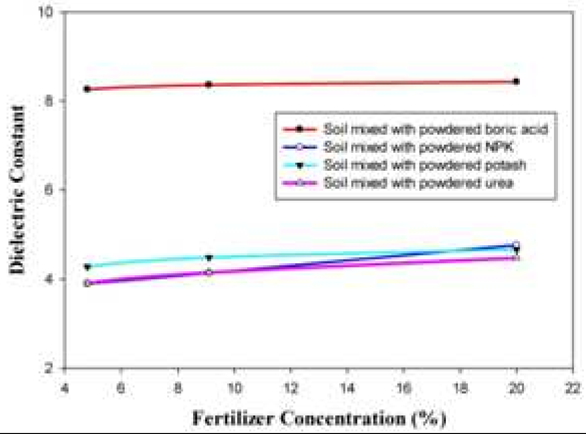

Fig. 5i pH = 7.4

CONCLUSIONS

The paper explores the relevance of usage of microwave frequencies for the dielectric-property extraction of soil. Study of the properties of dry and fertilized soil at microwave frequencies is useful in agriculture. Soil pH and availability and supply of nutrients are interrelated. Through this paper, dielectric constant values of a variety of soil samples, each with varying pH and TSS are measured, both at fixed and varying fertilizer-concentrations at the L, S and C-band frequencies. It has been observed that the dielectric constant of plain soil and soil mixed with fertilizers decreases with increase in frequency in the microwave band. The results obtained are useful for predicting the fertility of soil. It is also observed that at a given frequency of measurement, the dielectric constant of soil-fertilizer mixture increases with increase in fertilizer concentration. It is further concluded that the free-space transmission technique can be conveniently used along with a simple microstrip patch antenna and a suitable sample-holder for the study of soil properties. This study on the dielectric properties of dry and fertilized soils is thus useful not only in designing microwave sensors of soil-moisture estimation, but also needed in predicting the structure and chemical composition of soils. This data is helpful in designing sensors for microwave remote sensing and for the retrieval of soil-moisture content from the remotely-sensed satellite data. Hence, research in this area will enrich our knowledge of soil science and will prove beneficial to the agriculturists.

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