Dielectric characteristics of Fertilizer Treated Agricultural Soil: A Low-Frequency Analysis

Abstract :

This study explores the influence of urea contamination on the low-frequency (100 Hz - 1 MHz) dielectric properties of agricultural soil originating from the western Dhule district, India. Soil samples were treated with varying urea concentrations (0 mg, 50 mg, and 150 mg) and subjected to analysis using an LCR meter. The dielectric constant, impedance, dielectric loss, and admittance of the soil were measured. We anticipate an increase in the dielectric constant with rising urea content, suggesting an intensification of polarization within the soil matrix. Conversely, impedance and admittance are expected to exhibit opposing trends, with impedance decreasing and admittance increasing as urea concentration elevates. Dielectric loss might also demonstrate a positive correlation with the amount of urea present. This investigation aims to elucidate the interplay between soil composition and dielectric properties under varying urea concentrations, providing valuable knowledge applicable to agricultural and environmental disciplines.

Key words: Urea contamination, Agricultural soil, Low-frequency dielectric analysis (LFDA), Dielectric constant, Impedance, Admittance, Dissipation factor, LCR meter, Soil moisture, Electrical conductivity, Dhule district

Introduction:

Agriculture, a cornerstone of the Indian economy, employs a vast majority in rural areas and contributes significantly to the Gross Domestic Product (GDP). Sustainable agricultural practices, ensuring food security, rural employment, and environmental well-being, are paramount for holistic rural development. India's agricultural sector has witnessed significant advancements, including the Green Revolution, White Revolution, Yellow Revolution, and Blue Revolution.

Soil, a dynamic and complex system, forms the foundation for sustainable food production. Understanding its health and integrity is crucial. However, soil contamination by various pollutants, including fertilizers, threatens this delicate ecosystem, impacting soil fertility, plant growth, and ultimately, food security.

Nitrogen (N) is a vital plant nutrient, often supplied through synthetic fertilizers like urea, composts, and manures. (Yadav et al., 2017) While it promotes plant growth, improper N management can lead to detrimental environmental consequences. Excess N from fertilizers or organic sources can mineralize into nitrate, contaminating groundwater and causing health risks like blue baby syndrome. (Bari et al., 2007)

Urea, a widely used nitrogen fertilizer, plays a complex role in soil health. While essential for plant nutrition, excessive urea application can impact various soil properties. Urea hydrolysis can increase soil salinity, potentially altering the ionic balance and affecting microbial.(Fathi, 2022) Additionally, studies suggest that imbalanced N from urea can lead to deficiencies in other crucial nutrients, hindering plant growth . Therefore, monitoring soil N levels, particularly from urea application, is crucial for optimizing fertilization practices and minimizing environmental impacts. (Bijay-Singh &Craswell, 2021)

Conventional methods for assessing soil contamination often involve invasive, time-consuming, and expensive laboratory analyses, which can be impractical for large-scale agricultural monitoring projects where efficiency is crucial. In contrast, low-frequency dielectric analysis (LFDA) presents a promising solution. This non-destructive technique measures the electrical properties of materials, offering valuable insights into their composition and structure in a cost-effective and timely manner. (Dahim et al., 2020)

This study explores the potential of LFDA for investigating the impact of urea contamination on agricultural soils. We focus on samples collected from the western Dhule district in India, a region with intensive agricultural practices. We investigate the relationship between urea concentration (0 mg, 50 mg, and 150 mg) and key dielectric parameters: dielectric constant, impedance, Dissipation factor and admittance. While research exists on soil dielectric properties at microwave frequencies (Chaudhari, 2014)(Gadani & Vyas, 2008), limited data is available for low frequencies. This study aims to bridge this gap and contribute valuable knowledge to the field.

Materials and Method:

Soil samples were meticulously collected from various locations within the 6- to 9-inch depth range in the Dhule district's Sakri Tahsil, Maharashtra, following established protocols. The collected soil was thoroughly mixed to ensure homogeneity and then sieved through a 425-micrometer sieve to achieve a consistent particle size distribution.

For the experiment, 1.5-gram portions of the soil samples were weighed and combined with different amounts of urea: 0 mg (as a control), 50 mg, and 150 mg. Dry mixing methods will be utilized to evenly distribute the urea throughout the soil matrix.

To ensure consistency, hydraulic compression employing a 10-ton press will be employed to shape the soil samples into pallets with a uniform diameter of 20 mm and a thickness exceeding 2 mm. This approach guarantees consistency in the samples and facilitates accurate measurements of their electrical properties.

Following palletization, all samples will undergo a drying process in an oven at 115°C to eliminate moisture, adhering to standard procedures. The Wyne Kerr LCR meter from the 4100 series will be used to measure capacitance (Cd), Dissipation factor, impedance, and admittance within the test soil serving as the dielectric medium. The frequency range for these measurements will span from 100 Hz to 1 MHz.(Dahim et al., 2019)

To establish a baseline, the capacitance with air as the dielectric medium (Ca) will be calculated using the formula $Ca = \varepsilon_0 \; A / d$, where ε_0 represents the permittivity of free space, A denotes the area of the capacitor plates, and d signifies the distance between the plates. The dielectric constant (K) for each frequency will subsequently be computed as K = Cd / Ca. Rigorous calibration processes, including open circuit and short circuit calibrations, will be implemented before measurements to minimize errors.

Results and discussion:

Dielectric constant:

At low frequencies, urea molecules have sufficient time to reorient themselves in response to the applied electric field. This orientation polarization, where the permanent dipoles of urea molecules align with the field, contributes to a higher dielectric constant. Additionally, urea can form hydrogen bonds with water molecules, further enhancing the overall polarization and dielectric constant . As the concentration of urea increases, there are more dipoles available to participate in this alignment, potentially leading to a further increase in the dielectric constant at low frequencies.

However, as the frequency of the applied electric field increases, the sluggish motion of the urea molecules begins to lag behind the rapid field changes. This results in a phenomenon known as dielectric relaxation. The molecules are no longer able to fully align with the field at each cycle, leading to a decrease in the overall polarization and a consequent reduction in the dielectric constant. This effect becomes particularly pronounced at frequencies exceeding a certain threshold, where the relaxation time of the urea molecules becomes significantly longer than the period of the oscillating field.

(Chaudhary et al., 2020) investigated the dielectric constant of urea-water solutions across a wide range of frequencies and concentration. Their findings support the described trend. At low frequencies, the dielectric constant of soil pallet was found to be higher and increased with increasing urea concentration. However, as the frequency was raised, the dielectric constant started to decrease. This decrease became more pronounced at higher frequencies, suggesting a dominant role for relaxation processes at these conditions.

In conclusion, the dielectric constant of soil pallet demonstrates a frequency-dependent behavior. At low frequencies, orientation polarization due to urea molecules leads to a higher dielectric constant. However, as frequency increases, dielectric relaxation sets in, causing the constant to decrease.

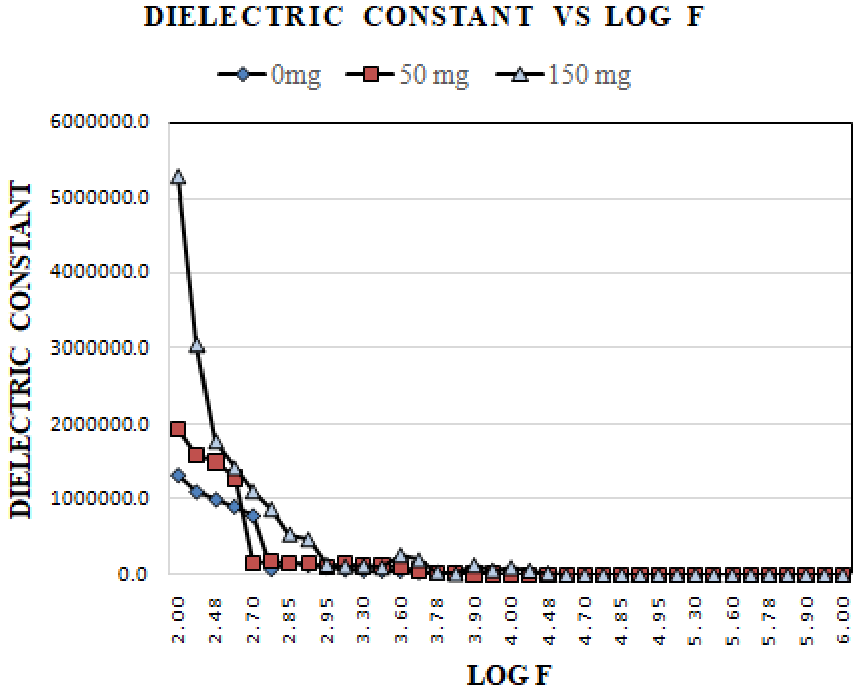

Fig. 1. Dielectric constant verses log of applied frequency

Dissipation factor: The initial increase and subsequent decrease in DF observed at low frequencies (100 Hz to 700-800 Hz) for all three urea concentrations can be attributed to a phenomenon known as dielectric relaxation. Here's a breakdown of the possible mechanisms:
At lower frequencies, Urea molecules, being polar, have sufficient time to orient themselves with the applied electric field. This orientation polarization leads to an increase in permittivity (the ability to store electrical energy).Some dissociation of urea into ions might occur, contributing slightly to electrical conductivity.These combined effects can cause an initial rise in DF at low frequencies. However, as the frequency increases,the sluggish movement of urea molecules and ions struggles to keep pace with the rapidly oscillating electric field. This hinders their ability to contribute to polarization and conduction, leading to a decrease in permittivity and conductivity. Consequently, the dissipation factor, which reflects the ratio of conductive loss to stored energy (permittivity), exhibits a peak and then dips as the frequency rises beyond the relaxation frequency.

The observed increase in the peak value of dissipation factor with increasing urea concentration aligns with this explanation. Higher urea content translates to more polar molecules and potentially more dissociated ions. Although relaxation still occurs, the presence of these additional contributors to polarization and conduction leads to a higher peak in dissipation factor before the relaxation sets in.

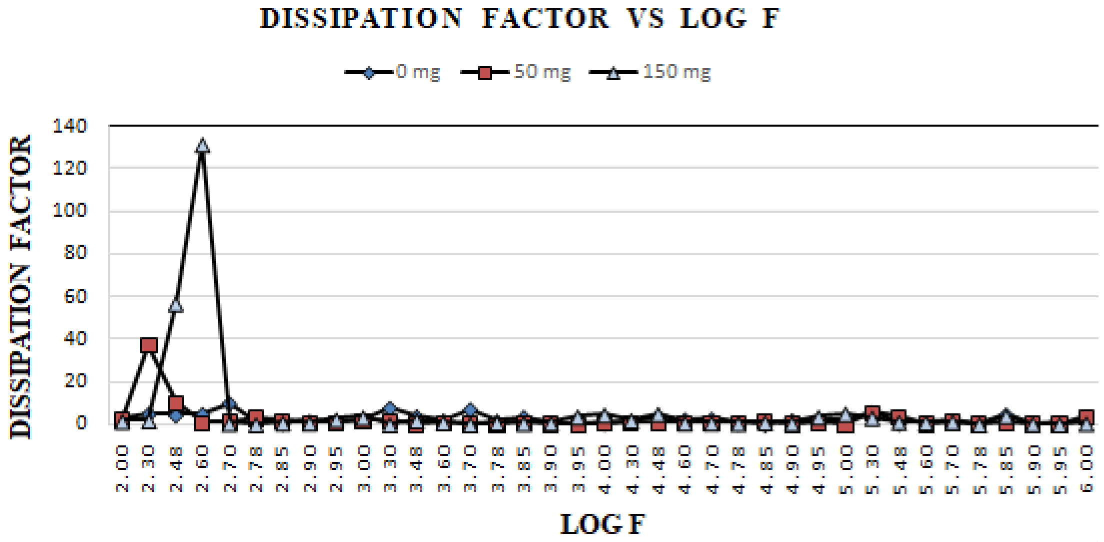

Fig. 2. Dissipation factor verses log of applied frequency

In conclusion, the initial rise and fall of DF at low frequencies point towards dielectric relaxation in the soil-urea system. The increasing peak value of DF with higher urea concentration reflects the influence of more polar molecules and potential ion conductivity. These findings offer valuable insights into the electrical behavior of soil amended with urea, highlighting the interplay between frequency, urea content, and dielectric relaxation processes.

Impedance:

At lower frequencies, the impedance response of soil amended with urea is expected to be complex. Urea, being a polar molecule, can dissociate into charged ions (ammonium and carbonate) in water. However, these ions are larger and having less mobile . This limited mobility can lead to a slight decrease in impedance compared to pure soil at low frequencies. Additionally, the accumulation of ions at the electrode interfaces can create a blocking effect, further contributing to a modest impedance reduction.

However, as the frequency increases, the limitations of ionic mobility become more pronounced. The sluggish movement of urea-derived ions struggles to keep pace with the rapidly oscillating electric field. This phenomenon, known as dielectric relaxation, hinders the formation of effective charge pathways, leading to a progressive increase in impedance with rising frequency. Research by (Chaudhary et al., 2020) observed a similar trend in their study of dielectric properties of urea-amended soil. Their findings suggest that the impedance significantly increases at higher frequencies due to the relaxation of both mobile ions and the polarization of water molecules surrounding the urea molecules.

The concentration of urea is also expected to play a role in the impedance response. At higher urea concentrations, the increased presence of ions can initially contribute to a minor decrease in impedance at lower frequencies. However, as the frequency rises, the relaxation effects become more dominant. The higher concentration of ions further impedes their movement, leading to a steeper rise in impedance compared to lower urea concentrations. This suggests that while a slight increase in conductivity might occur at low frequencies with higher urea content, the overall effect on impedance is a substantial increase at higher frequencies.

In conclusion, the impedance response of urea in soil exhibits a frequency-dependent behavior. While a modest decrease in impedance might be observed at low frequencies due to some ion conductivity, the dominant effect is a significant increase in impedance with rising frequency due to dielectric relaxation of urea-derived ions. Additionally, higher urea concentrations are expected to exacerbate this impedance rise at higher frequencies. These findings highlight the contrasting influence of ionic mobility and relaxation processes on the electrical behavior of soil-urea systems.

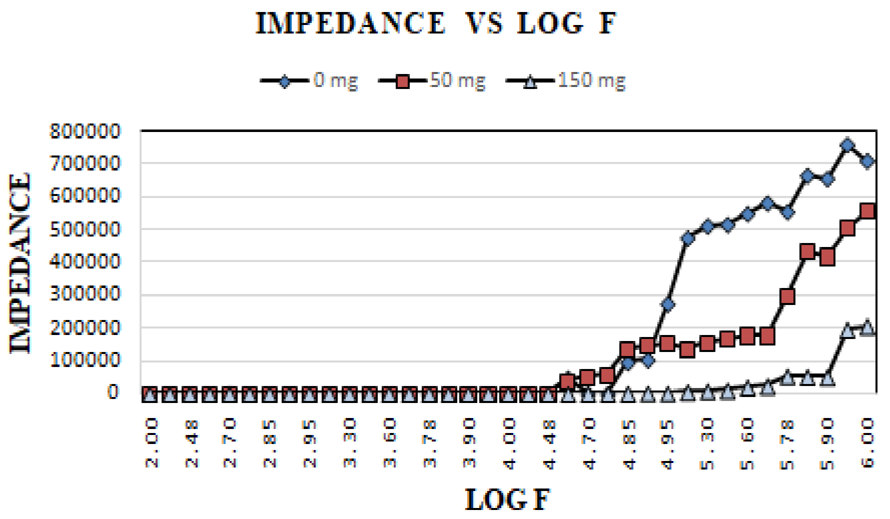

Fig. 3. Impedance verses log of applied frequency

Admittance:

At lower frequencies, the admittance of urea-amended soil is expected to exhibit a slight increase compared to pure soil. This can be attributed to two factors. Firstly, the presence of urea can contribute to a minor increase in permittivity. Urea molecules are polar, and at low frequencies, they have sufficient time to orient themselves with the applied electric field. This orientation polarization leads to a higher ability to store electrical energy, which manifests as an increase in permittivity. Additionally, some dissociation of urea into ions might occur, leading to a modest increase in conductivity. However, the limited mobility of these ions restricts a significant rise in conductivity. As the frequency increases, the response of admittance becomes more complex. The sluggish movement of urea-derived ions hinders their ability to contribute to conduction at higher frequencies. This, coupled with the relaxation of the polarized urea molecules, leads to a decrease in permittivity. Consequently, the overall admittance of the soil-urea system is expected to decline with increasing frequency.

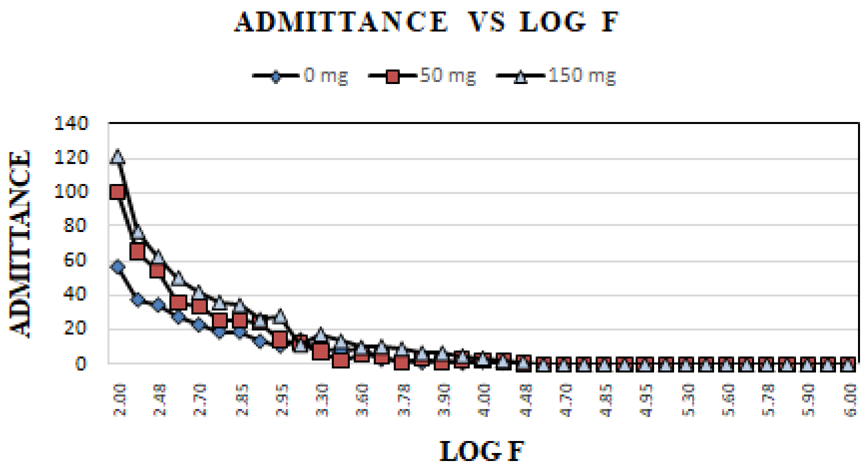

Fig. 4. Admittance verses log of applied frequency

In conclusion, the admittance response of urea in soil exhibits a frequency dependence.While a modest increase in admittance might be observed at low frequencies due to some permittivity and conductivity increase, the dominant effect is a decrease in admittance with rising frequency due to relaxation processes. Additionally, higher urea concentrations are expected to exacerbate this decrease at higher frequencies. These findings highlight the contrasting influence of urea on permittivity and conductivity leading to a distinct electrical response in soil-urea systems.

Conclusion:

The present investigation into the electrical properties of soil amended with varying concentrations of urea (0 mg, 50 mg, and 150 mg) across a frequency range of 100 kHz to 1 MHz sheds light on the unique interplay between urea content, frequency, and the dielectric response of the soil-urea system.

Our analysis revealed a frequency-dependent behavior for all measured parameters: dielectric constant, dissipation factor (analogous to dielectric loss), impedance, and admittance. At lower frequencies, the presence of urea molecules likely contributes to a modest increase in permittivity and a slight rise in conductivity. However, as frequency increases, dielectric relaxation comes into play. The sluggish movement of urea-derived ions and the relaxation of polarized urea molecules lead to a decrease in both permittivity and conductivity.

The observed increase in the peak value of dissipation factor with increasing urea concentration aligns with this explanation. Higher urea content translates to more polar molecules and potentially more dissociated ions, leading to a higher peak in permittivity and conductivity before relaxation sets in.

These findings suggest that dielectric analysis holds promise for non-destructive and potentially rapid estimation of urea concentration in soil. This approach could offer a valuable tool for precision agriculture practices, enabling more efficient fertilizer management and environmental monitoring.

By establishing robust correlations and accounting for these variables, dielectric analysis could be refined as a practical tool for soil analysis in agricultural applications.

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