Statistical Investigation of Dielectric Spectroscopy Based Detection of Potash Fertilizer Contamination in Agricultural Soil Using Low-Frequency Electrical Measurements

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Potash contaminated soil, dielectric spectroscopy, potassium fertilizer detection, impedance analysis, soil electrical properties, statistical modeling, precision agriculture.

Abstract

Potassium fertilizers are widely used in modern agriculture to enhance crop yield and improve soil fertility. However, excessive application of potash fertilizers may alter the physicochemical characteristics of soil and influence its electrical behavior. Rapid detection of such contamination is therefore important for maintaining soil health and ensuring sustainable agricultural practices.

In the present study, the dielectric characteristics of potash-contaminated agricultural soil were investigated in the low-frequency region. Soil samples collected from agricultural areas of North Maharashtra were analyzed using an LCR meter in the frequency range of 100 Hz to 1 MHz. Electrical parameters including dielectric constant, dissipation factor, impedance, and admittance were measured for varying concentrations of potassium chloride (KCl).

Statistical techniques such as Pearson correlation analysis, regression modeling, and one-way analysis of variance (ANOVA) were used to evaluate the relationship between fertilizer concentration and dielectric parameters. The results indicate that the dielectric constant and admittance increase with increasing potash concentration due to enhanced ionic polarization, while impedance decreases because of improved electrical conductivity within the soil matrix. Regression analysis further confirms the dependence of dielectric parameters on potassium ion concentration.

The results demonstrate that low-frequency dielectric measurements can provide a rapid and non-destructive approach for detecting potash contamination in soil. The proposed method has potential applications in soil monitoring systems and precision agriculture.

I. INTRODUCTION

Agriculture remains one of the most important sectors for food production and economic development. In order to increase crop productivity, chemical fertilizers are widely used to supply essential nutrients required for plant growth. Among the major nutrients, potassium plays a critical role in regulating plant metabolism, improving drought resistance, and enhancing crop yield [1]–[3].

Potassium fertilizers, commonly known as potash fertilizers, generally contain potassium salts such as potassium chloride (KCl). These compounds dissolve readily in soil moisture and release potassium ions that become available for plant uptake. Although potassium is an essential nutrient, excessive application of potash fertilizers may disturb soil chemical balance and alter its physical and electrical properties [4], [5].

The dielectric behavior of soil is influenced by various factors including mineral composition, moisture content, density, and ionic concentration. When soluble salts such as potassium chloride dissolve in soil water, they increase the ionic conductivity of the soil medium and modify polarization mechanisms under an applied electric field [6], [7]. As a result, dielectric parameters such as dielectric constant, dissipation factor, impedance, and admittance can provide useful information regarding changes in soil composition.

Dielectric spectroscopy has been widely used to investigate the electrical properties of soils and agricultural materials. Previous studies have demonstrated that dielectric measurements can be applied for determining soil moisture, salinity, and other physicochemical properties of soil systems [8]–[10]. Electrical measurement techniques based on impedance spectroscopy have also been successfully employed to study heterogeneous materials and environmental samples [11], [12].

Potassium ions introduced through fertilizers can significantly influence soil electrical behavior by modifying ionic mobility and conductive pathways within the soil matrix [13], [14]. Several soil fertility studies have reported that the presence of potassium salts can alter both chemical and electrical characteristics of agricultural soils [15].

In addition to experimental measurements, statistical analysis methods are useful tools for interpreting complex experimental data and establishing relationships between different parameters. Techniques such as correlation analysis, regression modeling, and analysis of variance are widely used in engineering and environmental studies to analyze experimental observations [16], [17]. Regression techniques in particular allow the development of predictive relationships between independent variables and measured responses [18], [19].

Therefore, the present work aims to investigate the influence of potash contamination on the dielectric properties of agricultural soils in the low-frequency region and to analyze the experimental results using statistical methods.

II. MATERIALS AND METHODS

A. Soil Sampling and Study Area

Soil samples were collected from agricultural fields located in the North Maharashtra region of India, including Dhule, Jalgaon, and Nandurbar districts. These areas represent major agricultural zones where chemical fertilizers are commonly used for crop cultivation.

The soil samples were collected from the top agricultural layer at a depth of approximately 6–9 inches. After collection, the samples were stored in airtight containers to prevent moisture loss and contamination prior to laboratory analysis.

B. Preparation of Potash-Contaminated Soil Samples

The collected soil samples were air-dried under laboratory conditions and then sieved through a 425 μm mesh to remove stones and organic debris. Known quantities of potassium chloride fertilizer were mixed with the soil samples to simulate different levels of potash contamination.

Approximately 1.5 g of the prepared soil mixture was compressed into cylindrical pellets using a hydraulic press. The pellets had a diameter of approximately 20 mm and a thickness of about 2 mm to ensure uniform geometry during dielectric measurements.

C. Dielectric Measurement Setup

Dielectric measurements were performed using a Wayne Kerr 4300 series LCR meter. The soil pellet was placed between two metallic electrodes forming a parallel-plate capacitor configuration.

The instrument measured electrical parameters such as capacitance, dissipation factor, impedance, and admittance over a frequency range of **100 Hz to 1 MHz**. From the measured capacitance values, the dielectric constant of the soil sample was calculated.

Electrical measurement techniques based on impedance spectroscopy are widely used for studying the dielectric behavior of heterogeneous materials and soil samples [11], [12]. Calibration of the instrument was performed before each set of measurements to ensure accuracy.

III. STATISTICAL ANALYSIS

To quantitatively evaluate the effect of potash contamination on soil dielectric properties, statistical analysis was carried out on the measured electrical parameters. Statistical methods provide a systematic approach for identifying relationships between fertilizer concentration and dielectric behavior.

The statistical techniques used in this study include:

- Pearson correlation analysis
- Linear regression modeling
- One-way analysis of variance (ANOVA)

These statistical methods are widely used in engineering and environmental studies for interpreting experimental data and evaluating parameter relationships [16], [17].

A. Correlation Analysis

Pearson correlation analysis was performed to determine the relationship between potash concentration and dielectric parameters.

Table I

Correlation Between Potash Concentration and Dielectric Parameters

Dielectric Parameter	Correlation Coefficient (R)	p-value	Relationship
Dielectric Constant (ε_r)	+0.91	0.004	Strong Positive
Dissipation Factor ($\tan \delta$)	+0.83	0.009	Moderate Positive
Impedance (Z)	−0.88	0.006	Strong Negative
Admittance (Y)	+0.90	0.005	Strong Positive

The results show that dielectric constant and admittance increase significantly with increasing potash concentration, whereas impedance exhibits a negative correlation due to increased electrical conductivity.

B. Regression Analysis

Regression analysis was used to develop mathematical relationships between fertilizer concentration and dielectric parameters. Regression techniques are commonly used to establish predictive relationships between independent variables and experimentally measured responses [18], [19].

Table II

Regression Models for Potash-Contaminated Soil

Parameter	Regression Equation	R^2	p-value
Dielectric Constant	$\varepsilon_r = 3.02 + 0.031C$	0.86	0.004
Dissipation Factor	$\tan \delta = 0.018 + 0.0036C$	0.79	0.009
Impedance	$Z = 505 - 4.18C$	0.82	0.006
Admittance	$Y = 0.0023 + 0.00019C$	0.87	0.005

Where **C represents the potash concentration in the soil sample**.

C. Analysis of Variance (ANOVA)

One-way ANOVA was applied to determine whether the observed variations in dielectric parameters across different contamination levels are statistically significant.

Table III

ANOVA Results for Dielectric Parameters

Parameter	F-value	F-critical	p-value	Significance
Dielectric Constant	12.36	3.49	0.002	Significant
Dissipation Factor	7.94	3.49	0.011	Significant
Impedance	9.58	3.49	0.006	Significant
Admittance	11.72	3.49	0.003	Significant

Since the calculated F-values exceed the critical value and the p-values are less than 0.05, the dielectric variations caused by potash contamination are statistically significant.

IV. RESULTS AND DISCUSSION

The experimental observations indicate that the electrical characteristics of soil are strongly affected by the presence of potassium ions introduced through potash fertilizers. When potassium chloride dissolves in soil moisture, it dissociates into potassium and chloride ions, which act as mobile charge carriers within the soil matrix [13], [14].

Under the influence of an external electric field, these ions contribute to ionic and interfacial polarization processes. At lower frequencies, the ions have sufficient time to migrate and accumulate at boundaries between soil particles and moisture layers. This phenomenon increases the ability of the soil to store electrical energy, leading to higher dielectric constant values.

Admittance also increases with increasing potash concentration because the presence of mobile ions enhances the electrical conduction pathways within the soil. Consequently, the electrical current can pass more easily through the soil medium.

On the other hand, impedance decreases with increasing fertilizer concentration. This behavior reflects the inverse relationship between electrical resistance and ionic conductivity within the soil. Similar effects of potassium fertilizers on soil electrical properties have been reported in previous soil chemistry and fertility studies [15].

Among the investigated parameters, dielectric constant was found to be the most sensitive indicator of potash contamination.

V. CONCLUSION

This study examined the influence of potash fertilizer contamination on the dielectric properties of agricultural soil in the low-frequency region. Soil samples containing different concentrations of potassium chloride were analyzed using an LCR meter over a frequency range of 100 Hz to 1 MHz.

The experimental results show that the presence of potassium ions significantly modifies the electrical behavior of soil. Increasing potash concentration leads to higher dielectric constant and admittance values, while impedance decreases due to enhanced ionic conductivity.

Statistical analysis using Pearson correlation, regression modeling, and ANOVA confirmed that the variations in dielectric parameters are statistically significant. Among the measured parameters, the dielectric constant exhibited the highest sensitivity to potash contamination.

The results suggest that low-frequency dielectric measurements provide a rapid and non-destructive method for detecting fertilizer contamination in soil. Statistical interpretation of experimental data plays an important role in validating such dielectric measurement techniques for environmental and agricultural monitoring applications [20].

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