

Comprehensive analysis of soil physical properties and their relationships: recommendations for optimized irrigation strategies

Abdulwahab Abdulrazaq Bichi^{1*}, Mustapha Mukhtar Khalil¹, Abdulyakin Usman²

(1. Department of Agricultural and Bio-environmental Engineering, Faculty of Engineering, Federal University Dutsin-Ma, P.M.B. 5001, Katsina Nigeria;

2. Department of Mechanical Engineering, Faculty of Engineering, Federal University Dutsin-Ma, P.M.B. 5001, Katsina Nigeria)

Abstract: This study aims to evaluate the soil physical properties in the Zobe Irrigation Area of Katsina State to determine the most suitable irrigation method for enhancing water use efficiency and crop yield. Soil samples were collected from six different locations and analysed for texture, bulk density, porosity, and water holding capacity. The results indicated that the soils are predominantly sandy loam, with an average sand content of 60.17%, silt 24.17%, and clay 15.7%. The mean bulk density was found to be 1.38 g cm⁻³, while the mean porosity was 47.67%. A strong negative correlation was observed between sand content and field capacity (-0.72), and a strong positive correlation between porosity and field capacity (0.983). Additionally, a strong negative correlation between bulk density and field capacity (-0.962) was identified, indicating that denser soils have lower water retention. Analysis within the soil profile revealed a decrease in sand content and bulk density with depth, and an increase in silt content and porosity. Based on these findings, drip irrigation is recommended as the most effective technique for the study area due to its ability to deliver water directly to the root zone, thus ensuring efficient water use and optimal moisture levels. Supporting studies confirm that drip irrigation maintains consistent soil moisture levels, crucial for maximizing plant available water capacity and promoting healthy plant growth. This research provides essential insights for developing climate-resilient irrigation strategies to support sustainable agriculture in semi-arid regions.

Keywords: irrigation efficiency, soil physical properties, water management, semi-arid agriculture, sustainable agriculture.

Citation: Bichi, A. A., M. M. Khalil, and A. Usman. 2025. Comprehensive analysis of soil physical properties and their relationships: recommendations for optimized irrigation strategies. *Agricultural Engineering International: CIGR Journal*, 27(2): 49-59.

1 Introduction

Climate change has introduced significant uncertainties in water availability, particularly for rain-fed agriculture in semi-arid regions such as the northern part of Nigeria. The region is experiencing

increased temperatures and altered precipitation patterns, leading to frequent drought and flood events. The semi-arid zone exhibits low and erratic rainfall patterns, with a notable increase in drought frequency and intensity over the last three decades (Olayide et

Received date: 2024-08-12 **Accepted date:** 2025-03-15

***Corresponding author:** Abdulwahab Abdulrazaq Bichi, Department of Agricultural and Bio-environmental Engineering, Faculty of Engineering, Federal University Dutsin-Ma, Katsina Nigeria. Email: aabdulrazaq@fudutsinma.edu.ng.

al., 2024). This variability poses a critical challenge to the sustainability of agriculture in this region.

Due to the uncertainties of rainfall in the region, farmers are increasingly shifting to irrigation to sustain agricultural productivity, which has now raised the need for effective water management strategy to ensure climate-resilient practices, particularly in this region where smallholder farmers are prevalent (Abimbola et al., 2022). Efficient irrigation planning is essential for optimizing water use, minimizing wastage, and enhancing agricultural productivity in semi-arid areas where water resources are scarce.

Traditionally, irrigation planning has focused on climatic factors and crop water requirements, but soil physical properties play an equally critical role in determining water infiltration, retention, and distribution within the soil profile. The choice of irrigation method is greatly influenced by soil properties such as texture, bulk density, and water-holding capacity (Eze et al., 2022). These factors dictate how efficiently water is delivered, absorbed, and retained, directly impacting irrigation effectiveness and crop yields.

Various irrigation techniques perform differently under different soil conditions. For instance, drip irrigation is highly effective in sandy soils due to its localized water delivery, which minimizes evaporation and runoff. However, flood irrigation may be more suitable for clayey soils that retain water efficiently (Durodola and Mourad, 2020; Towolawi et al., 2021). Understanding these relationships is critical for selecting the most appropriate irrigation method to maximize water use efficiency.

Despite extensive research on irrigation methods, there remains a gap in studies that focus solely on assessing soil physical properties as primary determinants of irrigation strategy selection. While factors such as climate, crop type, and socio-economic considerations play a role in irrigation management, they were not included in this study as primary selection criteria. The exclusion of these factors is based on the understanding that soil

properties remain constant over time, while climatic conditions and cropping patterns may vary seasonally or between farms. Additionally, economic constraints affect a farmer's ability to adopt a specific irrigation method but do not alter its technical suitability for a given soil type.

This study takes a more targeted approach by focusing solely on soil physical properties as the primary determinant of irrigation suitability. This scientifically grounded methodology provides a consistent, soil-based irrigation framework that eliminates external variabilities, ensuring a direct correlation between soil characteristics and irrigation efficiency. By isolating soil factors, the study contributes to the advancement of precision irrigation strategies, offering a data-driven model adaptable to similar semi-arid environments.

2 Literature review

2.1 Irrigation practices and efficiency in Northern Nigeria

Irrigation is a critical practice for ensuring food security and socio-economic development in Northern Nigeria, particularly given the region's climatic uncertainties and population growth. Northern Nigeria experiences a short rainy season and a long dry season, making irrigation essential for sustainable agriculture. Traditional irrigation methods, such as manual watering with buckets and planting on sloppy ridges, are commonly used, although some farmers employ water pumps. The main water sources include rivers and boreholes, but modern irrigation systems are largely absent (Shanono et al., 2022).

Large- and medium-scale irrigation schemes do exist in the region. However, they often suffer from under-utilization, poor management, and abandonment, leading to economic losses. Some schemes however function well, contributing significantly to food security and the well-being of rural communities (Shanono et al., 2022).

Modernizing irrigation systems in Northern Nigeria is necessary for improving agricultural

productivity and sustainability. Traditional methods, while still prevalent, are less efficient compared to modern irrigation technologies. Enhancing irrigation infrastructure, adopting efficient water management practices, and integrating soil and crop management techniques are essential steps towards achieving sustainable agriculture. This modernization is crucial for meeting the Sustainable Development Goals related to food security and rural development (Abimbola et al., 2022).

2.2 Soil physical properties and their influence on irrigation methods

Soil physical properties such as texture, bulk density, water holding capacity, and porosity play a critical role in determining the efficiency and suitability of different irrigation methods. These properties influence water infiltration, retention, and movement within the soil profile, which in turn affect plant water availability and overall irrigation efficiency.

Soil texture, defined by the proportion of sand, silt, and clay, significantly impacts irrigation practices. Sandy soils, with larger particles and more significant pore spaces, have higher infiltration rates but lower water holding capacities, necessitating more frequent irrigation. In contrast, clayey soils, with smaller particles and less pore space, have lower infiltration rates but higher water retention, allowing for less frequent but longer irrigation sessions (El-Banna et al., 2011). In the study conducted in Bauchi, Nigeria, it was found that sandy loam soils under sprinkler irrigation retained moisture effectively when mulched with grass, improving overall irrigation efficiency (Mahmood et al., 2023).

Compacted soils with higher bulk density often require specific irrigation methods like furrow irrigation, where water is applied directly to the root zone to maximize efficiency. The study by Vistro et al. (2022) showed that tractor wheel traffic increased bulk density but also enhanced water use efficiency in furrow irrigation by reducing infiltration and promoting lateral water movement.

The soil's water holding capacity is crucial for

determining irrigation frequency and volume. Soils with high water holding capacities, such as loamy and clayey soils, can retain water for longer periods, reducing the need for frequent irrigation. Conversely, soils with low water holding capacities, like sandy soils, require more frequent irrigation to maintain adequate moisture levels (Khalil and Abid, 2019). Soil porosity, the fraction of the soil volume occupied by pores, directly affects water infiltration and drainage. High porosity soils, such as those with good structure and organic matter content, facilitate efficient water movement and reduce surface runoff. Mulching has been shown to improve soil porosity, as demonstrated in the study where grass mulch at different depths significantly increased soil porosity and moisture retention under sprinkler irrigation (Mahmood et al., 2023).

Different irrigation methods are influenced by and, in turn, affect soil physical properties. For instance, furrow and basin irrigation methods can lead to changes in soil salinity and structure over time. A study conducted near Ziway Lake, Ethiopia, showed that these irrigation methods affected soil salinity and pH levels differently, which could impact crop productivity if not managed properly (Tefferu et al., 2019). Similarly, the study in the Huangshui River Basin demonstrated that irrigation significantly influenced soil moisture distribution and groundwater dynamics, emphasizing the need for tailored irrigation practices based on soil characteristics (Lv et al., 2022).

Understanding and managing soil physical properties is essential for optimizing irrigation practices. Tailoring irrigation methods to suit specific soil types can significantly enhance water use efficiency and crop yields. Future research and irrigation planning should focus on integrating soil physical characteristics to develop sustainable and efficient irrigation strategies.

3 Materials and methods

3.1 Study area

The study was conducted at Zobe Irrigation

Project area of Dutsin-Ma Local Government, in Katsina State of Nigeria. The study area lies around latitude 12.21°N and longitude 7.27°E coordinates of the Zobe Dam environs. This area falls under the Sudan Savanna ecological zone and is characterised by a tropical wet-and-dry climate. The annual rainfall in the area lies between a continental wet and dry type of climate with a maximum monthly temperature of 24 – 38 °C and a mean annual rainfall of 562 mm (Ibrahim and Aliyu, 2019) The dam was constructed in 1977 with the aim of providing drinking water and to support irrigation. It has a storage capacity of approximately 170 million cubic meters, surface area of 39.6 km² and is able to support over 8,137 ha of irrigated land.

3.2 Soil sampling

Soil samples were collected from various locations across the farm to capture the variability in soil properties. A random sampling method was used, with samples taken at 6 different locations. At each sampling point, soil was collected from three depths: 0-15 cm, 15-30 cm, and 30-45 cm. This stratified sampling approach helps in understanding the soil profile and its influence on water movement and retention.

3.3 Laboratory analysis

The collected soil samples were air-dried, crushed, and passed through a 2 mm sieve before laboratory analysis. The following soil physical properties were measured:

3.3.1 Soil texture

Determined using the hydrometer method, which separates soil particles into sand, silt, and clay fractions (Gee and Bauder, 1986).

3.3.2 Bulk density

Measured by the core method, where a known volume of soil is weighed after drying, and bulk density is calculated as mass per unit volume (Blake and Hartge, 1986).

3.3.3 Soil porosity

Calculated based on bulk density and particle density measurements, using the formula: $Porosity =$

$1 - (\text{bulk density}/\text{particle density}) \times 100\%$ (Blake and Hartge, 1986).

3.3.4 Water holding capacity

Measured using the pressure plate method to determine the soil's field capacity and permanent wilting point (Klute, 1986)

3.4 Data analysis

The data obtained from the laboratory analysis were subjected to statistical analysis to identify patterns and correlations between soil properties and irrigation suitability. Descriptive statistics, including mean, median, standard deviation, and coefficient of variation, were calculated for each soil property. Correlation analysis was performed to examine the relationships between soil texture, bulk density, porosity, and water holding capacity.

4 Results and discussion

4.1 Soil texture

Soil texture data across the 3 depth samples reveal similar texture, with the uppermost layer having lesser sand content compared to the lower layers. At 0-15cm depth, sand, silt, and clay content resulted in a mean value of 58.33%, 22.83%, and 14.67% respectively; at 15-30cm, 60.67%, 24.33%, and 15.67%; and at 30-45cm, 61.50%, 25.33%, 16.67%. The soil texture data from the six samples reveal that the soils in the study area predominantly consist of sand, with an average sand content of 60.17%. The silt and clay fractions have mean values of 24.17% and 15.7%, respectively, see Figure 1. The relatively high sand content suggests that the soils are likely to have good drainage properties, which can influence water infiltration and retention. The standard deviations for sand, silt, and clay are 5.587%, 2.757%, and 3.01%, respectively, indicating moderate variability in soil texture across the samples. This variability in texture can affect the uniformity of water distribution and retention in the soil profile, impacting irrigation efficiency.

4.1.1 Soil texture at sample points

The standard deviations for sand, silt, and clay are 5.587%, 2.757%, and 3.01%, respectively, indicating

moderate variability in soil texture across the samples. This variability in texture can affect the uniformity of water distribution and retention across the field, impacting irrigation efficiency. However, all samples

appear to fall under same soil type of Sandy Loam. This means that the variation in texture may not be significant and because of that same type of irrigation technique can be employed across the study area.

Table 1 Summary of result at sample points

| Sample | Sand (%) | Silt (%) | Clay (%) | Mean bulk density (g cm ⁻³) | Mean porosity (%) | Mean field capacity (%) | Mean permanent wilting point (%) | Mean plant available water capacity (%) |
|--------------|----------|----------|----------|---|-------------------|-------------------------|----------------------------------|---|
| 1 | 61 | 24 | 15 | 1.35 | 49 | 30 | 15 | 15 |
| 2 | 67.67 | 20.33 | 12 | 1.4 | 47 | 28 | 14 | 14 |
| 3 | 52.33 | 27.67 | 20 | 1.33 | 50 | 31 | 16 | 15 |
| 4 | 57.67 | 24.33 | 18 | 1.39 | 47 | 28 | 14 | 14 |
| 5 | 65 | 22 | 13 | 1.45 | 45 | 27 | 13 | 14 |
| 6 | 57.33 | 26.67 | 16 | 1.37 | 48 | 29 | 14 | 15 |
| Mean | 60.17 | 24.17 | 15.7 | 1.38 | 47.67 | 28.83 | 14.33 | 14.50 |
| Median | 59.34 | 24.17 | 15.5 | 1.38 | 47.50 | 28.50 | 14.00 | 14.50 |
| S. Deviation | 5.587 | 2.757 | 3.01 | 0.04 | 1.75 | 1.47 | 1.03 | 0.55 |
| Variance | 31.21 | 7.602 | 9.07 | 0.00 | 3.07 | 2.17 | 1.07 | 0.30 |
| Max | 67.67 | 27.67 | 20 | 1.45 | 50.00 | 31.00 | 16.00 | 15.00 |
| Min | 52.33 | 20.33 | 12 | 1.33 | 45.00 | 27.00 | 13.00 | 14.00 |

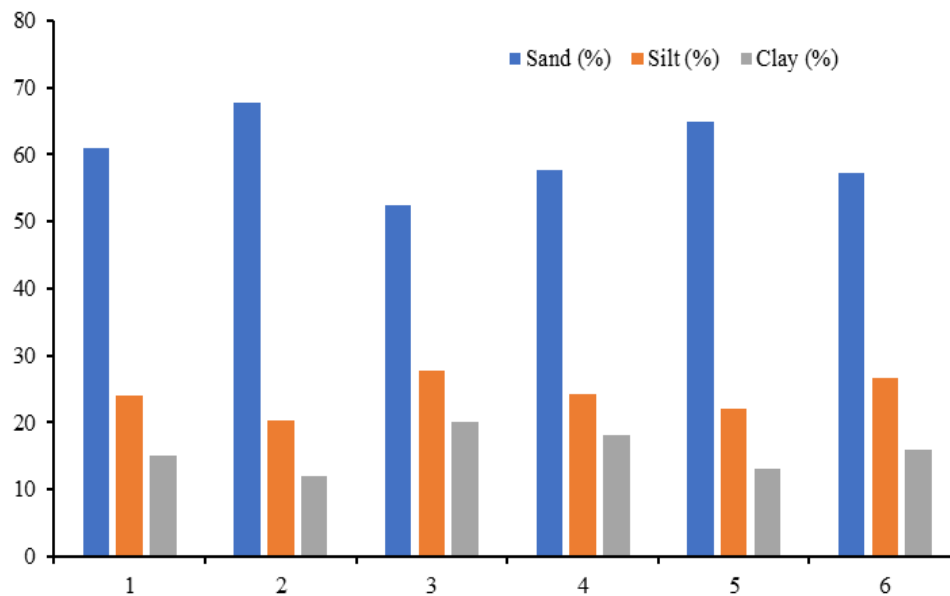


Figure1 Particle size distribution at individual sample points

4.1.2 Soil Texture vs field capacity at sample points

The correlation coefficient of -0.72 between sand content and field capacity indicates a strong negative relationship, meaning that as sand content increases, the soil's ability to retain water decreases significantly. This is due to the larger soil particles and pore spaces in sandy soils, which enhance drainage and reduce water retention. Consequently, sandy soils require more frequent irrigation to maintain adequate moisture levels for crops. Understanding this relationship is essential for selecting appropriate irrigation methods that can accommodate the lower water-holding capacity of sandy soils, ensuring

efficient water use and optimal crop productivity.

4.1.3 Soil texture within soil profile

The soil texture data within the soil profile (0-15 cm, 15-30 cm, and 30-45 cm) reveal a gradual decrease in sand content and an increase in silt content with depth, see Figure 2. The mean sand content decreases from 63% at the surface (0-15 cm) to 57.5% at the deepest layer (30-45 cm), while the mean silt content increases from 21.33% to 26.83% over the same depth range. This trend indicates that the soil becomes finer with depth, which could be due to the leaching of finer particles like silt and clay from the upper layers to the lower layers over time.

Such stratification can influence water infiltration and retention, with the upper sandy layers facilitating

quicker drainage and the deeper siltier layers retaining more moisture.

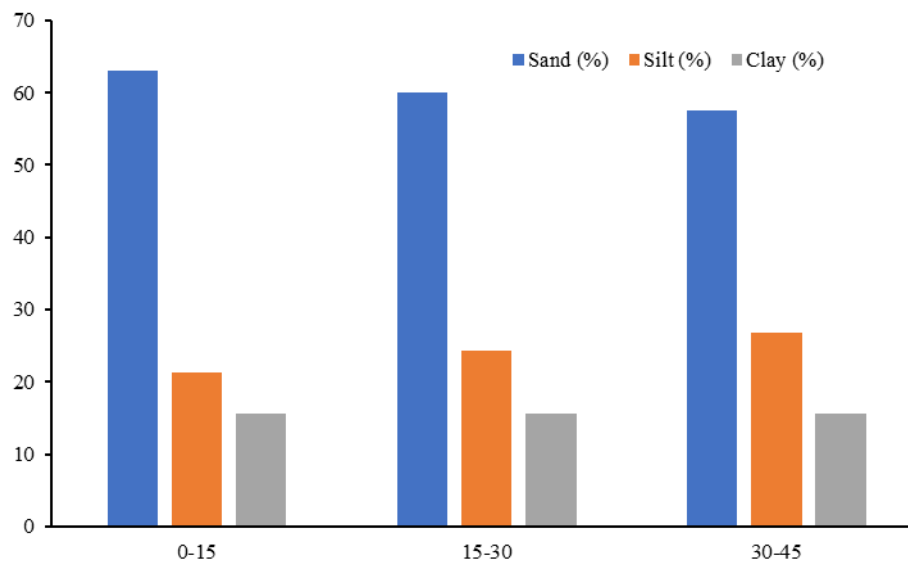


Figure 2 Particle size distribution within soil profile

4.1.4 Soil texture vs field capacity within profile

The correlation coefficient of -0.99863 between the sand content of the soil and its field capacity indicates an almost perfect negative relationship. This implies that as the sand content in the soil increases, the field capacity dramatically decreases.

4.2 Bulk density

Bulk density is the mass of soil per unit volume, typically expressed in grams per cubic centimetre (g cm^{-3}). It is an indicator of soil compaction and overall soil structure.

The results for bulk density across the six soil samples showed low variability. The mean bulk density is 1.38 g cm^{-3} , with a standard deviation of 0.04 g cm^{-3} , indicating low variability among the samples. The median value also matches the mean, reinforcing this observation of uniformity. This is also visually evident in the bulk density line graph in Figure 3. Bulk density values range from 1.33 g cm^{-3} to 1.45 g cm^{-3} . These low bulk density values generally suggest a loose soil structure with more pore spaces, which can be beneficial for root growth and water infiltration. The low variability in bulk density indicates uniform soil compaction across the study area.

4.3 Porosity

Porosity refers to the fraction of the soil volume

that is occupied by pores or voids. It is an indicator of the soil's ability to hold and transmit water and air.

Porosity across the field showed moderate variability. The mean porosity of the soil samples is 47.67% , with a standard deviation of 1.75% , indicating moderate variability. Porosity values range from 45% to 50% . Higher porosity reflects a greater volume of void spaces in the soil, which enhances its capacity to hold air and water. The moderate variability in porosity across the samples is an indication of relatively uniform soil structure within the study area. An inverse relationship between bulk density and porosity is evident in the data; as bulk density decreases, porosity increases. This relationship is crucial for understanding soil water retention and movement.

4.4 Bulk density vs fc at sample points

The strong negative correlation coefficient of -0.962 between soil bulk density and field capacity indicates a highly inverse relationship. As bulk density increases, the field capacity of the soil significantly decreases. This relationship suggests that denser soils, which have less pore space, are less capable of retaining water. High bulk density typically compresses the soil particles closer together, reducing the volume of pores that can hold water, thereby lowering the soil's field capacity, see Figure 3.

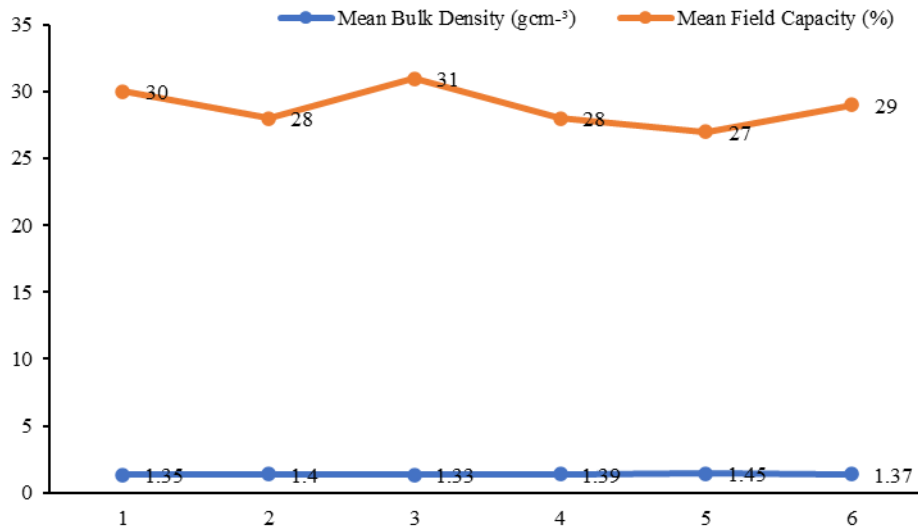


Figure 3 Relationship of bulk density to field capacity across sample points

4.5 Porosity vs FC at sample points

The very high positive correlation coefficient of 0.983 between soil porosity and field capacity indicates a strong direct relationship. This means that as soil porosity increases, the field capacity also increases significantly. High porosity implies a greater volume of pore spaces within the soil, which enhances its ability to retain water, thereby increasing the field capacity. This relationship is crucial for understanding soil water dynamics, as soils with higher porosity can hold more water and make it available to plants, which is beneficial for agricultural productivity, see Figure 4.

The results for bulk density indicate a decreasing trend with increasing soil depth. The mean bulk density is highest at the 0-15 cm depth (1.43 g cm⁻³) and gradually decreases to 1.33 g cm⁻³ at the 30-45 cm depth. This suggests that the surface soil is more compact, likely due to factors such as agricultural activities, foot traffic, and natural settling processes that commonly affect the upper soil layers. The standard deviation of 0.04 g cm⁻³ is consistent across all depths, indicating that the variability in bulk density measurements is similar throughout the soil profile.

4.6 Bulk density within soil profile

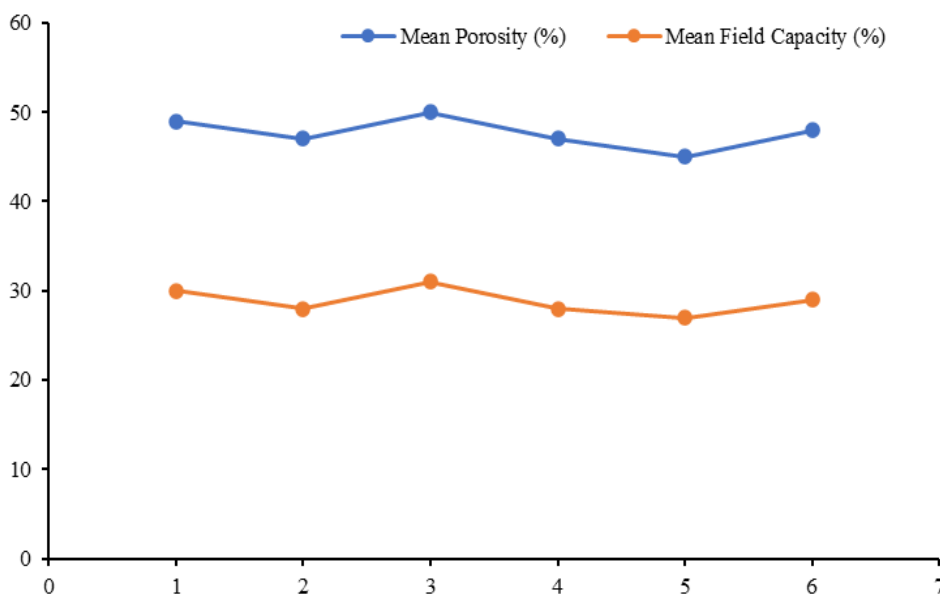


Figure 4 Relationship of porosity to field capacity across sample points

Table 1 Summary of results at within soil profile

| | Depth (cm) | Sand (%) | Silt (%) | Clay (%) | Mean bulk density (g cm ⁻³) | Mean porosity (%) | Mean field capacity (%) | Mean permanent wilting point (%) | Mean plant available water capacity (%) |
|--------------------|------------|----------|----------|----------|---|-------------------|-------------------------|----------------------------------|---|
| Mean | 0-15 | 63 | 21.33 | 15.67 | 1.43 | 45.67 | 26.83 | 13.33 | 13.5 |
| | 15-30 | 60 | 24.33 | 15.67 | 1.38 | 47.67 | 28.83 | 14.33 | 14.5 |
| | 30-45 | 57.5 | 26.83 | 15.67 | 1.33 | 49.67 | 30.83 | 15.33 | 15.5 |
| Standard Deviation | 0-15 | 5.66 | 2.8 | 3.01 | 0.04 | 1.75 | 1.47 | 1.03 | 0.55 |
| | 15-30 | 5.76 | 3.01 | 3.01 | 0.04 | 1.75 | 1.47 | 1.03 | 0.55 |
| | 30-45 | 5.39 | 2.56 | 3.01 | 0.04 | 1.75 | 1.47 | 1.03 | 0.55 |
| Median | 0-15 | 62.5 | 21 | 15.5 | 1.43 | 45.5 | 30.5 | 15 | 15.5 |
| | 15-30 | 59 | 24.5 | 15.5 | 1.38 | 47.5 | 28.5 | 14 | 14.5 |
| | 30-45 | 56.5 | 27 | 15.5 | 1.33 | 49.5 | 26.5 | 13 | 13.5 |
| Variance | 0-15 | 32 | 7.87 | 9.07 | 0 | 3.07 | 2.17 | 1.07 | 0.3 |
| | 15-30 | 33.2 | 9.07 | 9.07 | 0 | 3.07 | 2.17 | 1.07 | 0.3 |
| | 30-45 | 29.1 | 6.57 | 9.07 | 0 | 3.07 | 2.17 | 1.07 | 0.3 |

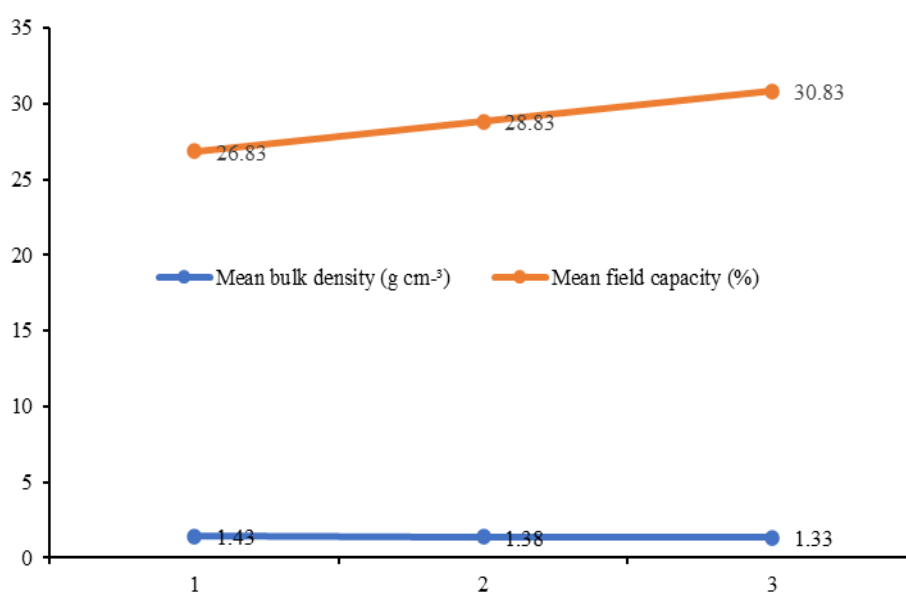


Figure 5 Relationship of bulk density to field capacity within soil profile

4.7 Bulk density vs FC within soil profile

A correlation coefficient of -1 between bulk density and field capacity indicates a perfect negative linear relationship between these two soil properties. In practical terms, this means that as the bulk density of the soil increases, its field capacity decreases in a consistent and predictable manner, see Figure 5.

4.8 Porosity within soil profile

For porosity, the result showed an increasing trend with increasing soil depth, inversely related to the bulk density. The mean porosity rises from 45.67% at the 0-15 cm depth to 49.67% at the 30-45 cm depth, indicating that deeper soil layers are less compact and have more pore space. This pattern is typical, as deeper soils are generally less impacted by

surface compaction and can retain more water and air, which are crucial for root growth and soil health. The standard deviation for porosity remains constant at 1.75% across all depths, suggesting consistent variability in porosity measurements.

4.9 Porosity vs FC within soil profile

A correlation coefficient of 1 between soil porosity and field capacity across the profile indicates a perfect positive linear relationship. This means that any increase in soil porosity directly results in an equivalent increase in field capacity. In practical terms, soils with higher porosity have more pore spaces available to retain water, thus enhancing the soil's ability to hold moisture see the linear relationship of porosity and field capacity in Figure 6.

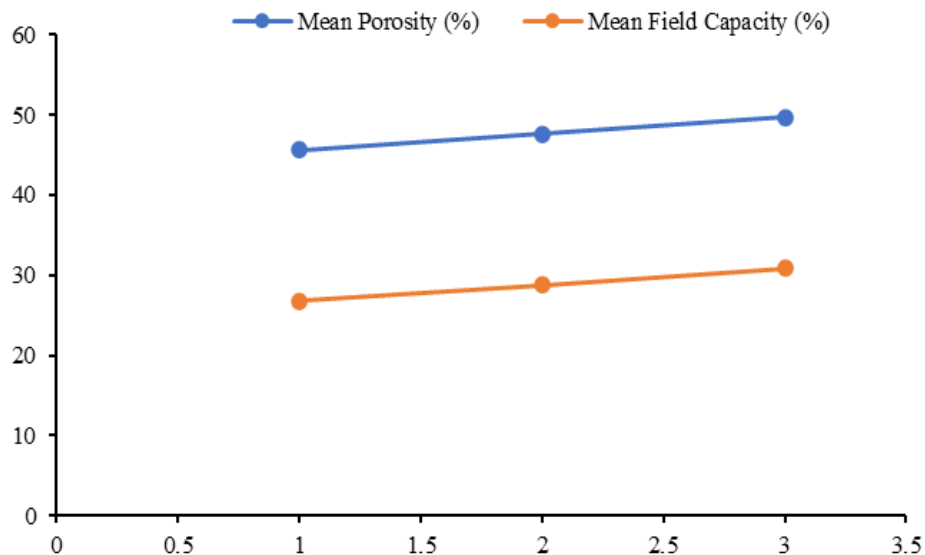


Figure 6 Relationship of porosity to field capacity within soil profile

5 Conclusion

The comprehensive analysis of soil physical properties in the Zobe Irrigation Area of Katsina State, Nigeria, has provided critical insights into optimizing irrigation strategies for enhancing agricultural productivity in semi-arid regions. The study has demonstrated the significant influence of soil texture, bulk density, porosity, and water holding capacity on the selection of appropriate irrigation methods. The predominantly sandy loam soil in the study area, characterized by high sand content and moderate silt and clay fractions, has shown good drainage properties but lower water retention capabilities.

The findings indicate that drip irrigation is the most suitable method for the study area, as it efficiently delivers water directly to the root zone, minimizing evaporation and runoff while ensuring consistent moisture levels. The mean bulk density of 1.38 g cm^{-3} and mean porosity of 47.67% further support the suitability of drip irrigation by indicating good soil structure and aeration. The strong negative correlation between sand content and field capacity (-0.72) and the positive correlation between porosity and field capacity (0.983) highlight the need for tailored irrigation approaches to maximize water use efficiency and crop yields.

The recommendation of drip irrigation is corroborated by existing literature, such as Aiswarya

et al. (2024), Zhang and Wu (2024), and Rodriguez-Sinobas et al. (2022), which emphasize the method's effectiveness in similar soil conditions. These studies underline the benefits of drip irrigation in maintaining soil moisture, reducing water loss, and enhancing water use efficiency.

5.1 Recommendations of irrigation techniques based on soil physical properties

Considering the summary of soil physical properties of the study area:

1) Soil texture: The soil texture is predominantly sandy loam, with sand content ranging from 52.33% to 67.67%, silt from 20.33% to 27.67%, and clay from 12% to 20%.

2) Bulk density and porosity: The mean bulk density is 1.38 g cm^{-3} , indicating moderate compaction. Mean porosity is 47.67%, showing good aeration and water movement.

3) Field capacity and permanent wilting point: The mean field capacity is 28.83%, and the permanent wilting point is 14.33%, suggesting moderate water retention capacity.

4) Plant available water capacity: The mean plant available water capacity is 14.5%, which is the water available to plants between field capacity and wilting point.

Based on the resulting soil Physical Properties, Drip irrigation is recommended as the most effective

technique in the study area. The soil's predominantly sandy loam texture, with high sand content (52.33%-67.67%) and moderate silt (20.33%-27.67%) and clay (12%-20%) contents, supports efficient water infiltration and distribution. Additionally, the mean bulk density of 1.38 g cm^{-3} and mean porosity of 47.67% indicate good soil structure and aeration, which are essential for maintaining consistent moisture levels. Drip irrigation's ability to deliver water directly to the root zone ensures that the soil remains within the optimal moisture range, as evidenced by the mean field capacity of 28.83% and permanent wilting point of 14.33%. This method also maximizes plant available water capacity (14.5%), enhancing water use efficiency and promoting healthy plant growth.

The recommendation of drip irrigation as the most effective technique for sandy loam soil is supported by several studies. One study by Aiswarya et al. (2024) highlighted that the vertical movement of water was faster in sandy loam soil under drip irrigation, ensuring efficient moisture distribution within the root zone, which is crucial for crops like chili. Another study by Zhang and Wu (2024) used computational fluid dynamics to show that subsurface drip irrigation effectively manages soil water dynamics in sandy loam soils, ensuring stable moisture levels. Furthermore, Rodriguez-Sinobas et al. (2022) compared surface and subsurface drip irrigation in loamy sand, demonstrating that subsurface drip systems maintain more consistent soil moisture levels, minimizing water loss. A study on grapes fields confirmed that drip irrigation maintains soil moisture effectively, with high uniformity and significant water use efficiency, crucial for sandy loam soil structures.

References

- Aiswarya, L., Siddharam, and M. Sandeepika. 2024. Soil moisture distribution pattern under drip irrigation in sandy loam soil using gravimetric method. *Asian Journal of Soil Science and Plant Nutrition*, 10(2): 198–204.
- Blake, G. R., and K. H. Hartge. 1986. Bulk density. In *Methods of Soil Analysis: Part I, Physical and Mineralogical Methods*, 2nd ed, ed. A. Klute, Ch. 14, 377-382. Madison, WI: American Society of Agronomy.
- Durodola, O. S., and K. A. Mourad. 2020. Modelling maize yield and water requirements under different climate change scenarios. *Climate*, 8(11): 127.
- El-Banna, E. B., Z. I. Ismail, A. E. Abu El-Magd, and M. A. El-Gamal. 2011. Irrigation water utilization as a function of soil mechanics and its properties. *Journal of Soil Sciences and Agricultural Engineering*, 2(7): 785–797.
- Eze, J. N., B. Z. Salihu, A. Isong, M. Musa, U. Aliyu, P. A. Ibrahim, A. U. Gbanguba, N. N. Ayanniyi, M. Alfa, P. A. Aremu, J. E. Ekaette, B. O. Olaniyan, M. O. Okachi, and M. Musa. 2022. Climate change impact on agriculture and water resources - A review. *Badeggi Journal of Agricultural Research and Environment*, 4(2): 72 – 85.
- Gee, G. W., and J. W. Bauder. 1986. Particle-size analysis. In *Methods of Soil Analysis: Part I Physical and Mineralogical Methods*, 2nd ed, ed. A. Klute, ch. 15, 388-411. Gidan District, North Wollo. *American Journal of Environmental Protection*
- Ibrahim, H., and M. Aliyu. 2019. Changes in River Channel form and Geometry below Dam Reservoir in Karadua Catchment, Katsina State, Nigeria. *Annals of Geographical Studies*, 2(3): 25–31.
- Khalil, L. A., and M. B. Abid. 2019. Numerical Simulation of Unsaturated Soil Water from a Trickle Irrigation System for Sandy Loam Soils. *Journal of Engineering*, 25(3): 38–52.
- Klute, A. 1986. Water retention: Laboratory methods. In *Methods of Soil Analysis: Part I Physical and Mineralogical Methods*, 2nd ed, ed. A. Klute, 635-662. 677 S. Segoe Road, American Society of Agronomy and Soil Science Society of America
- Lv, W., Y. Chang, D. Liu, and D. Li. 2022. Research on soil physical characteristics and dynamic response of groundwater to irrigation in typical irrigation area of Huangshui River Basin. *IOP Conference Series: Earth and Environmental Science*, 1035(1): 012002.
- Mahmood, A. B., A. U. Ibrahim, S. A. Abubakar, and S. M. Musa. 2023. Influence of selected grass mulches on soil physical properties under sprinkler irrigation system. *Global Journal of Engineering and Technology Advances*, 16(3): 82–89.
- Oladunni, A. A., U. A. Haruna, A. H. Olayemi, A. B. Adedoyin, A. C. Ndubisi, A. Terhemem, S. A. Umar, and D. E. Lucero-Prisno III. 2022. Agriculture and food security in Northern Nigeria, Part I: The implications of

- climate change. In *Advances in Food Security and Sustainability*, Vol. 7, ed. M. J. Cohen, ch. 6, 137-148. Amsterdam: Elsevier.
- Olayide, O. E., T. R. Alabi, J. Oyedepo, and R. Okechukwu. 2024. Assessing rainfall and extreme weather variability for climate resilient agricultural production systems in Nigeria. *Research Square*. <https://doi.org/10.21203/rs.3.rs-3808332/v1>
- Rodriguez-Sinobas, L., S. Zubelzu, J. J. Martín-Sotoca, and A. M. Tarquis Alfonso. 2022. Generalized Structure Function applied to Soil Water Content during surface and subsurface drip irrigation in a loamy soil. In *EGU General Assembly 2022*, EGU22-13526. Vienna, Austria, 23–27 May 2022.
- Shanono, N. J., N. M. Nasidi, and N. Y. Usman. 2022. Appraising the current state of irrigation schemes in northern Nigeria using sustainability pillars. *Environmental Research and Technology*, 5(4): 305–314.
- Teffera, Z. L., J. Li, T. Astatkie, and Z. M. Gebru. 2019. Effects of irrigation systems on physicochemical properties of soil at different depths: A case study at a farm near Ziway Lake, Ethiopia. *Irrigation and Drainage*, 68(2): 165–175.
- Towolawi, A. T., O. Oguntoke, B. S. Bada, and J. O Adejuwon. 2021. Water management and crop resistant varieties adaptation due to climate change by farmers. *Theoretical and Applied Climatology*, 155(4): 3405-3422.
- Vistro, R. B., M. A. Talpur, I. A. Shaikh, and M. A. Mangrio , 2022. Impact of tractor wheels on physical properties of different soil types and the irrigation efficiency of the furrow irrigation method. *Journal of Water and Land Development*, 52: 166–171.
- Zhang, H., and B. Wu. 2024. *Computational fluid dynamics investigation of subsurface drip irrigation 1 in sandy loam soil*. *Computers and Electronics in Agriculture*, 231: 109934.