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Review of Dielectric Properties of Sodic Soil at C-band Microwave Frequency

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Abstract

Soil dielectric properties have been extensively studied in the past decade. This review focuses on understanding the dielectric behaviour of soils, particularly sodic soils. The dielectric characteristics of soil can be analyzed to gain insight into the presence and quantities of contaminants. Soil texture, composition, and salinity play a crucial role in determining soil erodibility, nutrient losses, and intensity of erosion. The salt of the earth (SOTE) model is introduced to evaluate the risk of long-term soil degradation. The Salt of the Earth model is used to simulate the progression of sodicity in soils exposed to shallow, Na-rich groundwater and experiencing clear dry seasons. The SOTE model can be used to assess soil degradation, providing an alternative method for soil analysis and the development of sensors for soil response analysis. In this paper, we discuss the importance of understanding soil dielectric behaviour, focusing on soil microbial communities and their interactions within soil profiles. The results show that sandy soil has lower dielectric property, whereas Dookie clay soil has higher dielectric loss factors.

Introduction

The dielectric properties of soils are crucial in various fields such as geophysical exploration, agriculture, and remote sensing. These properties are influenced by factors such as physical characteristics, chemical composition, and geographic location. The moisture content in the soil is the main factor that affects its dielectric behaviour, with different types showing distinct characteristics that are enhanced as the soil moisture content increases. The presence of bound water in the soil poses a challenge when modelling the permittivity of the soil, as its complex permittivity is not well defined. Radiofrequency heating can be used to address contaminated soil, while electromagnetic region-based studies offer an alternative approach. The dielectric properties of polluted soils can be analyzed to gain insight into the presence and quantities of contaminants. The dielectric behaviour is mainly influenced by its moisture content, with both the dielectric constant (Ɛ') and the loss factor (Ɛ") increasing as soil moisture increases. The dielectric properties of soil can be effectively modelled using advanced techniques such as deep neural networks, which consider various factors including frequency, texture, moisture content, temperature, and salinity.

Several methods are available to measure the dielectric properties of soil, including the parallel plate capacitance technique, complex dielectric spectroscopy, transmission line system design, time-domain reflection (TDR) for reflection-decoupled analysis (RDA), and VNA. These techniques enable measurement of parameters such as the dielectric constant and the loss factor, which are influenced by factors such as frequency, texture, moisture content, and temperature. The dielectric properties of soil have significant implications for both agriculture and the environment. Dielectric heating has proven to be a valuable tool in agriculture, offering a range of applications, including the treatment of seedborne pathogens, effective insect control, improved seed treatment for better germination, and the conditioning of products to enhance their nutritional value and maintain quality. The detection of moisture content and other quality factors in agricultural products can also be achieved by using dielectric properties. The dielectric properties of the environment can be used for soil treatment to effectively manage pests, improve nutritional value, and deactivate weed seeds and plant-infecting organisms. In addition, the dielectric properties of soil can be used to study the effects of sewage pollutants on soil contamination, providing an alternative method for soil analysis and the development of sensors for soil response analysis.

The dielectric properties of agricultural materials and products can be used for the detection of moisture content and other quality attributes that are crucial for the production, handling and processing of agricultural and food products. The dielectric properties have the potential to enhance agricultural and environmental practices in various ways. They can be used for non-destructive sensing of product moisture content and other quality factors, ensuring maximum storage conditions and guaranteeing the highest quality of the product. Additionally, dielectric heating can facilitate the drying process of agricultural products, control insects in stored goods, and enhance their nutritional value. The application of dielectric properties in agriculture allows improved control over product quality, pest management, and soil fertility, leading to the advancement of agricultural and environmental practices. However, dealing with sodic soils can be challenging due to their physicochemical properties that are not conducive to crop production. The development of salt-tolerant cultivars for sodic soils is a complex task due to difficulties in reproduction and limited genetic diversity among main crops. The application of gypsum for reclamation in wetland areas can be challenging due to inadequate drainage in sodic soils. However, amendments such as press mud, gypsum, and Mangala Setright can improve the overall condition of the sodic soil, making it more conducive to crop production. In salt-stressed areas, using the microbiome for bioremediation can provide a safe and effective solution to restore soil structure.

Agricultural challenges arise from the dielectric properties of sodic soils. Remote microwave detection of saline soils has a significant impact on the monitoring and management of soil conditions. These properties play a crucial role in ensuring the effectiveness of the process. An investigation was conducted to examine changes in the dielectric properties of sodic solonchak, a saline soil, in response to fluctuations in moisture and temperature. The dielectric properties of sodic solonchak are influenced by the various phases of water that it contains, including bound water, crystallization water, and soil solution. It is crucial to have precise measurements of these properties to enhance the accuracy of remote microwave sensing of saline soils and to properly interpret satellite data. The presence of soil sodic conditions can have detrimental effects on plant growth and crop productivity. These conditions can result in poor ventilation, limited root development, and increased susceptibility to root diseases. Therefore, it is crucial to understand and effectively handle the dielectric properties of sodic soils to address these agricultural challenges.

Various studies have been conducted to analyze the dielectric properties of different soil types, including soil texture, microwave response to soil salinity, and the Dobson semiempirical dielectric mixing model. Geophysical electromagnetic methods offer an efficient and non-invasive approach to measuring these properties, which can provide valuable information on the nature and quantity of pollutants within the soil. Buliya et al. (2013), Ahire et al. (2014), and Itolikar et al. (2020) have made several significant contributions. Gaining a comprehensive understanding of the dielectric properties of soil is crucial for efficient soil management and accurate environmental characterization. This knowledge yields valuable information on soil contamination levels and hydrophysical properties, enabling informed decision-making. Researchers have favoured conducting low-frequency conductivity measurements (less than 100 kHz) instead of high-frequency dielectric response measurements (greater than 1 MHz), as low-frequency measurements are relatively straightforward to carry out. The findings obtained from a modified oedometer cell can enhance our understanding of the soil-water electrolyte system. Farahani et al. (2005) conducted a study on the relationship between soil properties and ECa, focusing on three pivot-centre irrigated fields in eastern Colorado over a six-year period from 1998 to 2003. The study found that the relationship between ECa and soil properties changed due to significant variations in soil solution concentration (ECw). Changwen et al. (2011) used Fourier transform mid-infrared photoacoustic spectroscopy (FTIR-PAS) as a rapid method for analyzing greenhouse soils, providing a quick and efficient solution for greenhouse soil management without the need for sample pretreatment or a large sample mass.

Huang et al. (2014) developed epoxy nanocomposites containing BaTiO3 nanoparticles, which were modified with six different surface chemistries, leading to improved nanocomposites. The study examined how the surface chemistry of the nanoparticles affected the dielectric properties of epoxy nanocomposites using broadband dielectric spectroscopy. Soil science plays a crucial role in advocating for ecological intensification in agriculture, and Andrea et al. (2017) explored the intricate connection between soil and ecosystem services using evidence from case studies in Italy. Chaney et al. (2019) published a publication on the probabilistic mapping of soil properties using SSURGO (POLARIS), which contains detailed soil property maps for the continental United States (CONUS). The database contains 21,481 distinct soil series, each accompanied by its own set of vertical profiles detailing soil properties. The initial POLARIS soil series maps underwent improvements by integrating data from traditional soil maps, resulting in improved accuracy in predicting soil series. Chatterjee et al. (2021) discovered the accurate prediction of various soil properties using partial least squares regression (PLSR) models with pXRF spectra, with validation values R2 determined to be 0.81, 0.74, 0.73, 0.68, and 0.64, respectively, on the Pedon scale. However, the performance of the PLSR models was somewhat lacking in soil pH. Blonquist et al. (2005) and Schröder et al. (2016) made significant contributions to soil science, including a study on the microwave response to soil salinity at the L-band frequency of 1.25 GHz, a polynomial model that can accurately predict soil moisture levels using permittivity measurements at 100 MHz, and insights provided by Qadir et al. (2002) to improve soil management practices for long-term sustainable agriculture.

The application of sulfuric acid and gypsum-like by-products has shown potential in tackling soil crusting and restoring calcareous sodic soils. A study by Amezketa et al. in 2005 evaluated the effectiveness of four different amendments, including the use of sulfuric acid, the extraction of gypsum from mining, coal gypsum, and lacto gypsum, to prevent crusting in non-sodic and calcareous soils. The study also investigated the potential of these amendments to reclaim sodic soil. Approximately 60% of salt-affected soils worldwide are sodic and alkali soils, which requires cost-effective and environmentally friendly methods to enhance their quality. Qadir et al. (2007) explored various techniques to improve nutrient management and agricultural practices, but also addressed the obstacles that prevent widespread adoption of these methods on a larger scale. Sabath et al. (2004) examined high-power microwave (HPM) narrow-band source technologies and their corresponding HPM open-area radio-frequency (RF) test capabilities in four European countries. Rheem et al. (2004) delves into the analysis of various water surface conditions and their effects on microwave scattering using X- and C-band microwave scatter meters. Ding et al. (2014) explored research on the RF output envelope of a c-band multibeam klystron, focusing on the shoulder and tilt of the MBK RF output envelope of the C-band broadband MBK. Yang et al. (2014) presented a groundbreaking and versatile multiband frequency conversion scheme for satellite repeater applications, using optical frequency combs (OFCs) to achieve their objectives.

Recent advances in micro- and nanotechnologies and microwave dielectric spectroscopy have led to a notable surge in the miniaturization of high-frequency biosensors. This study examines a microfluidic sensor that uses a one-port coplanar interdigital capacitor (IDC) to make a valuable contribution to the advancement of this intriguing and challenging area of research. Ramachandran et al. (2023) explored the intricate nuances of a metamaterial design that showcases a fascinating multilayered symmetry, focusing on the implementation of this design in the C and X-band frequencies. Swift et al. (1986) and Yu et al. (2018) conducted a comprehensive exploration that delves into the dielectric properties of soils, with a specific emphasis on sodic soils.

This review article discusses the agricultural difficulties associated with sodic soils, provides possible remedies and highlighting the importance of effectively managing dielectric properties to ensure sustainable crop production under these conditions. Understanding the dielectric properties of soils, particularly sodic soils, is of utmost importance for a wide range of applications, including geophysical exploration, agriculture, and remote sensing. By examining the impact of frequency, moisture content, and salinity on soil dielectric behaviour, valuable insights can be obtained to support decision-making in related domains.

II. Dielectric Properties of Soil

Various factors, such as frequency, texture, moisture content, and temperature, can affect the dielectric properties of the soil. Understanding these properties requires examining the dielectric constant and loss factor, which are crucial indicators of the electrical properties. Factors such as soil pollution, sewage waste, and contamination can affect these properties. As contaminants increase, so do the dielectric constant and loss factor. Techniques such as vector network analyzers and open-ended coaxial probes can measure these properties, providing valuable information on the electrical behaviour. Understanding soil dielectric properties is crucial in fields like agriculture, geotechnical engineering, and environmental science, as it helps evaluate soil quality and identify potential contamination hazards.

A. Definition and significance of dielectric properties

Dielectric properties refer to a material's ability to absorb and release microwave energy as heat, which is crucial in various applications such as radio-frequency and microwave processing, heating, and cooking of food materials. These properties can be affected by factors such as frequency, temperature, moisture content, and density. In the food industry, dielectric properties are used in processes such as drying, pasteurization, sterilization, and quality monitoring of fats and oils. They also help to evaluate the excellence of food materials and improve the consistency of dielectric heating.

Research on the relationship between dielectric properties and frequency and temperature can be understood through the concepts of dielectric relaxation and ionic conduction. A study conducted by Selig et al. in 1975 examined the correlation between soil moisture levels and dielectric properties. The study provided a brief overview of the sensors developed to monitor moisture in soils and highway materials, focusing on their dielectric properties. However, the semi-empirical model was found to be ineffective in predicting the real part of the dielectric constant when there is a lot of moisture present.

Curtis' 2001 study focused on how moisture affected the dielectric properties of soils, using a polynomial model for predicting soil moisture based on permittivity measurements at 100 MHz. Lin et al. (2001) investigated the application of the time-domain reflectometry (TDR) technique in determining the physical properties of soils by analyzing their electromagnetic characteristics. Miyamoto et al. (2003) used TDR to study the structure of aggregates and their impact on the dielectric property of Andisol soil.

Over the past twenty years, researchers have extensively studied the dielectric properties of soil to measure water content, but encountered surprising outcomes when dealing with saline or smectite clays. Logsdon (2005) focused on developing a procedure for determining complex permittivity spectra for soils. Measurement of dielectric properties can be useed to estimate physical and chemical properties, provided that the correlation between dielectric properties and other relevant factors is thoroughly investigated and understood.

Farid et al. (2007) explored the use of microwave dielectric measurements to infer soil density and moisture content in engineering applications. Palta et al. (2021) presented the relationship between moisture content and dielectric properties in the Faridkot region (Punjab) at the 9.08 GHz X-band frequency. The study found that higher-density soils exhibited lower values for both parameters, suggesting that microwave dielectric measurements have the potential to accurately estimate soil moisture content and density in engineering applications.

B. Factors Influencing Dielectric Properties in Soils

The properties of materials significantly influence how electromagnetic fields interact with them, making them crucial in the design of efficient dielectric heating processes. Zhang et al. (2019) examined the dielectric properties of pecan kernels using a Novocontrol broadband dielectric spectrometer, while Kabir et al. (2020) studied soil properties using a vector network analyzer. Cho et al. (2020) investigated soil decontamination and found that soil dielectric properties were influenced by temperature changes. imeková et al. (2020) explored the impact of atmospheric water precipitation on soil properties, using dielectric barrier discharge (DBD) to prepare PAW. Szypowska et al. (2021) explored the connections between factors such as organic matter content, dry bulk density, volumetric water content, and dielectric permittivity.

Umar et al. (2021) provided a comprehensive assessment of the existing literature on different dielectrics. The dielectric properties have been extensively studied, and recent studies have shed light on additional factors that significantly impact estimation. Yamada (2022) provides practical insight for scientists and engineers working in interdisciplinary fields. Soil erodibility (K factor) and saturated hydraulic conductivity (Ks) play a crucial role in determining the intensity of erosion and nutrient losses, which are essential for assessing the quality of land reclamation. Qian et al. (2022) collected 132 soil samples from 22 soil profiles and analyzed various soil physicochemical properties, providing valuable information on the characteristics of these soils. Guo et al. (2022) investigated the impact of polypropylene microplastics on the hydraulic properties of various soil textures, finding that larger particles had a less pronounced impact on the infiltration properties.

Table 1: Dielectric Property Investigations in Various Materials and Environments

Material Investigated	Frequency Range	Temperature/Moisture Conditions	Method/Instrumentation	Study
Pecan Kernels	10 - 3000 MHz	5-65 °C, 10-30% wb moisture content	Novocontrol broadband dielectric spectrometer	Zhang et al., 2019
Soil (Clay, Clay Loam, Loam, Loamy Sand)	700–7000 MHz	Room temperature (25 ± 2°C)	Vector network analyzer with open-ended coaxial probe kit	Kabir et al., 2020
Soil (Total Petroleum Hydrocarbons removal mechanism)	Microwave Heating	-	Not specified	Cho et al., 2020

Dielectrics for non-contact bioelectrodes	-	-	Literature review on various dielectrics	Umar et al., 2021
Textile Materials	-	-	Overview and Discussion of dielectric properties of textile materials	Yamada, 2022
Reclaimed Soils in Pingshuo opencast coalmine, China	-	Soil physicochemical properties, particle size distribution, bulk density	Measurement of soil erodibility (K factor) and saturated hydraulic conductivity (Ks)	Qian et al., 2022
Soil (Loam, Clay, Sand) with Polypropylene Microplastics	-	Different particle sizes (20, 200, 500 μm), concentrations up to 6%	Investigation of Effects on hydraulic properties of soils	Guo et al., 2022

The dielectric properties are influenced by factors such as moisture content, compaction level, contamination of sewage waste and bound water. Moisture content increases permittivity, while compaction level affects permittivity because of higher dry density. Soil composition changes with sewage waste, affecting the dielectric constant and loss factor. Bound water, including strongly and weakly bound water, influences soil complex permittivity. Existing models use dielectric algorithms for bound water, which are reliable but require further research to understand the impact of bound water on soil properties and improve accuracy. Studying the effects of temperature and soil moisture content on dielectric permittivity could provide a more comprehensive understanding of soil behaviour.

1. Moisture content

Robinson et al. (2019) and Wilczek et al. (2020) have explored the role of biological feedbacks in soil structure, revealing that these feedbacks from plants, macrofauna and the microbiome directly impact soil hydraulic parameters and water content signals. These changes can have long-lasting effects, leading to alternative stable soil moisture. Wilczek et al. (2020) developed a soil moisture sensor and analyzed signals to accurately determine bulk dielectric permittivity. Pizarro et al. (2020) established calibration models that connect moisture variation and dielectric permittivity in compacted tropical soils, highlighting the importance of developing specific calibrations for these types of soils.

Table 2: Moisture Content

Material Investigated	**Methods/Techniques**	**Key Findings**	**References**
Soil structure, soil hydraulic parameters, soil water content	Biological feedbacks, alternative stable states (ASS) of soil moisture	Irreversible changes in soil hydraulic function due to biological feedbacks	Robinson et al., 2019
Soil Moisture Sensor Design and Signal Analysis	Determined dielectric permittivity determination	Research Results on soil moisture sensor design and signal analysis	Wilczek et al., 2020
Compacted Tropical Soils	Calibration models, dielectric permittivity, moisture variation	High-density and magnetic properties influence dielectric permittivity	Pizarro et al., 2020
Soil	Relations among organic matter, bulk density, water content, dielectric permittivity	Investigation in the 10–500 MHz frequency range	Szypłowska et al., 2021
Subgrade Slope	Calibration calculation model, TDR, moisture content, dry density	Significant influence of moisture content and dry density on dielectric constant	Xiao et al., 2021
Soil	Effect of fertigation, limiting field moisture capacity, stable wilting moisture content	Assessment of the physicochemical properties under fertigation	Ziganshin et al., 2021
Soil	Optimal cement and water content, degree of compaction, temperature	Influence of compaction and temperature on moisture conductivity	Nikolaeva, 2021
Treated Subgrade Soil	Resilient modulus-suction relationship, soil additive, mechanical properties	Improved soil mechanical properties under various moisture contents	Muhammad et al., 2021
Black Locust Plantations	Understory composition, stratification, environmental factors	Effects of the understory on soil moisture content, altitude, organic carbon	Wu et al., 2021

Szypowska et al. (2021) examined the correlations between factors such as organic matter content, dry bulk density, volumetric water content, and dielectric permittivity, focusing on the frequency range of 10 to 500 MHz. Xiao et al. (2021) developed a calibration calculation model that evaluates the moisture content of subgrade slopes using the TDR testing principle, providing valuable insights into moisture levels. Ziganshin et al. (2021) examined how fertigation impacts the physicochemical properties of the soil, finding that the soil's limiting field moisture capacity is 34%, while the moisture content at stable wilting is 21%. Nikolaeva (2021) focused on determining the most suitable cement and water content for soil, examining how compaction and temperature affect the coefficient of moisture conductivity in thawed and frozen soils.

Muhammad et al. (2021) conducted extensive experiments to determine the relationship between the resilient modulus and suction in the treated subgrade soil. Muhammad et al. (2021) demonstrated that the addition of a soil additive can significantly improve the mechanical properties of the soil, even when subjected to different levels of moisture. Wu et al. (2021) explored the impact of the composition and stratification on environmental factors within black locust plantations, finding that factors such as soil moisture content, altitude, and soil organic carbon content played a significant role in determining understory stratification of the understory.

2. Soil texture and composition

Understanding soil texture is crucial, as it has a significant impact on various soil characteristics. In a recent study by Zimmermann et al. (2020), it was found that performing particle size analysis without any pretreatment had a significant impact on the composition of the samples. The clay content was reduced by 54-89% compared to the content after particle size analysis with pretreatment. However, the silt content increased by 13–36% and the sand content increased by 3-483% in all sample groups. Soil physical properties have a significant impact on the estimation of soil water and energy fluxes. In a recent study by Tafasca et al. (2020), the focus was on examining how soil texture influences soil water fluxes and storage on various scales.

Table 3: *Soil Texture and Composition*

Material Investigated	**Methods/Techniques**	**Key Findings**	**Study**
Soil Particle Size Distribution	Particle size analysis, pretreatment, clay, silt, sand content	Impact of pretreatment on clay, silt, and sand content in soil samples	Zimmermann et al., 2020
Soil	ORCHIDEE LSM, soil water fluxes and storage, soil texture maps	Impact of Soil Texture on soil water fluxes at different scales	Tafasca et al., 2020
Lancangjiang River Basin Soil	Vertical distributions, soil organic carbon, soil pH, soil texture	Variation in pH with soil depth in two soil profiles	Zhou et al., 2020
Soil	High-throughput sequencing of marker genes, bacterial and fungal distribution	Soil texture as the second most important factor in shaping microbial community	Xia et al., 2020
Different Soil Types	Soil amendment effectiveness, second maize plantation season	Evaluation of soil amendment effectiveness in different soil types	Karamina et al., 2020
Soil	Relations among organic matter, bulk density, water content, dielectric permittivity	Investigation in the 10–500 MHz frequency range	Szypłowska et al., 2021
Northern Loess Plateau Soil	Vegetation types, soil properties, transport parameters	Correlations between Soil Properties and transport parameters	Pei et al., 2021
Agricultural Soils (Sandy, Sandy Loam)	USS applications, sludge-soil interactions	Influence of USS Applications on sludge-soil interactions	Hechmi et al., 2021
Not specified	Not specified	Mentioned as influential work	Oliveira et al., 2020
Not specified	Not specified	Mentioned as influential work	Wang et al., 2022

The research team used the ORCHIDEE LSM model to analyze the soil properties and their interactions within two soil profiles in the Lancangjiang River Basin. They found that soil pH ranged from 4.50 and 5.74, with an upward trend as soil depth increased. Xia et al. (2020) used high-throughput sequencing to investigate the patterns of bacteria and fungi in relation to soil texture. Soil texture emerged as a crucial factor that had a significant impact on the soil microbial community.

Biochar and organic fertilizers can significantly improve soil properties. Karamina et al. (2020) evaluated the efficacy of soil amendment in enhancing the second maize plantation season across various soil types. Szypowska et al. (2021) explored the correlations between soil properties, such as organic matter content, dry bulk density, volumetric water content, and dielectric permittivity. Pei et al. (2021) investigated the impact of vegetation types on waterwind erosion in the northern Loess Plateau region. They found a strong connection between soil properties and transport parameters, with factors such as bulk density, number of macropores, pore connectivity density, saturated hydraulic conductivity, soil organic carbon content, and particle composition that significantly affect transport parameters. Hechmi et al. (2021) found that transport parameters were significantly affected by annual applications of USS in agricultural soils, and the presence or absence of vegetation had a notable impact on sludge-soil interactions in both sandy and sandy loam soils.

3. Soil salinity and sodicity

A study by Liu et al. (2019) investigated the impact of soil salinity and sodicity on silt loam and clay soil materials. The study found that soil properties play a crucial role in regulating evaporation, with irrigation water salinity having a minor impact. Researchers used electromagnetic induction (EMI) methods and inversion techniques to capture images of electromagnetic conductivity of the soil, providing valuable information on the electrical conductivity (σ). Paz et al. (2020) also investigated the prediction of soil salinity and sodicity using electromagnetic conductivity imaging, focusing on the correlation between these factors and methods for accurately assessing and forecasting them. The study provides valuable information on the use of electromagnetic conductivity imaging as a tool for assessing soil quality and its impact on agricultural productivity. Craats et al. (2020) used the HYDRUS-1D model to simulate the progression of sodicity in soils exposed to shallow, Na-rich groundwater and experiencing clear dry seasons.

Scientists have made successful predictions about saturated soil hydraulic conductivity (Ksat) and the soil water characteristic curve by considering factors such as soil texture, bulk density, and other physical properties of the soil. Klopp et al. (2021) conducted an analysis of the performance of pedotransfer functions (PTFs) in saline and sodic soils, aiming to develop predictive models that consider both clay mineralogy and solution composition. Qadir et al. (2021) explored a proposed parameter to evaluate irrigation water quality, the potassium adsorption ratio (PAR), and two numerical coefficients that can be changed to account for the effect of potassium (K) and magnesium (Mg) as dispersing cations. They examined 600 water samples from irrigated regions around the world using this novel parameter and presented updated guidelines for assessing soil permeability hazards.

Table 4*: Soil Salinity and Sodicity*

Material Investigated	Methods/Techniques	Key Findings	Study
Silt Loam, Silty Clay	Different levels of soil sodicity, impact on soil properties	Soil Properties crucial in regulating evaporation	Liu et al., 2019
Soil	Electromagnetic conductivity imaging, EM38 instrument, inversion algorithm	Prediction of soil salinity and sodicity using electromagnetic conductivity imaging	Paz et al., 2020
Shallow, Na-rich Groundwater, Normal Weather Regime	HYDRUS-1D model, simulation of sodicity development in soils	Simulation of Sodicity Development in soils exposed to Na-rich groundwater	Craats et al., 2020
Saline and Sodic Soils	Pedotransfer functions (PTFs), Analysis of PTF performance on saline and sodic soils	Analysis of PTF performance on saline and sodic soils	Klopp et al., 2021
Irrigation Water Quality	Sodium Adsorption Ratio (SAR), Potassium Adsorption Ratio (PAR)	Proposed parameter to assess irrigation water quality	Qadir et al., 2021
Soil	Effects of salinity and sodicity on soil properties, PGPR role	Comprehensive review of salinity impact and management	Al-Tawaha et al., 2021
Soil	Spatial variability mapping, EC values, soil salinization	Mapping the Spatial Variability of soil salinity and sodicity	Günal, 2021

Soil salinity has a significant impact on crop productivity, hampering plant growth, and resulting in lower yields. Al-Tawaha et al. (2021) investigated the origins of soil salinity and its impact on different soil properties, such as chemical, physical, and hydraulic properties. The authors also explored the role of plant growth-promoting rhizobacteria (PGPR) in improving tolerance to saline stress and offered valuable insights into practices for managing salinity. Günal (2021) conducted a study that quantified and mapped the spatial variability of soil salinity and sodicity, finding that incorporating PGPR into agricultural practices could be an effective strategy to manage and mitigating the effects of soil salinity.

III. Microwave frequency and Soil Interaction

The frequency significantly impacts soil properties, leading to changes in pH, nutrient composition, and bacterial diversity. The intensity and duration of exposure directly influence the impact. Microwave applicator designs can affect the depth and pattern of soil heating. The highest heating rate indicates the potential for pest control without harming beneficial microorganisms. The frequency of microwave radiation affects the response of the soil, with higher frequencies causing localized heating and lower frequencies affecting deeper soil. Understanding this relationship is crucial for optimizing pest control methods.

A. Introduction to C-band microwave frequency

Frequency hopping has significantly advanced high power microwave sources, with new microwave generators and antennas designed for various applications. Mazhar et al.'s 2020 study focused on a quad band antenna with CPW feed, specifically for wireless and satellite applications. Itolikar et al.'s 2020 study measured the complex dielectric constant of sorghum vegetation at room temperature and the C-Band microwave frequency. Dash et al. introduced a sleek and efficient substrate integrated waveguide-backed self-quadruplexing antenna for quad-band applications. Chang et al. (2020) design of a silicon-germanium 130-nm bipolar complementary metal-oxide-semiconductor technology-based E-band low-noise amplifier (LNA) monolithic microwave integrated circuit (MMIC) demonstrated impressive performance, achieving a measured S21 ranging from 16 to 21 dB. Liu et al. (2021) successfully designed an ultrathin microwave absorber with a Jerusalem cross resonator for a broad low-frequency absorption bandwidth. Qin et al. (2022) created a sympathetically cooled ion microwave frequency standard in a Paul trap, offering improved stability and accuracy for precise measurements and potential advancements in telecommunications, navigation systems, and scientific research.

B. Mechanisms of interaction between microwaves and soil particles

Xiang et al. (2019) studied the sorption mechanism, kinetics, and isotherms of degradable petroleum gas (DBP) on six different paddy soil. The study found that hydrophobic and ionic interactions in different parts of the soil affect the amount of organic matter, the surface area, and the number of pores. Microwave pretreatment of crumb rubber before blending it with an asphalt matrix can effectively solve the modification issue of crumb rubber modifier (CRM) asphalt plants. Cho et al. (2020) investigated the removal of total petroleum hydrocarbons (TPH) from soil using microwave heating, revealing an impressive removal efficiency of 91.1% for coarse soil. Chen et al. (2020) examined the kinetics, isotherms, and mechanisms of PFOS sorption in six different soil particle-size fractions of paddy soil. Jie et al. (2022) studied the interaction between microwave radiation and solid Fe catalysts, focusing on the deep dehydrogenation of hexadecane.

Liu et al. (2023) investigated the use of magnetic fe-doped silicon carbide to activate microwave-induced persulfate for the removal of decabromodiphenyl ether. The combination of microwaves and Fe@SiC demonstrated remarkable catalytic performance, resulting in an impressive 90.1% degradation of BDE209 in 15 minutes. More research is needed to optimize the process conditions and investigate its applicability in real-world scenarios.

C. Relevance of the frequency in soil studies

The dielectric constant (ε") was obtained by analyzing the SAR data at the C-band frequency (5.36 GHz) under three different moisture conditions: 25%, 50%, and 70%. A new dielectric model was introduced that has shown promise in accurately measuring soil salinity. Domenech et al. (2020) presented a novel technique that uses C-band radar data to predict soil properties in a spatial context, which contributes to the field of soil property prediction and offers valuable information for future research. Remote sensing techniques can gain valuable insights from the interaction between microwaves and earth resources, such as soil and vegetation. Itolikar et al. (2020) conducted laboratory measurements to determine the complex dielectric constant of sorghum vegetation at room temperature (30°C) and at the C-band microwave frequency. The upcoming launch of the NISAR mission in 2021 offers opportunities to use observations at multiple frequencies, including the L, S, and C-bands. Monsiváis-Huertero et al. (2020) explored the impact of soil and vegetation water content on multifrequency observations.

The L-band Synthetic Aperture Radar (SAR) satellite mission, Radar Observing System for Europe, is just around the corner, combining L-band SAR with existing C-band satellite missions. Mengen et al. (2021) introduced a P-band SAR moisture estimation method that provides a more accurate understanding of soil properties, allowing for improved agricultural planning and water resource management.

IV. Sodic soil characteristics

Sodic soils with high exchangeable sodium and low total salts are common in semi-arid and arid regions. They can negatively impact soil quality, agricultural productivity, and plant growth. High sodium content can cause nutrient imbalances, elevated pH levels, and soil structure degradation. Variables such as soil type, texture, drainage conditions, and irrigation water affect symptoms. Sodic soils can also hinder the availability of nutrients, cause poor soil structure, and increase soil salinity. Excess sodium can also cause osmotic stress, reducing plant growth and nutrient absorption.

A. Definition and classification of sodic soils

Sodic soils, characterized by high concentrations of exchangeable sodium and low total salts, can negatively impact soil health, reduce productivity, and hinder plant growth. They often have poor structure and drainage, and high pH levels can lead to nutrient deficiencies or imbalances. The soil classification depends on factors such as exchangeable sodium percentage (ESP) and alkalinity levels. Soils with high sodium content are found in various environments, including semiarid and arid regions, as in well as wetlands.

Soil classification has evolved as a result of human influence and natural formation. Kabaa et al. (2019) explore the principles, classification scheme and rules of Soil Group 6 (SGP6), while Basak et al. (2020) discuss the classification and behaviours of soils with high salinity, as well as the threats associated with it. Rai et al. (2021) provide a comprehensive overview of saline ecosystems, discussing their concept, classification, and impact on climate, soil organic carbon (SOC), and nutrients. Khadbaatar (2021) presents an innovative method that combines thermal remote sensing and machine learning techniques to accurately forecast wheat genotype biomass and grain yields under varying water stress in sodic soil conditions. This approach can help farmers and breeders optimize agricultural productivity under sodic soil conditions.

B. Challenges associated with sodic soils in agriculture

The conversion of salt-affected land into productive agricultural areas is crucial for food security. Factors related to salt-affected soils, particularly in arid regions, are discussed in various studies. The Salt of the Earth (SOTE) model is introduced to evaluate the risk of long-term soil degradation. Conservation agriculture, which supports soil-related services and improves biotic potential, is examined on a large scale. Phytoremediation in arid and semi-arid soils presents technical challenges, including the limited availability of PTEs and difficulties in plant growth.

Conservation agriculture practices, when implemented with Agrimat incorporation, can increase food production while reducing the need for input resources. Agrimat can improve soil quality and promote food security among small farmers. Factors such as climate, lithology, topography, and pedology contribute to natural causes, whereas human causes are primarily related to agricultural land use. Smart solutions in conservation agriculture are evaluated in the Mediterranean Basin, focusing on the evolution of conservative tillage systems and their impact on crop productivity, weed control, and business viability. The economic implications of adopting smart solutions include cost effectiveness and long-term sustainability.

C. Importance of understanding the dielectric properties of the sodic soil

The correlation between soil dielectric response and soil water content has seen a significant increase in sensors, both ground-based and remote, highlighting the importance of considering soil structural properties in understanding and forecasting soil dielectric response. Factors such as climate, lithology, topography, and pedology contribute to natural causes, while human causes are primarily related to agricultural land use, particularly irrigated agriculture. The increase in saline, sodic, and saline-sodic croplands has led to rapid degradation of land and expansion of desert areas, which poses a significant threat to the environment and food security. Soil fertility has been a strong correlation throughout agricultural development, with the soil being a dynamic system driven by energy and matter flows caused by organic compounds. Research has also explored the impact of surface roughness on dielectric films, soil microbial communities, and the nature of interactions between multiple factors or stressors.

Hongde et al. (2021) analyzed the correlation between the shear strength of unsaturated soil, the salt content and particle content in coastal reclamation areas, while Balasubramaniam et al. (2021) analyzed the reflections of GNSS-R over land, which has demonstrated the ability to detect changes in soil moisture on land. The HFEMI system may use important soil features, such as induced polarization and dielectric permittivity, linked to relaxation phenomena.

V. Dielectric Properties of Sodic Soil in the C-band

The dielectric properties of different soil types were examined in a study by Kabir et al. (2020), using four textural classes of soil. The results showed that sandy soil had lower dielectric properties, whereas Dookie clay soil had higher dielectric loss factors. Itolikar et al. (2020) conducted laboratory measurements to determine the complex dielectric constant of the sorghum vegetation, using the least-square fitting technique. Periasamy et al. (2020) investigated the effectiveness of a semi-empirical dielectric model in measuring soil salinity, highlighting the potential of C-band SAR data in accurately measuring salinity levels in both bare and vegetated soil. The electrical properties of the soil can significantly impact the process and the properties of grounding electrodes also play a role.

Ground penetrating radar (EMI) methods and inversion techniques have been used to acquire electromagnetic conductivity images of the soil, providing valuable information on soil salinity and other soil properties. Fu et al. (2020) examined the effects of maize roots on soil properties in the root zone. Szypowska et al. (2021) explored the connections between organic matter content, dry bulk density, volumetric water content, and dielectric permittivity.

A. Historical perspective on sodic soil research

In 1981, the Biomass Research Center in Banthra, India, conducted screening trials for fuelwood production, focusing on the impact of babul trees on soil enrichment. In 1995, researchers investigated the microwave response to soil salinity using L-band frequencies, highlighting the potential to differentiate between saline and sodic soils. A greenhouse pot trial in 1994-1995 evaluated the use of tree plantations to reclaim sodic soils for the growth of agricultural crops. In 1998, grain yields in the Prosopis soil were significantly higher than in the reference farm soil. In 2013, Khotabaei et al. investigated the use of soil amendments in saline-sodic soil, finding that organic and/or inorganic amendments can improve soil quality.

Recently, anionic polyacrylamide (PAM) has gained popularity for soil rehabilitation and control of soil erosion. In 2014, Mansour et al. assessed the effectiveness of industrial by-products, such as sugar lime, vinasse and aluminum sulfate, as soil amendments, revealing significant improvements in the chemical and physical properties of sodic saline soils. Researchers have introduced a revolutionary "soil continuum model" that challenges traditional notions about soil organic matter, proposing that soil organic matter is a complex mixture of organic fragments of varying sizes. This discovery has significant implications for understanding soil composition and its role in ecosystem processes. Baveye et al. (2019) explore the intricate world of soil humus and humic substances, while Amin et al. (2019) focus on examining research gaps and potential future directions for soil carbon management in Australia.

Lehmann et al. (2020) explore the concept of soil health and its potential for the future. Wadoux et al. (2020) provide a comprehensive overview of data-driven soil research, highlighting the challenges and possibilities of extracting knowledge from soil data. Karki et al. (2021) provide a comprehensive analysis of soil fertility management in Nepal, examining climate and topography, and providing policy recommendations to improve practices. Yuan et al. (2021) explore the shear strength, permeability, formation, and development of desiccation cracks in sodic soil. Alteio et al. (2021) examine the technical challenges and limitations associated with marker gene amplicon sequencing, proposing various statistical and experimental approaches to tackle the intricate spatiotemporal complexity of soil and the vast diversity of organisms found within it. Qu et al. (2023) focus on Shanxi province, reconstructing meteorological data from the early years of Guangxu in the Qing dynasty.

B. Overview of studies that focus on dielectric properties

Dielectric properties studies explore materials' response to electric fields, which is crucial in electronics, telecommunications, and materials science. Factors such as temperature, frequency, and composition influence dielectric behaviour, aiding in technology development and improving existing ones.

1. Review of key methodologies and techniques

Itolikar et al. (2020) conducted laboratory measurements to determine the complex dielectric constant of sorghum vegetation at room temperature and the C-band microwave frequency. Fu et al. (2020) explored the impact of maize roots on soil heat capacity, thermal conductivity, and dielectric constant within the root zone. Kojima et al. (2020) introduced a novel thermo-TDR method for estimating θi, using a dielectric mixing model to improve accuracy. Tashayo et al. (2020) created land suitability maps for maize farming in Marvdasht Plain, Iran, using analytic hierarchy process, GIS, and geostatic. WiEps (2020) measures dielectric properties without contact using WiFi signals.

Sagar et al. (2021) proposed a novel approach to localize EM-fields in a rectangular waveguide using a dual layer metamaterial interface. Barrett-Lennard et al. (2021) explored solutions to alleviate soil stress, proposing microwater harvesting on the soil surface and soil improvement using gypsum, elemental sulfur, or a combination of both. Pérez et al. (2023) developed a compact and cost-effective microwave time domain transmission (TDT) sensor for accurate soil dielectric properties. This nondestructive and efficient method has the potential to revolutionize soil analysis and aid in precision agriculture practices.

VI. Methodologies for Dielectric Property Measurement

Time-domain reflection (TDR) and Frequency Domain Reflectometry (FDR) are widely used methodologies for measuring soil dielectric properties. TDR involves sending electromagnetic waves through the soil, while FDR analyzes the soil's frequency response to an applied electromagnetic field.

A. Laboratory techniques for measuring dielectric properties

1. Time Domain Reflectometry)

Time-domain reflectometry (TDR) is an efficient and non-destructive method for assessing soil moisture, with applications in agriculture and engineering. It has gained popularity because of its sensitivity and resolution capabilities. However, the cost of probes and data loggers can be a challenge. Several studies have explored the application of two-dimensional weighting theory, the calculation of the spatial sensitivity of TDR probes, and numerical simulation techniques.

TDR has been used to measure θi at temperatures near freezing points and it has proven effective in assessing contaminated soil sites. Comegna et al. (2020) investigated the impact of olive mill wastewater on the dielectric response of contaminated soils, while Lee et al. (2020) presented an alternative approach to determine hydraulic conductivity using TDR. Yan et al. (2021) presented a novel experimental setup for the precise measurement of dynamic moisture profiles, focusing on high spatial and temporal resolution. This study contributes to understanding the dynamics of soil moisture and provides valuable insights for agricultural and environmental applications. By accurately measuring dynamic moisture profiles, farmers can optimize their irrigation schedules and reduce water waste, thereby benefiting agricultural productivity and sustainable use of water resources.

2. FDR (frequency domain reflection)

The study explores the use of time-domain reflectometry (TDR) signals to measure dielectric behaviours, including apparent dielectric constant (Ka) and complex dielectric spectroscopies. The Dual Reflection Analysis (DRA) method was introduced to accurately measure the CDP spectrum within the frequency range of 10 MHz to 1 GHz. A seven-rod sensor was developed to measure the soil water content using TDR and FDR techniques, providing precise measurements within a specific sample volume. The study also examined the performance of a seven-rod probe in determining the soil dielectric permittivity. Other techniques to measure soil water content include point-scale sensors and satellites that use microwave technology.

The study also examined the accuracy and reliability of the formulae used to convert dielectric permittivity data from ground penetrating radar measurements. The study also focused on mapping the physical and dielectric properties of the layered soil using ground penetration radar. The study also developed a portable frequency domain reflection instrument (NIP-FDR) for continuous and automatic monitoring of soil water content. The study also validated the performance of a soil moisture sensor using a porous weighing ceramic cone filled with soil. The FDR method was found to be a reliable and accurate alternative to the core method for measuring soil moisture content, indicating its versatility and applicability in various agricultural settings.

3. Resonant cavity methods

The demand for precise and sophisticated systems to accurately measure material moisture content is significant in various industries. Cheng et al. (2020) explored microwave detection technology to measure the dielectric coefficient and moisture content using 3D printing technology. Gutierrez-Cano et al. (2020) developed a portable instrument to measure the complex permittivity of dielectric materials at microwave frequencies. Deng et al. (2020) presented an efficient method to detect soil moisture in low salinity and low organic matter content. Kim et al. (2020) explored variations in resonant frequency and Q factor of a cavity, allowing for consecutive measurements at each resonance mode.

Sheng et al. (2020) introduced a novel testing system focusing on electromagnetic parameters of microwave materials, allowing for accurate and reliable results. Tu et al. (2020) useed the strip line ring resonator principle to determine the dielectric constant of thin films. Wang et al. (2020) introduced a novel electromagnetic material measurement method using a commercially available material characterization kit (MCK) and a vector network analyzer (VNA). Wen et al. (2021) developed a model using Gaussian beam theory to accurately measure the dielectric properties of materials with low-loss characteristics. Wang et al. (2022) investigated the behaviour of high dielectric sheet materials using the perturbation method, offering an innovative approach for measuring the permittivity of high dielectric constant and loss. Zou et al. (2023) presented an innovative method for accurately measuring permittivity and loss tangent of low-loss materials using a cylindrical resonant cavity.

B. Field-based techniques and challenges for measuring the dielectric properties of sodic soil

Wilczek et al. (2020) discuss research on soil moisture sensors and their ability to accurately determine bulk dielectric permittivity. Itolikar et al. (2020) used the least squares fitting technique to determine the complex dielectric constant of the sorghum vegetation. Ju et al. (2020) used thermotime domain reflectometry (TTDR) to investigate the impact of NAPL contamination on unsaturated soils. Choudhari (2020) found a strong correlation between the soil dielectric constant and the water content, allowing an accurate measurement of surface soil moisture levels. Lee et al. (2020) proposed an alternative method for determining hydraulic conductivity using TDR.

Yu et al. (2021) introduced a new dielectric tube sensor (DTS) to measure soil water content and soil matrix potential in heterogeneous soil profiles. Mukhlis et al. (2021) compared various techniques and developed a versatile sensor capable of measuring soil water content, electrical conductivity, temperature, and matric potential simultaneously.

VII. Applications and Implications

The development of this sensor has significant implications for precision agriculture, as it allows farmers to make informed decisions about irrigation scheduling and fertilizer application based on real-time soil data. Additionally, the sensor’s ability to measure electrical conductivity can help identify areas of soil salinity, allowing farmers to take corrective measures to improve crop productivity. Overall, this sensor has the potential to revolutionize agricultural practices and contribute to sustainable farming methods.

A. Agricultural applications of the dielectric properties of sodic soil

Soil moisture content can be measured effectively by detecting the soil dielectric constant. Deng and colleagues (2020) developed a method to detect soil moisture in low salinity and low organic matter content. A study found that mixing nanofine sandy soil with sandy soil significantly improved its hydrophysical properties. Banti's article provides an overview of electrical conductivity in food, with a focus on fruits and vegetables. Zhong et al. (2021) introduced the modified general agricultural products effective medium (MGAPEM) formula to calculate dielectric properties in the microwave band.

Sheoran et al. (2021) studied the benefits of using pressmud, a waste product from the sugar industry, on soil properties and plant adaptation. Barman et al. (2021) found that pressmud positively impacts soil fertility and sodicity levels in the Ghaghar basin, influenced by factors such as land use, irrigation practices, and groundwater salinity.

B. Environmental Implications and Sustainability Dielectric Properties of Sodic Soil

The article discusses the sustainability of electrokinetic remediation, focusing on its applications and potential solutions. Highlights the challenges of this approach, including its lack of sustainability and the need for cost effectiveness. The increasing presence of saline, sodic, and saline-sodic crops has led to land degradation and desert expansion, threatening the environment and food security. The study by Kunakh et al. (2023) explores factors influencing soil macrofauna diversity in protected ecosystems, while Omar et al. (2023) explores management options to boost agricultural productivity in rice-growing regions. Hu et al. (2023) discuss advances in nanobiochar for metal-contaminated soil remediation, emphasizing the need for efficient nanobiochars to promote environmental sustainability.

Nackley et al. (2024) analyze the physical and chemical properties of tectonite and emphasize the importance of incorporating waste by-products into agricultural practices to promote environmental and economic sustainability. This approach can reduce greenhouse gas emissions and improve soil fertility, reducing the need for synthetic fertilizers and promoting sustainable farming practices.

C. Integration with remote sensing technologies.

Field sampling is a common method for soil mapping, but its size is limited due to factors such as labour availability and funding. Wang et al. (2019) proposed a sampling design method to improve precision, focusing on spatial coverage and feature space coverage. Remote sensing applications have seen significant progress with microwaves in the frequency range of 3 to 30 GHz. The correlation between soil dielectric constant and water content allows for an accurate assessment of surface soil moisture levels. Active radar remote sensing technology has immense potential for agricultural monitoring, with applications in crop identification, soil moisture inversion, crop growth parameter inversion, crop phenology retrieval, agricultural disaster monitoring, and crop yield estimation.

Advancements in remote sensing techniques have improved the effectiveness of mapping and monitoring saline soils, with the detection of the application of soil dielectric constant finding in irrigation. A study by Klc et al. (2022) examined the salinity levels of surface soils in central Anatolia, Turkey, highlighting the importance of targeted management strategies for sustainable agriculture in arid regions.

VIII. Challenges and future directions

One of the main challenges identified in this study is the need for improved irrigation practices to mitigate the effects of salinity on crop production. Additionally, future research should explore the possible impact of climate change on soil salinity levels in arid regions, as this could further exacerbate the problem.

A. Limitations of current research methodologies.

Current research methodologies for studying dielectric properties of sodic soils have limitations, including a lack of a comprehensive theory and the intricate connection between measured quantities and soil permittivity. Real-world sensors are crucial for accurate measurements. The study of dielectric properties becomes more complex as a result of the diverse nature of the soil. Advanced techniques such as electromagnetic induction and ground-penetrating radar can improve accuracy and reliability. Incorporating machine learning algorithms and data fusion techniques can also enhance these measurements.

B. Unexplored aspects in C-band dielectric property investigations

Kushwaha's 1999 study found that the size of the lowest band-gap increases with greater dielectric and plasmon frequency mismatch. Wang et al.'s 2008 study found a connection between moisture distribution and coal's dielectric properties. The 2014 study by Hashemi et al. validated the presence of carbonation in mortar samples using microwave technology. Mannodi-Kanakkithodi et al. explored compounds made from elements of Group 14 for energy storage and electronics applications. Tahseen et al.'s 2016 article discussed the extraction of a material's relative dielectric constant using the resonance method.

Bhattacharjee et al. (2020) investigated the dielectric, optical, transport and magnetic properties of the double perovskite BaSrFeVO6. Mao et al. (2020) found that compressive stress affects the dielectric property of feldspar minerals at higher frequencies, suggesting a potential correlation between stress and changes in the electrical behaviour. More research is needed to fully understand the relationship between stress and the dielectric properties of rock at higher frequencies for engineering applications.

C. Future research directions and potential advancements

The study of soil's C-band dielectric properties can provide valuable insight into soil interactions with electromagnetic fields. Including multifrequency SAR data and incorporating factors like soil type, texture, temperature, and salinity can improve accuracy. New methods such as two-component decomposition and hybrid scattering models can improve soil moisture estimation. Sensor technology that can measure multiple soil properties simultaneously is crucial for smart agriculture. Research on adapting dielectric property models to challenging environmental conditions is essential.

Field testing and validation studies are crucial to ensure reliability and accuracy. These advances could revolutionize monitoring and management of natural resources, leading to more efficient decision-making.

Conclusions

This review explores the dielectric properties of sodic soil exposed to the C-band microwave frequency, which are crucial for geophysical exploration, agriculture, and remote sensing. Factors such as frequency, moisture content, texture, temperature, and salinity influence the behaviour of the soil. Different soil types display different dielectric characteristics, providing information on levels of environmental pollution. Techniques such as vector network analyzers and deep neural network models measure the properties of the soil. Understanding soil properties helps farmers make informed decisions about irrigation, nutrient application, water use, and salinity levels, promoting sustainable farming practices and allowing targeted interventions for optimal soil health and productivity.

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