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Research Article

Soil Dielectric Properties in the Context of Heavy Metal Contamination and Agricultural Productivity: A Review

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ABSTRACT

Dielectric properties of industrial soil at microwave frequencies are very important to understand its behavior in different applications such as telecommunications and remote sensing. These characterist,ics determine how soil affects the signal transmission and attenuation in a wireless communication system by modifying the way the electromagnetic radiation interacts with the soil. Knowing the dielectric constant and loss tangent of industrial soil can improve methods of antenna design optimization, radar signal interpretation, and assessment of soil moisture. A typical step in examining these properties is the complex permittivity of soil samples at various temperatures and moisture levels, which provides significant information into how well the samples operate in practical settings. Accurate soil classification is important in the development of land management plans, environmental monitoring systems, and more efficient agricultural operations. Industrial soil's dielectric qualities are critical for agricultural and remote sensing applications.

1 Introduction

Soil, one of the vital resource for life on the planet (for biodiversity, agriculture and human life) is so far safe just pending before the effects of industrial developments and overexploitations of plants to which Soil gets polluted and contaminated by heavy metals and chemicals especially in the vicinity of waste sites. Soil dielectric properties (responsiveness of soil to an electric field) is an important approach for pollution detection, moisture sensing and agriculture advancement. The variations of these properties as a result of the soil texture, the water content, the replacement of the minerals etc. can be detected in-depth using ground penetrating radar (GPR) and dielectric spectroscopy (DS). Covering recent insights in soil electromagnetic behavior, this review elaborates how their understanding could be used for detecting pollutions, improving biomass yields and generating conservation measures leading to more sustainable land uses, ultimately resulting in improved environmental management.

2 Literature Review

Land is an essential resource, where the ecological system and human utilization are interdependent. Soil testing helps to determine the nutrient balance that can help in optimizing agricultural productivity. Balanced fertilizer application is necessary to achieve economically optimum crop production. The basic nutrients needed for plant growth consist of 16 elements, which are primarily obtained from the soil matrix. Carbon, hydrogen, and oxygen together constitute about 94-99.5% of the biomass of fresh plant material. A study research explored the involvement of soil microorganisms in nutrient uptake in flooded rice cultivation. Soil is a mixture of organic and inorganic constituents, along with water and air, and its texture is defined by the percentage of sand, silt, and clay. Quality of soil is vital to enable ecosystem services and generate benefits for humans. Soil quality is expressed in terms of its capacity to maintain productivity and maintain ecological integrity. [1]

Concentrations of heavy metals were found to be elevated in the top soil layer, with the highest values found near the soil surface and near waste disposal sites, with the concentration dropping off significantly as distance and depth increased. The relative concentration of heavy metals in the soil matrix was found to be Zn, Pb, Fe, Cr, Mn. The study further revealed that leachate from industrial waste disposal sites significantly contributes to the aggravation of heavy metal contamination both in soil and aquatic systems.[2]

Dhiware et al., 2018 The organic carbon content, nitrogen, phosphorous, and potassium levels of the soil samples from Dindori Taluka were varying, which reflected that the fertility state was changing from place to place. Availability of potassium, phosphorus, and nitrogen showed highly positive association with organic carbon, showing that increasing organic matter can enhance soil fertility. The study identifies electrical conductivity, pH, and soil texture as some of the important variables that influence nutrient availability and general soil health. These are both necessary for sustained agricultural production. Because overuse of chemicals can deteriorate soil quality, the outcome of this research has demonstrated balanced fertilizer application as a requirement to take care of soil health and excellent crop yield. [3]

A study done on the dielectric properties of soils at microwave frequencies has shown in Kumari et al. 2024: "In these results, one finds a generally downward trend as microwave frequency increased in ε′. These processes reflect a relationship with relaxation events that determine dipole orientation processes of soil materials; it indicates reduced ability for this to be realized as the frequency of microwaves increase further". Conversely, the imaginary part of the dielectric constant (ε″), which indicates energy loss within the material, tends to increase with rising frequency. This increase is due to the higher energy dissipation associated with the inability of dipoles to follow the rapidly oscillating electromagnetic field, resulting in greater dielectric losses. The work by Kumari et al. contributes to understanding the frequency-dependent behavior of the dielectric properties of soil, which is fundamental when considering applications such as soil moisture sensing and environmental monitoring. [7]

The study by Palta et al. emphasizes the importance of taking into account regional differences in soil texture and environmental conditions when analyzing dielectric properties. These differences can have a huge impact on the accuracy of soil moisture measurements and remote sensing applications. By understanding how these factors influence dielectric properties, researchers and practitioners can develop more accurate models and improve the interpretation of soil dielectric data for various applications. [8]

Kumari et al. (2024) conducted extensive research on the dielectric properties of soil with varying microwave frequencies. Their results showed that the real part of the dielectric constant (ε′) or the stored energy decreased with an increase in microwave frequency. This phenomenon was explained by the relaxation properties of the dielectric materials existing in soil; at higher frequencies, dipole molecules reoriented effectively, which resulted in a reduction in ε′. Conversely, the imaginary part of the dielectric constant, ε″, that expresses energy loss in the material, grows with increasing frequency. This is because the higher energy dissipation is associated with the inability of dipoles to follow the rapidly oscillating electromagnetic field, thus resulting in higher dielectric losses. The study by Kumari et al. provides valuable insights into the frequency-dependent behavior of soil's dielectric properties, which is crucial for applications like soil moisture sensing and environmental monitoring. [7]

The study by Palta et al. emphasizes that regional differences in soil texture and environmental conditions must be considered in the interpretation of dielectric properties. This may significantly impact the accuracy of soil moisture measurements and remote sensing applications. It is possible that, by understanding how these factors influence dielectric properties, more accurate models will be developed for improving the interpretation of soil dielectric data in different applications. [8]

In addition to moisture content, temperature and vegetation cover also become the significant environmental conditions that influence dielectric properties complicating the interpretation of measurements from practical application. Itolikar et al. uses a soil sample from Gwalior, Madhya Pradesh, India to analyze the dielectric characteristics of bare or uncovered soil and soil covered with plant (grass) at C-band microwave frequency. [10]

Kumar & Sharma shows that the dielectric response of soil can also be used to inform agricultural practices by providing insights into soil moisture dynamics. [9]

Palta et al. concentrate on the dielectric properties of soil, specifically measuring Ɛ' and Ɛ" across a variety of parameters like frequency, moisture content, and texture. When predicting soil parameters, the DNN model performed better than the RSM model. Based on a number of variables, the DNN model accurately forecasts dielectric characteristics. Use of deep neural networks to investigate the behavior of soil dielectrics based on temperature, moisture, texture, and frequency, the model forecasts characteristics.[11]

With increasing moisture content, the dielectric constant varies gradually at certain frequencies, such as 9.44 GHz, in a way that implies the two are strongly correlated with each other. Large changes occur both prior to and after the introduction of water, and the dielectric constant increases with moisture content. (Chaudhari & Shinde, 2011). Such applications as ground-penetrating radar, that rely on an accurate determination of water, rely\don\t\ton\t\tthis\t\trelationship. [12] Itolikar et al. examined how the varied dielectric properties of vegetation-covered versus bare soil influence remote sensing interpretations of soil moisture. The complicated dielectric constant of bound water in soil has also been modeled, indicating the effects of moisture and soil texture on dielectric behavior. Jin et al. demonstrates that variations in soil composition and environmental factors can result in inconsistent measurements and predictions and therefore warrant further research to refine these models.[13]

Kabir et al. Different types of soils have different dielectric responses; the dielectric properties of sandy soils are generally lower than those of clay-rich soils. A study reported that dielectric constants have strong correlations with physical parameters like sand and bulk density, while silt and clay have negative correlations (Chaudhari & Ahire, 2014).[14,15]

Kabir et al. suggests that when soil moisture is increased, dielectric properties (real or dielectric constant, and imaginary or loss factor) both increase as well, but it is not directly proportional. In fact, the difference can be seen clearly by the comparison between different soil types, which reveals that dry soils have significantly smaller dielectric properties than moist soils. Increased moisture content leads to higher dielectric constants and loss factors.The dielectric properties of sandy soils are notably lower than those of clay and loam soils.Models indicate that moisture is the primary factor affecting dielectric behavior, with penetration depth of electromagnetic waves decreasing with higher moisture and frequency levels.[16]

With improved semiempirical models, like the Wang–Schmugge model, which incorporate free soil water effects and soil texture into the complex dielectric constant of soils, estimation of complex dielectric constants is now better made. These models were further perfected by Liu et al. (2018), who found it to be much more accurate, especially at higher frequencies, where the impact of soil moisture becomes less important. This has huge implications in the application for remote sensing and agricultural management. The models not only consider the soil moisture but also other important factors such as soil mineralogy and temperature. These factors contribute significantly to dielectric properties. Different minerals present in the soil have electrical properties, while temperature can alter the mobility of soil water molecules that affects the total dielectric behavior. These advanced models can predict soil dielectric properties better, which provides valuable insights into soil moisture dynamics and informs better agricultural practices and environmental monitoring. Liu et al.'s study underscores the importance of developing precise models that account for various soil conditions, ultimately contributing to more effective decision-making in managing soil health and optimizing land use.[17]

Dielectric Properties of Soils at UHF and Microwave Frequencies (Hoekstra & Delaney, 1974) Several models were obtained in order to characterize the properties for different soil types and moisture levels. Results show that sandy soils have lower dielectric proprieties than clay-rich soils. This is due to the mineral content and structure of the soil particles that play a crucial role in the way EM waves couple with the soil. Because of the particle being much coarser and sparser for sandy soils, the interaction to electromagnetic waves is relatively poor and less which means they have lower dielectric properties. Hence in comparison to clay soils containing more fine particles and thus larger surface area, the dielectric properties will be increased as more electromagnetic waves will be interacted. [4,16]

Tikhonov (1994) showed that the dielectric properties had frequency-dependent implications, demonstrating that lower frequencies could penetrate deeper into the soils than higher frequencies. This is significant, for example, in scenarios like ground-penetrating radar, where we want to study deeper layers of soil. At lower frequencies, the wave is attenuated after travelling less distance in the soil. Soil and settling: higher frequencies (shorter wavelengths) will be more easily absorbed/scattered by the soil particles, limiting penetration depth. [5]

Kleshchenko et al. (2000) stated that a proper installation of the database of the dielectric properties of soil will help for better interpretations on remote sensing and the help of dielectric property of soil we can distinguish the bound water present in the matrix with the free water. The bound water is described as that which is tightly held by matrix particles and dielectric properties have single variance between bound waters and free water. In some cases it is possible to identify the change from bound water to free water by analyzing the changes in the dielectric constant and loss factor. This data is useful for multiple purposes, such as soil moisture detection, irrigation control, and environmental observation. [6]

All these studies together underline the importance of soil dielectric properties for both practical applications and scientific research. Development of the right models and databases will be a step to improve our capability in interpreting the remote sensing data, managing the health of soils, and optimizing agricultural practices.

The dielectric properties of contaminated soils vary significantly based on the type and concentration of contaminants. Kaya and Fang (1997) investigated soils contaminated with heavy metals, revealing a direct correlation between contamination levels and dielectric constant variations [18]. Shang et al. (2015) applied dielectric spectroscopy to detect hydrocarbon contamination, demonstrating its effectiveness in distinguishing contaminated regions [19].

Al-Qadi and Lahouar (2005) demonstrated the application of GPR for detecting hydrocarbon contamination in soils, reinforcing the importance of dielectric methods in environmental assessments [20]. Benedetto and Benedetto (2011) discussed how remote sensing techniques, when integrated with dielectric measurements, enhance soil contamination detection [21].

Industrial soil studies benefit greatly from dielectric measurements. Robinson et al. (2008) reviewed dielectric methods for soil water content measurement in industrial settings, highlighting the impact of contaminants on dielectric behavior [22]. Wilcke (2000) explored polycyclic aromatic hydrocarbons (PAHs) in industrial soils, showing how dielectric properties change in contaminated environments [23].

Further studies by Adriano (2001) and Kumpiene et al. (2017) have demonstrated the significance of dielectric measurements in soil contamination assessments [24,25].

3 Conclusion

Soil properties are then related to environmental conditions and human actions, creating a delicate balance that needs sustainable soil management. Summary: The review provides a summary of key insights into soil dielectric properties and heavy metal pollution in industrial and agricultural areas. This also shows the impact of industrial leachate on soil and water quality as evidenced by the greater concentration of heavy metals (e.g., zinc, lead, iron, chromium, and manganese) detected outside the waste disposal site. This gradient of concentration with distance and depth extremifies the necessity for waste management and remediation of soil. There are dielectric properties of soil which are significant for such applications as remote sensing and agriculture, which depend on the soil moisture content, texture, temperature, and vegetation cover. Higher dielectric constant and loss factor, both very germane to ground-penetrating radar, come from more moisture. More complex models, such as deep neural networks, can improve predictions of soil dielectric properties, and can provide useful information for agricultural practices in soil moisture dynamics. These outcomes underscore the need for further research and improved models and technologies for soil analysis. Sustainable practices employed and precision tools can enhance our understanding of soil properties to aid in conserving this key resource as well as effective utilization.

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