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Investigating the Impact of Water and Sand on Resistivity and Dielectric Constant of Soil

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Authors' contributions

This work was carried out in collaboration between both authors. Author VVN conceived the idea and designed the experiment. Author SRJ performed the experiment. Author VVN and SRJ conducted the data analysis. Author SRJ wrote the draft of the manuscript. Author VVN revised the manuscript. Both authors read and approved the final manuscript.

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Abstract

The variation in resistivity, volumetric water content, dielectric constants, and pH has been measured with the addition of water for two agricultural soil samples. Also, the effect of increasing percentage and size of sand on resistivity, dielectric constant, pH, porosity, and bulk density has been recorded for a soil sample by a series of experiments in the laboratory. The resistivity was measured with an indigenously developed two-probe resistivity meter, and the volumetric water content by a wet sensor. From the knowledge of volumetric water content, the dielectric constants were estimated. The results show that the initial resistivity of soils decreases sharply and then becomes constant with the addition of water content. Optimum soil conditions for crop growth were identified with 10-20% sand content and 50% porosity, exhibiting higher water holding capacity. The series of sand texture experimental results indicates that the higher the percentage and size of sand in soil, the lower the water content, and the higher the resistivity. The findings are significant for precision agriculture, irrigation development, and soil health assessment, as resistivity and dielectric properties can serve as rapid, non-destructive indicators of soil moisture and texture. The study highlights the potential of electrical measurements for improving soil management practices, improving water use efficiency, and supporting sustainable agricultural productivity.

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Keywords: Resistivity; dielectric constant; volumetric water content; bulk density; porosity; pH; black soil samples.

1. Introduction

The resistivity of soil provides an idea about the rusting capacity of the soil. The decrease in soil resistivity relates to an increase in rusting activity of the soil that needs a protective treatment. The presence of sand in soil determines the water-holding capacity of the soil, which is useful for crop growth. In civil engineering, the knowledge of electrical resistivity is the key factor in deciding structural stability. It varies widely from field to field, changes seasonally, and has a direct impact on the degree of corrosion in underground pipelines. Soil resistivity data is also useful to make subsurface geophysical surveys. It affects the design of a grounding system and helps to qualify the soil (Barker, 1989; Datsios et al. 2017; Eric et al., 2006; and Gardner, 1986). Electrical resistivity has applications in different fields of science such as environmental engineering, Geotechnical engineering, hydrology, civil engineering, mineral applications, mining applications, and archaeological fields (Giao P H et. al. 2003; Sudha K. et al. 2009 and Kibria G et al. 2012; Fano et al., 2019).

The electrical measurements have applications for studying soil water content, which provides a useful tool for geotechnical engineering (Ozcep et al. 2009; Zhang et al. 2022; Abdularaheem et al., 2024).

In agricultural science, the conductivity, which is the inverse of resistivity ($\rho = 1/R$), is one of the simplest and least expensive soil measurements available to farmers (Teletos et al. 2025; Afriani & Perdana, 2022). Conductivity refers to the electrical conductivity (EC) of a solution, that is, the electric current generated by charged ions in the solution. The electrical conductivity does not differentiate among the various elements; it measures the total solutes. Plants tend to take up nutrients in an ionic form, so the conductivity of a soil solution gives an idea about the nutrient content in the soil. Measuring the electrical conductivity (McNeil, 1992; Hossain & Nuruddin, 2012) will give an idea of what type of adjustments should be made to keep the solution in balance for the crop growth and maximum yields. There are a number of reports available about the measurement of electrical resistivity by four-probe and two-probe methods. The authors Wayal and Sitharam (2019) and others reported on the geo-electric assessment of the compacted sand-bentonite mixes using a two-probe method to enhance the electrical resistivity. Assessment of soil resistivity on grounding of electrical systems: a case study of North-East Zone, Nigeria was conducted by Gabriel and Kehinde (2011) using a two-probe resistivity meter. Seasonal variation of soil resistivity and soil temperature in Bayelsa State was reported by Afa and Anaele (2010).

Studying the effect of sand size and percentage on soil resistivity is critical for geotechnical engineering, electrical engineering, electrical grounding system design, and corrosion assessment of underground structures. The sands' properties directly influence the soil's pore structure and water retention, which in turn determine its ability to conduct electricity (Vincent et al.; 2017, Malik et al., 2023; Unde & Tathe, 2020). The addition of sand to soil generally decreases electrical conductivity and increases its electrical resistivity, primarily because sand particles act as a relative insulator compared to other soil components like clay and water (Gomma et al. 2023, Hou et al. 2023; Wang et al. 2023). The dielectric constant helps assess soil salinity, texture, and compaction, all of which directly impact on nutrient uptake, plant health, and crop yield (Xu et al., 2022; Nwankwo et al., 2013).

This study reveals a previously unexplored relationship between sand size and percentage on soil properties like resistivity, dielectric constant, bulk density, porosity, and pH for a single soil sample. The study first investigates the relationship between soil water content and electrical properties (resistivity and dielectric constant) using two agricultural soil samples. Subsequently, one selected soil was modified with varying sand percentages to examine the influence of sand fraction on these water-electrical property relationships, with significant use in geotechnical, agricultural, and environmental applications.

This study aims to establish experimental relationships among soil water content, electrical resistivity, and dielectric constant based on measured data, rather than developing detailed theoretical or mechanistic models.

2. Materials and Methods

2.1 Field location

The soil samples were collected from an agronomy farm near Chhatrapati Sambhajinagar *(*19° 52' 39.25" N, 75° 20' 32.14" E) (M.S.) India. The colour of the soil sample was black. Under average climate conditions, the area is arid and receives 500 mm to 650 mm of average precipitation that occurs in July through October. March through May is the driest period for crop growth. Little precipitation occurs during the winter months of November and December. The mean annual temperature is around 29°C during the day and 21°C at night.

2.2 Soil texture

The soil texture of the collected soil samples was determined from the soil survey office of Aurangabad, Maharashtra, to know the percentage of sand, silt, clay, organic carbon, and pH in the soils. The textural analysis of the two soils is given in Table 1.

2.3 Soil sampling

Soil samples were collected at 10 to 15 cm depth at different points on the agricultural farms. Around 10 to 12 soil samples were taken from each site, and after removing surface organic materials, fine roots were mixed thoroughly to make one composite sample. The soil samples are then transported to the laboratory in rigid containers to prevent atmospheric changes and damage to the soil aggregates. After air drying for a week, the soil samples were used for further study. It is clarified that the experiment included five different-sized sands with varying percentages (0-80%). The experiment was conducted in two stages. In the first stage, two agricultural soils were independently tested at different water contents to establish continuous relationships between water content and electrical resistivity and dielectric constant. In the next stage, one of two soils was amended with different sand percentages to study the effect of sand percentages on the measured electrical properties, while maintaining the same experimental protocol.

2.4 Soil Resistivity

The soil resistivity was measured in the laboratory by an indigenously developed two-probe resistivity meter. The meter is also useful for on-field resistivity measurement. Before experimentation, the indigenously designed resistivity meter used in this work was tested for accuracy and consistency. Standard reference measurements were collected to ensure dependable performance, and all readings were taken under similar laboratory circumstances to reduce instrumental and environmental variability. The resistivity meter works by inserting the two probes into the soil. The probes are made from copper, tapered at one end and wired at the other end. The probes are very sensitive to changes in soil parameters. When probes are inserted into the soil, they establish an electrical contact with the soil. The meter injects a constant current through the soil via the probes. The current flowing through the soil develops a potential difference between the two probes. Measuring V and I, the resistance per centimetre was determined, and the resistivity was estimated by using the following equation:

$$\rho = \frac{RA}{h} \tag{1}$$

Where R is the electrical resistance measured with the meter, A and h are the area and height of the soil sample.

In this study, each value of resistivity is the average of three repeated measurements.

2.5 Soil Water Content

A wet sensor made by Delta-T Devices was used to measure the soil water content in the laboratory. The sensor measures volumetric soil moisture content or volumetric water content (Ɵv) by responding to the changes in the apparent dielectric constant of moist soils. These changes are then converted into a DC voltage in mV, which is then converted to soil moisture content with the help of a moisture meter. Measurement of water content was repeated at least five times, and the average value of those readings was taken as the volumetric water content of that soil sample. The uncertainty in the measurement of water content given by the manufacturer is about ± 3%.

2.6 Dielectric Constant

The dielectric constant of soil was determined from volumetric water content by the following equation given by (Topp et al. 1980).

$$\varepsilon = 3.03 + 9.3\theta_v + 146.0\theta_v^2 + 76.7\theta_v^3 \tag{2}$$

In the above equation θ_v is the volumetric water content.

2.7 Bulk Density

Bulk density is an important physical property of the soil. Bulk density of collected soil samples with the addition of sand texture was measured by the formula:

$$Bulk\ density\ (\rho) = \frac{Mass\ (M)}{Volume\ (V)} \tag{3}$$

Where ρ, M, and V are the bulk density, mass, and volume of the soil samples. The volume of the soil sample was measured by the equation:

$$\mathrm{V} = \Pi\ \mathrm{r}^2\mathrm{h} \tag{4}$$

Where r and h are the radius and height of the sample holder. From the knowledge of bulk density, the soil porosity was estimated using the equation:

$$Porosity = 1 - \left(\frac{Bulk\ density}{Particle\ density}\right) \tag{5}$$

In the above equation, the particle density is taken as 2.65 g cm^{-3}, i.e., the particle density for the normal soil sample. The soil P^H was measured with the help of a handheld P^H meter.

3. Results and Discussion

Table 1. Texture analysis of two black soils

Name	Content	
	Soil 1	**Soil 2**
Organic carbon	0.57%	0.54%
pH	7.1	7.6
Bulk Density	1.30g cm^{-3}	1.35g cm^{-3}
Coarse sand	14.49%	10.00 %
Fine sand	07.51%	08.00 %
Silt	25.32%	27.00 %
Clay	52.68%	55.00 %

Table 1 lists the textural analysis of the two black soils. From Table 1, according to the soil rating chart, both soils have medium fertility. As the pH of soil1 is 7.1 and soil2 is 7.6, it is clear that the soils are slightly alkaline. From data both soils are clay because of high percentage of clay. Table 2 gives the variation in resistivity, volumetric water content, dielectric constant, and pH of the two soils with the addition of water.

The variation in resistivity with the addition of tap water is graphically presented in Fig. 1. As Fig. 1 shows, the resistivity is high at low water content, then decreases sharply and remains constant with the addition of water content. This may be due to the addition of water content; at 0% water content, the volumetric water content is around 0.12 %, which is very low; therefore, the resistivity is high. As the water content increases, the resistivity decreases sharply; this may be due to the chemicals present in the soils. The chemicals present in the soils may dissolve, which increases the conductivity of the soils, resulting in a decrease in the resistivity. With further increase in water content, the resistivity remains constant because at higher water content, soil pores are fully saturated with water, leading to no or less pore space, which results in constant resistivity. The observed plateau in soil resistivity at higher water contents is typically not due to a single cause, but rather a combined effect of pore saturation and ionic equilibrium. The results agree with the earlier results of Wayal and Sitharam (2019) and Datsios et al. (2017).

From Table 2, it is also observed that the volumetric water content of soil initially increases slowly up to 15% water content, then increases sharply, and with further increase in water content, it increases slowly or remains constant. This may be due to the soil porosity. Initially, when water is added to the soil, all porous parts of the soil may be filled with water, and after 15 % water content, there may be more free water available in the soil; therefore, there is a sharp rise in volumetric water content. With a further increase in water content, the soil gets saturated; therefore, there may be a slow increase in volumetric water content.

The results agree with the earlier results of Hallikainen et al. (1985). The variation in volumetric water content of the two soil samples with the addition of tap water is graphically shown in Fig. 2.

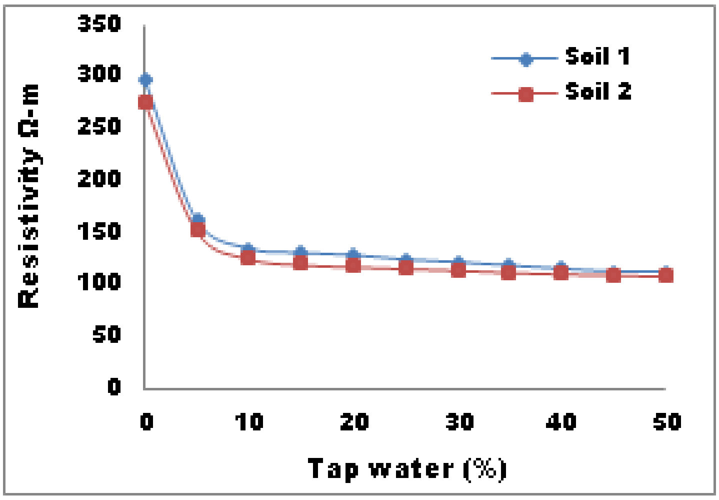

Fig. 1. Variation in resistivity of the two soils with the addition of tap water

Table 2. Variation in resistivity, volumetric water content, dielectric constant, and pH of two soils with the addition of tap water

Tap water (%)	Resistivity (ϱ / Ω-m) Soil 1	VWC (θv%) Soil 1	Dielectric constant (ε) Soil 1	pH Soil 1	Resistivity (ϱ / Ω-m) Soil 2	VWC (θv%) Soil 2	Dielectric constant (ε) Soil 2	pH Soil 2
0	298.15	0.12	3.04	7.0	276.22	0.12	3.04	7.3
05	161.78	1.40	3.16	7.0	152.09	1.76	3.23	7.3
10	134.54	2.30	3.32	7.1	125.94	2.84	3.41	7.4
15	130.64	4.28	3.70	7.1	120.20	4.71	3.79	7.5
20	128.47	10.15	5.55	7.1	118.13	11.24	6.02	7.5
25	124.21	20.64	11.84	7.1	116.63	21.72	12.72	7.5
30	121.67	26.76	17.44	7.1	114.88	26.82	17.50	7.5
35	118.43	30.91	22.11	7.2	112.78	30.98	22.20	7.6
40	115.32	33.86	25.89	7.2	111.34	33.96	26.03	7.6
45	112.65	37.28	30.76	7.2	110.45	38.31	32.33	7.6
50	112.65	40.07	35.13	7.2	109.18	42.12	38.58	7.6

Each value in the table is the average of three replicated measurements

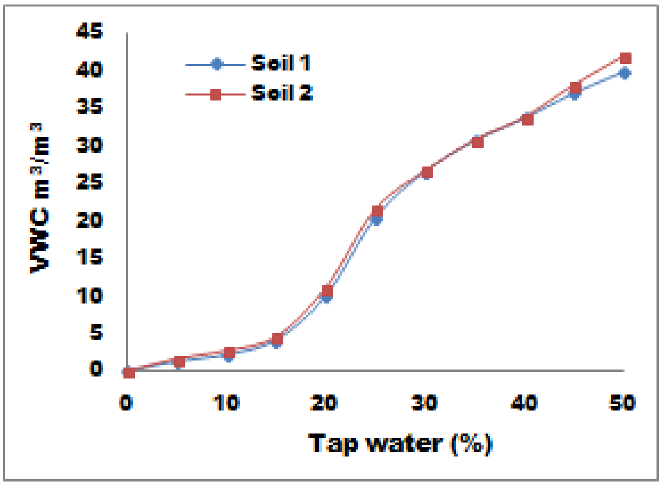

Fig. 2. Variation in volumetric water content of the two soils with the addition of tap water

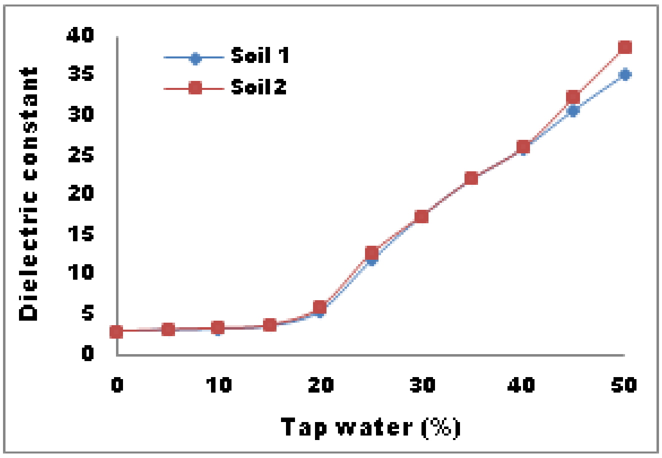

Fig. 3. Variation in dielectric constant of soils with the addition of tap water

Table 3. Variation in resistivity, bulk density, porosity, pH, volumetric water content, and dielectric constant of the soil with the addition of (0.050 - 0.099 mm) sand

Sand (%)	Resistivity (Ω-m)	Bulk density (g cm^{-3})	Porosity (%)	pH	VWC (θv %)	Dielectric constant (ε)
0	298.15	1.23	53.5	7.4	0.12	3.04
10	191.65	1.25	52.8	7.5	3.47	3.53
20	170.81	1.28	51.6	7.6	2.80	3.40
30	167.46	1.31	50.5	7.6	2.03	3.27
40	161.48	1.35	49.0	7.6	1.43	3.19
50	150.72	1.38	47.9	7.7	1.07	3.14
60	125.60	1.42	46.4	7.8	0.77	3.11
70	83.73	1.47	44.5	7.8	0.23	3.05
80	74.42	1.50	43.3	7.8	0.00	0.00

Each value in the table is the average of three replicated measurements

The variation in dielectric constant with water content is given in Table 2 and illustrated graphically in Fig. 3. The dielectric constant of soils increases slowly up to a transition point, then increases sharply with the addition of water content (Wang & Schmugge. 1980). Since the dielectric constant of the material depends on concentration, activity of permanent electric dipoles, ionic conduction, and degree of dipole alignment with the applied field. At lower water content, the increase in dielectric constant is due to bound water. Below the transition point, water is tightly bound to the soil particles by metric and osmotic forces, and it is difficult for water molecules to polarise. As soil water increases, the water can move more freely around the soil particles, and the chemicals present in the soil may dissolve and form a soil-water mixture of higher concentration. This free water with a higher ionic solution has a dominant effect on the dielectric constant of the soil after the transition point. The results are in agreement with the earlier results of Godio (2007), Boyarskii et al. (2002); Brady and Weil (2008). Hallikainen and Ulaby (1983) study was used while studying soil dielectric properties.

Tables 3 to 7 illustrate the variation in resistivity, volumetric water content, dielectric constant, bulk density, porosity, and pH of a soil with the addition of increasing percentage and size of sand. From Tables 3 – 7, it is observed that as the sand size in soil increases from 0.050 - 0.099 mm to 1.00 to 1.999 mm, the resistivity, porosity decrease, the bulk density, P^{H} increase, and there is an increase and decrease in volumetric water content and dielectric constants of the soil. The dielectric constant decreases with increasing sand percentage in soil because sand particles are larger and have a lower water retention capacity compared to clay and silt. This results in lower moisture content and a lower ability to store electrical charge, which is the primary reason for the decrease in dielectric constant (Jaiswal, 2012). From the same Tables, it is also noted that at 80% of sand texture, the volumetric water content is 0%, and the resistivity is high. This indicates that the higher percentage and size of sand in the soil will lower the water content and increase the resistivity. The results agree with the earlier results of Wayal et al.2019.

From Tables 3 to 7 it is also noted that around 10% of sand in soil, the volumetric water content is high and with further increase in sand there is decrease in volumetric water content. This suggests that soil having nearly10% of sand is good for water holding capacity of the soil which is good for crop growth and maximum yield.

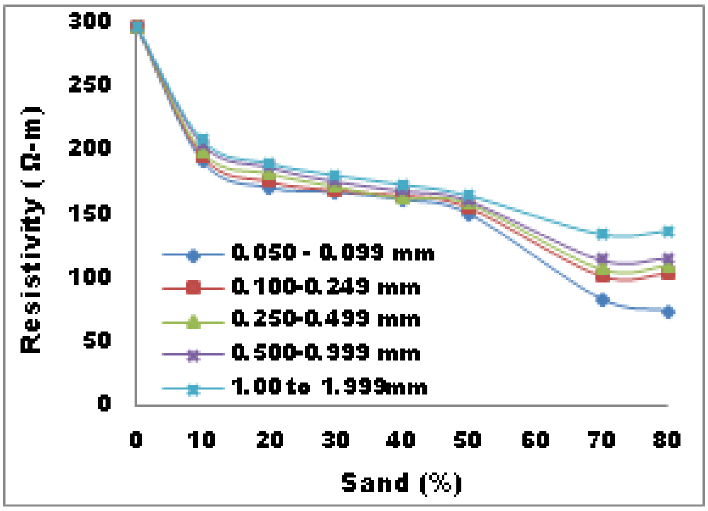

Fig. 4. Variation in resistivity (Ω-m) of soil with the addition of different sizes of sand (%)

Table 4. Variation in resistivity, bulk density, porosity, pH, volumetric water content, and dielectric constant of the soil with the addition of (0.100-0.249 mm) sand

Sand (%)	Resistivity (Ω-m)	Bulk density (g cm^{-3})	Porosity (%)	pH	VWC (θv%)	Dielectric constant (ε)
0	298.15	1.23	53.5	7.4	0.12	3.04
10	195.91	1.25	52.8	7.6	2.93	3.42
20	176.21	1.28	51.6	7.7	1.93	3.26
30	169.24	1.31	50.5	7.7	1.37	3.18
40	165.36	1.35	49.0	7.7	1.00	3.13
50	156.15	1.38	47.9	7.8	0.47	3.07
60	138.65	1.42	46.4	7.8	0.23	3.05
70	102.73	1.49	44.5	7.9	0.03	3.03
80	104.54	1.51	43.0	8.0	0.00	0.00

Each value in the table is the average of three replicated measurements

Table 5. Variation in resistivity, bulk density, porosity, pH, volumetric water content, and dielectric constant of the soil with the addition of (0.250-0.499 mm) sand

Sand (%)	Resistivity (Ω-m)	Bulk density (g cm^{-3})	Porosity (%)	pH	VWC (θv%)	Dielectric constant (ε)
0	298.15	1.23	53.5	7.4	0.12	3.04
10	199.31	1.25	52.8	7.4	3.03	3.44
20	182.70	1.28	51.6	7.4	2.77	3.40
30	172.46	1.31	50.5	7.4	2.43	3.34
40	163.24	1.35	49.0	7.5	1.97	3.27
50	159.44	1.38	47.9	7.6	1.57	3.21
60	143.54	1.44	45.6	7.6	0.83	3.11
70	108.21	1.49	43.7	7.6	0.33	3.06
80	110.57	1.52	42.6	7.7	0.00	0.00

Each value in the table is the average of three replicated measurements

Table 6. Variation in resistivity, bulk density, porosity, pH, volumetric water content, and dielectric constant of the soil with the addition of (0.500-0.999 mm) sand

Sand (%)	Resistivity (Ω-m)	Bulk density (g cm^{-3})	Porosity (%)	pH	VWC (θv%)	Dielectric constant (ε)
0	298.15	1.23	53.5	7.4	0.12	3.04
10	205.55	1.25	52.8	7.4	3.45	3.52
20	187.46	1.28	51.6	7.4	3.03	3.44
30	176.26	1.31	50.5	7.4	2.17	3.30
40	169.06	1.35	49.0	7.5	1.73	3.23
50	161.41	1.39	47.5	7.6	1.10	3.15
60	145.43	1.45	45.2	7.7	0.50	3.08
70	115.18	1.50	43.3	7.8	0.10	3.03
80	116.52	1.53	42.2	7.8	0.00	0.00

Each value in the table is the average of three replicated measurements

Table 7. Variation in resistivity, bulk density, porosity, pH, volumetric water content, and dielectric constant of the soil with the addition of (1.000 to 1.999 mm) sand

Sand (%)	Resistivity (Ω-m)	Bulk density (g cm^{-3})	Porosity (%)	pH	VWC (θv%)	Dielectric constant (ε)
0	298.15	1.23	53.5	7.4	0.12	3.04
10	208.55	1.25	52.8	7.6	3.35	3.50
20	190.46	1.28	51.6	7.6	2.91	3.42
30	181.26	1.32	50.1	7.7	2.52	3.35
40	174.06	1.35	49.0	7.8	1.81	3.24
50	165.41	1.40	47.1	7.8	1.12	3.15
60	150.43	1.46	44.9	7.9	0.62	3.09
70	135.23	1.51	43.0	8.0	0.24	3.05
80	137.55	1.54	41.8	8.1	0.0	0.00

Each value in the table is the average of three replicated measurements

From Tables 3 to 7, it is also observed that porosity depends on the bulk density of soil. As bulk density increases, the porosity decreases, as seen from Tables 3 - 7. The highest porosity of the soil is about 53.5 % without the addition of sand, and the lowest porosity is 41.8%, which was recorded for 80 % sand of size 1.000 to 1.999 mm in the soil. According to Brady and Well (2008) if the ideal porosity value for soil is around 50%, that is good enough for crop production.

4. Conclusions

This investigation explored how water content and the proportion of sand affect soil resistivity, dielectric content, volumetric water content, porosity, bulk density, and pH under controlled lab conditions. The electrical resistivity significantly decreased as the water content increased, while both the dielectric constant and volumetric water content increased, demonstrating a direct and continuous correlation with soil moisture. An increase in the percentage of sand and particle size resulted in higher resistivity and bulk density, decreased porosity, and fluctuating trends in water content and dielectric constant, highlighting the impact of soil texture on electrical and hydraulic characteristics.

A sand content of 10-20% appears to be optimal for water retention; however, further pot and field studies are needed. The findings highlight the relevance of soil electrical and physical properties for agricultural, electrical, and civil engineering applications. The study is limited to a specific soil type, and future work should examine a wider range of soils.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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Competing Interests

Authors have declared that no competing interests exist.

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