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Spatial Variability of Soil Properties and Implications for Climate-Smart Rice Production in four Agricultural Zones in Anambra State, Nigeria

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Abstract

Spatial variability in soil properties strongly influences water dynamics, nutrient availability, and crop productivity in tropical agroecosystems, thereby affecting the sustainability of climate-smart rice production systems. This study evaluated the spatial variability of selected soil physical, hydraulic, and chemical properties across four agro-ecological zones (Awka, Anambra, Aguata, and Onitsha) of Anambra State, southeastern Nigeria. Surface soil samples (0–30 cm) were collected from georeferenced locations differing in elevation and landscape characteristics. Laboratory analyses were conducted to determine particle size distribution, bulk density (BD), saturated hydraulic conductivity (Ksat), soil pH, and organic matter (OM). Descriptive statistics, analysis of variance (ANOVA), correlation analysis, and principal component analysis (PCA) were employed to evaluate variability and relationships among soil properties. Results revealed considerable spatial heterogeneity across the study area. Sand content ranged from 332 to 582 g kg^{-1}, while clay content varied between 218 and 354 g kg^{-1}. Bulk density ranged from 1.346 to 1.458 g cm^{-3}, whereas Ksat varied from 0.0182 to 0.0468 cm hr^{-1}. Soil pH was moderately acidic (5.3–5.7), while OM content ranged from 2.2 to 3.3%. ANOVA indicated no significant zonal differences in Ksat and BD, suggesting that micro-scale variability exerted a stronger influence than agro-ecological classification. PCA explained 96.5% of total variability, with soil texture and hydraulic properties constituting the dominant controlling factors. The findings highlight the importance of site-specific soil and water management strategies for improving rice productivity, enhancing water-use efficiency, and strengthening climate resilience in southeastern Nigeria.

Keywords: climate-smart agriculture; hydraulic conductivity; precision agriculture; rice production; soil variability; sustainable soil management

Introduction

Soil is a fundamental resource underpinning global food security, supporting nearly 95% of food production worldwide (FAO, 2015). In tropical agroecosystems, soil water availability remains one of the most critical constraints to crop productivity, particularly for water-intensive crops such as rice. According to Lal (2020), the capacity of soil to store and transmit water is governed by its physical properties, including texture, structure, bulk density, and pore size distribution. These properties directly influence infiltration, hydraulic conductivity, and plant-available water, thereby determining crop performance under varying climatic conditions (Brandy & Weil, 2016; Wahab et al, 2025).

In recent decades, climate change has intensified variability in rainfall patterns, increasing the frequency of droughts and flooding events across sub-Saharan Africa. Nigeria is considered highly vulnerable to these changes, with rain-fed agricultural systems facing increasing uncertainty in water availability. In southeastern Nigeria, rice production is particularly sensitive to soil water dynamics, as both water deficit and excess can significantly reduce yield. Consequently, understanding the spatial variability of soil hydraulic properties is essential for developing adaptive and resilient agricultural systems (Wahab et al., 2024).

Soil heterogeneity, driven by variations in parent material, topography, land use, and management practices, results in significant differences in water retention and movement even within small geographic areas (Ball, 2001). Traditional agro-ecological zoning often fails to capture this micro-scale variability, leading to inefficient resource use and suboptimal crop performance. Advances in precision agriculture emphasise the importance of site-specific soil management, where inputs and practices are tailored to localised soil conditions to improve efficiency and sustainability (John et al., 2018; Wahab et al., 2024).

Furthermore, soil plays a critical role in climate change mitigation through carbon sequestration and the regulation of greenhouse gas emissions, thereby improving soil management practices, including optimised water and nutrient management, as it can enhance soil organic carbon stocks while reducing carbon dioxide emissions from agricultural systems. Integrating soil hydraulic characterisation with climate-smart agricultural practices, therefore, offers a pathway to achieving both productivity and environmental sustainability.

Despite the importance of soil water dynamics, there is limited spatially explicit information on the hydraulic properties of rice-growing soils in Anambra State. This knowledge gap constrains the development of effective irrigation strategies, drainage systems, and soil management interventions tailored to local conditions.

This study was therefore designed to evaluate the spatial variability of soil hydraulic properties across the four agricultural zones of Anambra State, determine the relationships among key soil physical properties influencing water movement, and assess the implications of these properties for climate-smart rice production and sustainable soil management.

Materials and Methods

Study Area

The study was conducted in Anambra State, southeastern Nigeria, located within the humid tropical rainforest agro-ecological zone. The area experiences a bimodal rainfall pattern with an annual precipitation range of approximately 2000–3000 mm and mean temperatures between 25 and 27°C. Relative humidity ranges from 75% to 95%, reflecting the high moisture regime typical of the region. The climate is characterised by two distinct seasons: a

rainy season extending from March to October and a dry season from November to February. The state is divided into four major agricultural zones, which are Aguata, Awka, Onitsha, and Anambra (Figure 1). Each exhibits variations in topography, soil type, and land use patterns. These zones collectively support extensive rice farming activities under predominantly rain-fed conditions.

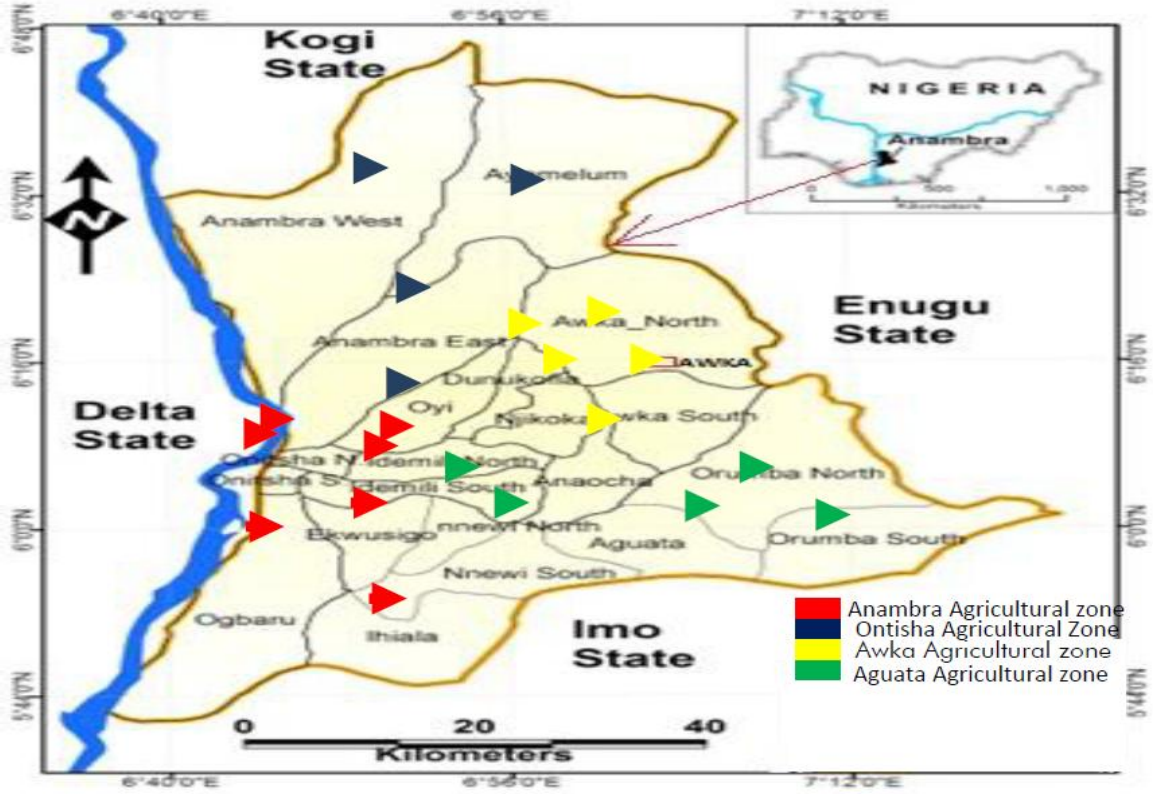


Figure 1. Anambra State Map showing the four (4) Agroecological zones used for the study

Experimental Design and Soil Sampling

A spatial sampling design was adopted to capture variability across the four agricultural zones. In each zone, twenty (20) sampling points were systematically selected, resulting in a total of eighty (80) sampling locations. Geographic coordinates and elevation data for each sampling point were recorded using a Global Positioning System (GPS) device.

Soil samples were collected from the surface layer (0–30 cm), representing the active root zone for rice cultivation. At each sampling point, disturbed soil samples were collected for laboratory analysis, while in-situ measurements of infiltration rate were conducted using a Mini-Disk Infiltrometer. Soil moisture content was also measured using a portable soil moisture meter.

Laboratory Analysis

Soil samples were air-dried, gently crushed, and sieved through a 2 mm mesh before analysis. The following standard procedures were employed: Particle size distribution (texture) was determined using the Bouyoucos hydrometer method (Kroetsch & Wang, 2008). Bulk density

(BD)wasmeasured using the core method (Quraishi & Mouazen, 2013). Hydraulic conductivity (Ksat)was determined under laboratory conditions (Bagarello et al., 2006). Soil organic matter was determined using the Walkley–Black oxidation method (Mylavarapu et al., 2014). Soil pH was measured using a pH meter in a soil-water suspension (Wahab et al., 2018). These parameters were selected due to their critical roles in controlling soil water retention, movement, and availability to crops.

Statistical and Multivariate Analysis

Descriptive statistics, including mean and standard deviation, were used to summarise soil properties across sampling locations and zones. A one-way Analysis of Variance (ANOVA) was performed to evaluate differences in Bulk density and hydraulic conductivity among the four agricultural zones. The Least Significant Difference (LSD) test at the 5% probability level was used for mean separation.

Principal Component Analysis (PCA) was conducted to identify the dominant factors controlling soil variability and to reduce dimensionality in the dataset. Eigenvalues and component loadings were used to interpret the contribution of each soil property to the observed variability. Correlation analysis was performed to examine relationships among soil physical properties, particularly those influencing water movement. All statistical analyses were carried out using appropriate analytical tools, while graphical outputs (scatter plots, PCA plots, and heatmaps) were generated to support interpretation.

Spatial Analysis (Framework)

Although spatial interpolation techniques such as kriging were considered for mapping soil properties, the current analysis focused on point-based evaluation of variability. Geographic coordinates were retained to support future geostatistical modelling and digital soil mapping applications.

Results and Discussion

Geographical spread of the study Area

The geographical data presented in Table 1 highlight notable spatial variation across the sampling locations. Although the towns fall within a narrow latitudinal band between 5.90°N and 6.54°N, indicating a shared humid tropical climate, there is considerable heterogeneity in their longitudinal and altitudinal positions. Longitude ranges from 6.69°E to 7.26°E, reflecting the east–west spread of the study area across different physiographic zones. A key pattern in Table 1 is the broad variation in altitude, spanning from 10 m in low-lying floodplain towns, Ogbaru (Onitsha Zone), to 76 m in upland locations like Ezira (Aguata Zone). These elevation differences are important because they influence drainage conditions, soil water dynamics, erosion potential, Infiltration, and runoff generation as stated by Vogel et al. (2019), thereby determining the pedological characteristics of each study area. The intermediate elevations observed in Awka and Anambra (27–44 m) suggest a transitional landscape positioned between the floodplain and upland environments.

Spatial Variability in Soil Physical and Hydraulic Properties Across Agro-Ecological Zones

The study revealed considerable spatial variability in soil physical and hydraulic properties across the four agro-ecological zones (Awka, Anambra, Aguata, and Onitsha) of Anambra State, reflecting the heterogeneous nature of tropical soils and the influence of landscape position, parent material, and land-use history, which aligned with Okebalama et al. (2025)

findings under two distinct depth layers in Nssuka, Enugu State. Sand content varied markedly across sampling locations (55–58%), with sandy loam (SL) and sandy clay loam (SCL) dominating several sites, while clayey (27–32%) soils were observed in locations such as Oba Ofemili and Ogboji. Bulk density (BD) ranged from approximately 1.26 to 1.50 g cm^{-3} (Table 2), indicating moderate soil compaction under cultivated conditions, whereas saturated hydraulic conductivity (Ksat) varied from 0.013 to 0.088 cm hr^{-1}, suggesting substantial differences in soil water transmission capacity. This texture typically supports good drainage and moderate water-holding capacity, consistent with USDA soil texture classifications. This observed variability was further influenced by topographic conditions and elevation differences among the sampling points. Low-lying locations are likely susceptible to prolonged saturation and seasonal flooding, while upland areas may experience rapid drainage and increased moisture deficits. Such topographic effects strongly influence runoff generation, infiltration, and redistribution of soil moisture within landscapes (Nearing et al., 2017; Vogel et al., 2019). The predominance of sandy and sandy clay loam soils in several locations implies relatively high infiltration rates but reduced water-holding capacity, whereas clay-rich soils exhibited greater moisture retention but lower permeability. Similar observations have been reported for tropical rice-growing soils in West Africa, where textural heterogeneity strongly controls water dynamics and nutrient availability (Bationo et al., 2018; Adekiya et al., 2020). The moderate bulk density values observed in the present study suggest that the soils remain within acceptable thresholds for root proliferation and water movement; however, localised compaction may still restrict aeration and infiltration in finer-textured soils.

The statistics in Table 3 provide an overview of the soil physical properties across all study locations. The mean clay content of 289 gkg^{-1} (SD = 135 gkg^{-1}) indicates a moderate dominance of finer particles in the soils, while the mean sand content of 434 gkg^{-1} (SD = 181 gkg^{-1}) reflects a significant proportion of coarse particles, consistent with the prevalence of sandy clay loam and sandy loam textures. Silt content averages 277 gkg^{-1} (SD = 126 gkg^{-1}), highlighting moderate intermediate particle fractions. The substantial standard deviations across all particle-size fractions suggest considerable heterogeneity in soil texture within the study area, likely influenced by variation in parent material, topography, and depositional environments (Brady and Weil, 2016; Buol et al., 2011). The mean hydraulic conductivity of 0.026 cm/hr (SD = 0.020) demonstrates generally low to moderate water transmission through the soils, reflecting the mixed textural composition and the presence of fine fractions that restrict water flow. Similarly, the mean bulk density of 1.39 g/cm^3 (SD = 0.08) indicates moderate compaction and good structural stability. The relatively low variation in bulk density compared to particle-size fractions suggests that, despite textural differences, soil compaction remains relatively uniform across locations.

The textural data presented in Table 2 shows clear spatial variation in the proportions of sand, silt, and clay across the study locations. Most of the sites are dominated by Sandy Clay Loam soils, characterised by moderate clay content and high sand fractions, as observed in towns such as Ugbenu, Ebenebe, Umubo Enu, Umumbo Ani, Ufuma, Omor, Ogbakuba, Osamara, and Ogbaru.

Measures of Central Tendency of Soil Physical and Hydraulic Properties Across Anambra Agro-Ecological Zones

Table 3 presents the mean values and standard deviations of selected soil physical and chemical properties across the four agro-ecological zones of Anambra State. The particle-size distribution revealed distinct textural variability among the agro-ecological zones. Awka and

Onitsha zones were predominantly sandy loam, characterised by high sand fractions of 546 and 582 g kg^{-1}, respectively. In contrast, Aguata recorded the highest clay content (354 g kg^{-1}), followed by Anambra (308 g kg^{-1}), resulting in clay and clay loam textural classifications. The overall mean soil texture across the zones was classified as clay loam, indicating moderate water-holding potential and structural stability.

The dominance of sandy loam soils in Awka and Onitsha suggests enhanced infiltration and drainage capacity due to the prevalence of macropores associated with coarse-textured soils. This observation was supported by the relatively higher Ksat values recorded in these zones. The Awka zone exhibited a mean Ksat of 0.0468 cm hr^{-1}, while Onitsha recorded 0.0421 cm hr^{-1}, indicating comparatively rapid water transmission. Sandy soils are generally associated with larger pore spaces and lower tortuosity, which facilitate rapid water movement but reduce water retention capacity (Zhao et al., 2018; Rahman et al., 2022).

Table 1. Geographic Characteristics of the Study Locations

Town	Zone	Latitude (°N)	Longitude (°E)	Altitude (m)
Mgbakwu	AWKA	6.29559	7.084598	42
Urum	AWKA	6.306895	7.063015	44
Oba Ofemili	AWKA	6.400368	7.072161	27
Ugbenu	AWKA	6.394439	7.077545	32
Ebenebe	AWKA	6.319670	7.256867	42
Umubo Enu	ANAMBRA	6.519923	6.986858	37
Umumbo Ani	ANAMBRA	6.523608	6.696614	39
Omo Enu	ANAMBRA	6.542068	6.960090	29
Omo Ani	ANAMBRA	6.454383	6.933053	36
Anaku	ANAMBRA	6.454383	6.933053	36
Ufuma	AGUATA	6.088848	7.218368	60
Akpu	AGUATA	6.024925	7.189122	68
Ogboji	AGUATA	6.017550	7.180243	72
Ezira	AGUATA	6.004443	7.172224	76
Omor	AGUATA	6.081503	7.159485	66
Ogbakuba	ONITHSA	5.914980	6.712871	10
Osamara	ONITHSA	5.903963	6.711108	14
Abon Atani	ONITHSA	5.984557	6.768723	17
Ogbaru	ONITHSA	6.026473	6.749403	10
Ogbakuba	ONITHSA	5.960353	6.731711	12

Table 2. Soil Texture Composition of the Study Locations

Town	Clay gkg^{-1}	Silt gkg^{-1}	Sand gkg-1	ksat $cmhr^{-1}$	Bulk density gcm^{-3}	Soil Class
Mgbakwu	100	260	640	0.088	1.50	Sandy Loam
Urum	110	260	630	0.081	1.50	Sandy Loam
Oba Ofemili	310	340	350	0.023	1.34	Clay Loam
Ugbenu	290	160	550	0.021	1.38	Sandy Clay Loam
Ebenebe	280	160	560	0.021	1.40	Sandy Clay Loam
Umubo Enu	270	160	570	0.022	1.42	Sandy Clay Loam
Umumbo Ani	280	160	560	0.021	1.45	Sandy Clay Loam
Omo Enu	360	450	190	0.014	1.29	Silty Clay Loam
Omo Ani	310	350	340	0.020	1.32	Clay Loam
Anaku	320	350	330	0.014	1.33	Clay Loam
Ufuma	280	160	560	0.033	1.46	Sandy Clay Loam
Akpu	350	510	140	0.014	1.28	Silty Clay Loam
Ogboji	510	250	240	0.013	1.26	Clay
Ezira	340	520	140	0.030	1.31	Clay Loam
Omor	290	120	580	0.031	1.42	Sandy Clay Loam
Ogbakuba	280	150	570	0.023	1.45	Sandy Clay Loam
Osamara	290	160	560	0.024	1.45	Sandy Clay Loam
Abon Atani	270	160	570	0.025	1.43	Sandy Clay Loam
Ogbaru	280	160	560	0.021	1.43	Sandy Clay Loam
Ogbakuba	120	230	650	2.014	1.53	Sandy Loam

Table 3. Measures of Central Tendency (Mean ± SD) of Selected Soil Physical and Chemical Properties Across Anambra State Agro-Ecological Zones, Nigeria

Zone	Clay (g kg⁻¹)	Silt (g kg⁻¹)	Sand (g kg⁻¹)	Ksat (cm hr⁻¹)	Bulk Density (g cm⁻³)	pH	Organic Matter (%)	Soil Class
AWKA	218	236	546	0.0468	1.424	5.7	2.2	Sandy Loam
ANAMBRA	308	294	398	0.0182	1.362	5.4	3.1	Clay Loam
AGUATA	354	312	332	0.0242	1.346	5.3	2.9	Clay
ONITSHA	248	172	582	0.0421	1.458	5.6	3.3	Sandy Loam
Across Zone	289	277	434	0.0260	1.395	5.5	2.7	Clay Loam
SD	13.5	12.6	18.1	0.0201	0.08	0.4	0.2	—

In contrast, sandy soils with low aggregation tend to experience rapid organic matter turnover and reduced carbon stabilisation. Conversely, Aguata and Anambra zones, characterised by higher clay and silt fractions, recorded lower hydraulic conductivity values of 0.0242 and 0.0182 cm hr^{-1}, respectively. The reduced conductivity observed in these zones may be attributed to smaller pore diameters, greater pore discontinuity, and increased resistance to water movement in fine-textured soils. Similar findings have been reported in tropical paddy soils where clay accumulation significantly reduced infiltration and saturated flow rates (Li et al., 2020; Adekiya et al., 2020).

Bulk density values ranged from 1.346 g cm^{-3} in Aguata to 1.458 g cm^{-3} in Onitsha. The relatively lower bulk density observed in Aguata may be associated with higher clay content and improved aggregation, whereas the higher bulk density recorded in Onitsha suggests greater susceptibility to compaction in coarse-textured soils. Sandy soils often exhibit weak aggregate stability and are prone to densification under repeated cultivation and low organic matter input (Blanco-Canqui and Ruis, 2018). Despite the moderate variation observed among zones, the overall mean bulk density of 1.395 g cm^{-3} indicates that the soils remain within acceptable limits for root development and water movement in most tropical cropping systems. However, values approaching 1.45 g cm^{-3} may begin to restrict root penetration and reduce infiltration in compacted locations, particularly under intensive rice cultivation (Rabot et al., 2018). The soil reaction across the agro-ecological zones ranged from moderately acidic to slightly acidic, with pH values varying between 5.3 and 5.7.

Aguata recorded the lowest mean pH (5.3), while Awka exhibited the highest value (5.7). The overall mean pH of 5.5 indicates that the soils of the study area are generally acidic, a condition commonly associated with highly weathered tropical soils under humid climatic conditions. Soil pH across all zones was moderately acidic (5.3–5.7), typical of humid tropical soils. Organic matter content was moderate, with the highest value observed in Onitsha (3.3%), likely influenced by lowland depositional processes and moisture retention. Although the pH values recorded are within ranges generally suitable for rice cultivation,

moderately acidic soils may reduce the availability of essential nutrients such as phosphorus, calcium, and magnesium while increasing the solubility of potentially toxic elements such as aluminium and manganese (Brady and Weil, 2016). Soil acidity also influences microbial activity, organic matter decomposition, and nutrient cycling, thereby affecting overall soil productivity and ecosystem functioning (Lal et al., 2021).

Organic matter (OM) content ranged from 2.2% in Awka to 3.3% in Onitsha, with an overall mean of 2.7%. The relatively higher OM values recorded in Onitsha and Anambra may be linked to lowland hydrological conditions that favour sediment deposition and slower decomposition rates due to periodic saturation. Conversely, the lower OM content observed in Awka may be attributed to rapid organic matter mineralisation and erosion losses associated with coarse-textured sandy loam soils. The moderate organic matter levels observed across the study area indicate a fair soil quality status for tropical agricultural systems. Organic matter plays a central role in improving soil aggregation, moisture retention, nutrient buffering capacity, and biological activity. It also contributes significantly to climate change mitigation through soil carbon sequestration (Paustian et al., 2019; Lal et al., 2021).

The standard deviation values obtained for clay (13.5 g kg^{-1}), sand (18.1 g kg^{-1}), Ksat (0.0201 cm hr^{-1}), and bulk density (0.08 g cm^{-3}) further confirm substantial spatial heterogeneity within the study area. Such variability indicates that generalised soil management recommendations may not adequately address localised differences in hydraulic behaviour and soil quality. Also, the relatively narrow standard deviation (SD = 0.4, 0.2 for pH and OM, respectively) suggests moderate spatial variability in soil pH and OM across the study area. However, even small changes in pH and OM can substantially alter nutrient dynamics and crop response under tropical conditions. Consequently, site-specific liming and nutrient management strategies may be required to optimise soil fertility and improve rice productivity (Lal et al., 2021.

Analysis of Variance (ANOVA) of Hydraulic Conductivity (Ksat) and Bulk Density (Bd)

The one-way ANOVA showed that Ksat and Bd did not differ significantly ($p = 0.228$ & $p = 0.081$, respectively) among the four agro-ecological zones (Table 4). The calculated F-values (1.603; 2.694, for Ksat and Bd, respectively) were lower than the critical value at $\alpha = 0.05$, indicating that zonal classification alone was insufficient to explain variability in Ksat. Furthermore, the Least Significant Differences ($LSD_{0.05}$ = 0.0298 cm hr^{-1} & 0.0918 g cm^{-3}) indicated that appreciable differences in Ksat and Bd are required before statistical separation among zone means can occur. This finding reflects substantial within-zone heterogeneity likely arising from localised differences in tillage intensity, puddling history, soil texture, organic matter content, machinery traffic, and seasonal wetting and drying cycles (Blanco-Canqui and Ruis, 2018; Rabot et al., 2018).

The non-significant zonal effect suggests that soil hydraulic characteristics are more strongly controlled by localised soil conditions than by broad ecological boundaries. This observation is consistent with recent studies emphasising that micro-scale variations in texture, aggregation, organic matter distribution, and land management exert a stronger influence on soil hydraulic behaviour than regional agro-ecological delineation (Minasny and McBratney, 2016; Zhang et al., 2021). However, the large within-zone variability observed in the present study may be attributed to differences in cultivation intensity, puddling history, residue management, and soil structural development. Rice cultivation systems often experience substantial spatial heterogeneity due to repeated wetting and drying cycles, which modify aggregate stability and pore continuity (Chen et al., 2018). Consequently, management

recommendations based solely on agro-ecological zoning may fail to adequately address field-level variability.

Principal Component Analysis (PCA) of Soil Properties

Principal Component Analysis revealed that the first two principal components (PC1 and PC2) accounted for 96.5% of the total variance (Table 5a), indicating strong data structure and efficient dimensional reduction. PC1 explained 72.3% of the variability and was positively associated with sand content, bulk density, and hydraulic conductivity, while clay content contributed negatively. PC2 accounted for 24.2% of the total variance and was primarily influenced by silt content and Ksat. The PCA loading pattern (Table 5b) indicates that PC1 represents a "soil water transmission axis," distinguishing coarse-textured soils characterised by rapid infiltration and high conductivity from fine-textured soils with greater water retention but restricted permeability. This reflects the fundamental role of particle-size distribution in determining pore geometry and hydraulic function (Rabot et al., 2018). The PC2 captures secondary variation related to intermediate particle sizes and structural influences.

The clustering pattern observed in the PCA plot (Figure 2) indicates that sandy soils promote rapid infiltration but low water retention. These relationships align with fundamental soil physics principles and confirm that texture-driven processes dominate soil water dynamics in the study area. In contrast, clay-rich soils clustered toward the negative region, indicating stronger water retention and reduced permeability. Similar clustering behaviour has been reported in studies evaluating soil hydraulic variability in rice ecosystems under tropical conditions (Li et al., 2020; Rahman et al., 2022).

Correlation Among Soil Physical Properties

Correlation analysis (Figure 3) revealed strong interactions among the measured soil properties. Sand content exhibited a strong positive relationship with bulk density, whereas clay content showed a strong negative correlation with hydraulic conductivity. These relationships indicate that texture was the dominant factor controlling soil water transmission across the study area.

Table 4: Effect of Agro-Ecological Zone on Hydraulic Conductivity (Ksat) and Bulk Density (Bd)

Ksat (cm/hr)

Source	SS	df	MS	F	p-value
Between Zones	0.002371	3	0.000790	1.603	0.228
Within Zones	0.007889	79	0.000493	—	—
Total	0.010260	82	—	—	—

Bd (g/cm^3)

Source	SS	df	MS	F-value	p-value
Between Zones	0.03788	3	0.01263	2.694	0.081
Within Zones	0.07500	16	0.00469	—	—
Total	0.11288	19	—	—	—

Ksat $LSD_{(0.05)}$ = 0.0298 cm hr^{-1} and Bd $LSD_{(0.05)}$ = 0.0918 g cm^{-3}

Table 5a: Principal Component Analysis (PCA) of Soil Properties

PCA	Eigenvalue	Variance Explained
PC1	3.62	72.3%
PC2	1.21	24.2%
PC3	0.13	2.5%
PC4	0.05	0.9%
PC5	~0	~0%

PC = Principal Component

Table 5b: PCA Loadings Matrix

Variable	PC1	PC2	PC3	PC4	PC5
Sand	+0.498	-0.284	-0.060	+0.328	-0.749
Silt	-0.344	+0.679	-0.331	-0.167	-0.533
Clay	-0.462	-0.388	+0.540	-0.435	-0.394
BD	+0.515	-0.044	-0.239	-0.822	+0.018
Ksat	+0.393	+0.554	+0.734	+0.004	-0.005

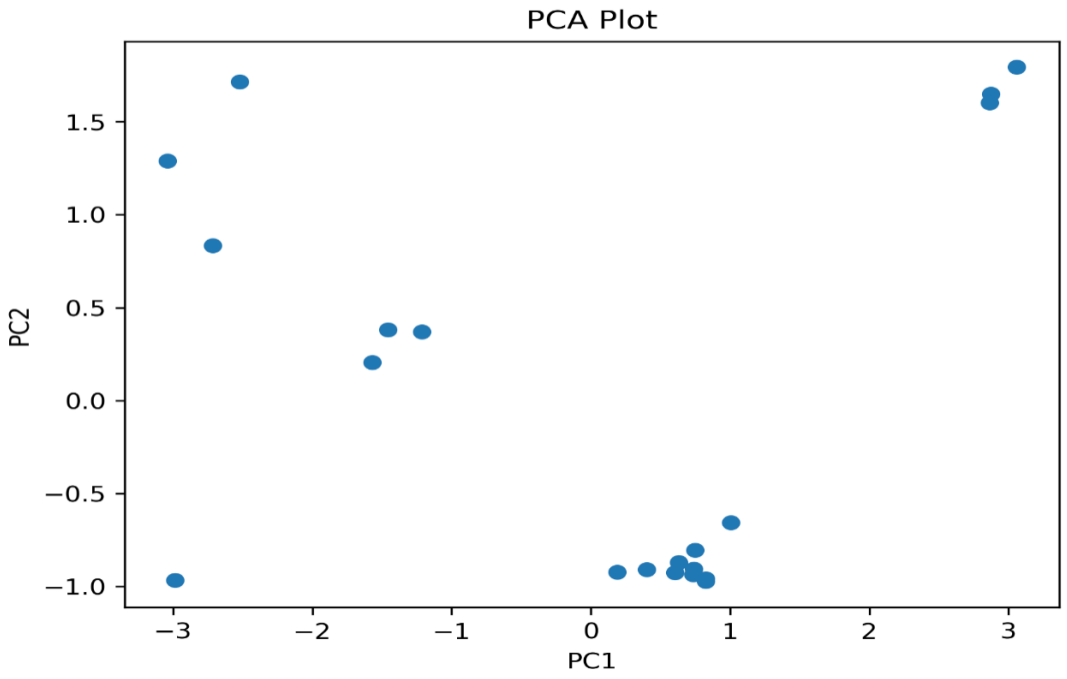


Figure 2. PCA plot for the clustering pattern of soil properties

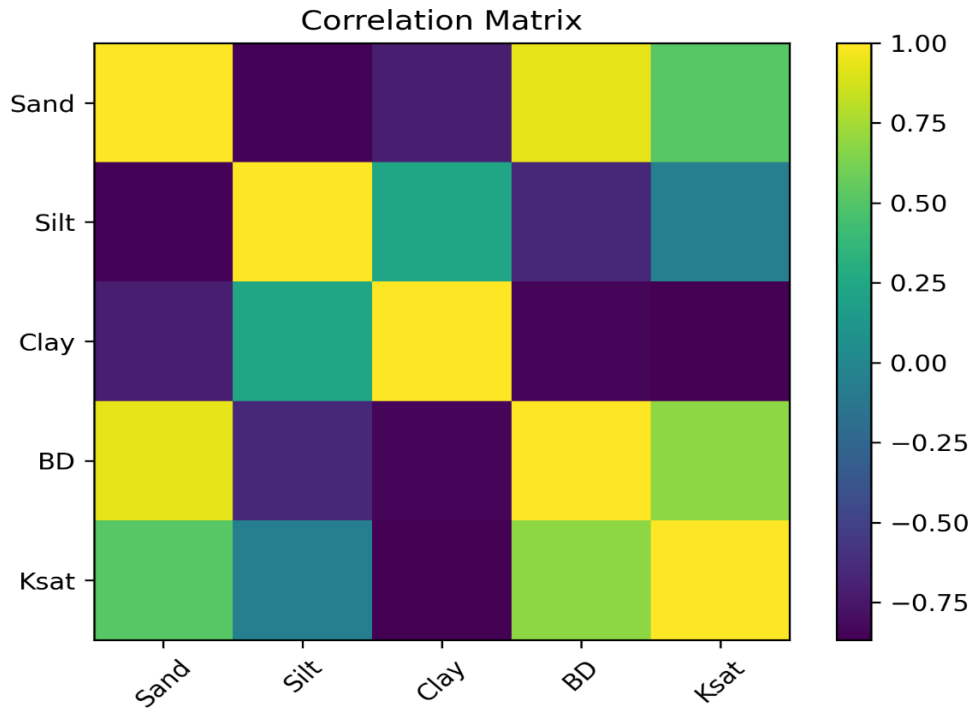


Figure 3. Correlation Matrix for the soil properties

The inverse relationship between clay content and Ksat reflects the reduced continuity of macropores in fine-textured soils. Clayey soils generally possess smaller pore spaces and higher tortuosity, which restrict water movement despite their high moisture retention capacity (Zhao et al., 2018). Conversely, sandy soils are characterised by larger pore diameters that facilitate rapid infiltration and drainage.

Interestingly, the moderate positive relationship observed between bulk density and hydraulic conductivity suggests that some sandy soils retained relatively high conductivity despite increased density. This observation may be attributed to the persistence of structural macropores or biological channels that maintain pore connectivity even under compacted conditions. Similar findings have been reported in structurally stable tropical soils with high biological activity (Blanchart et al., 2017).

Zone-Based Comparison of Soil Hydraulic Characteristics

Although slight differences were observed in mean hydraulic conductivity and bulk density among the four agro-ecological zones, these differences were not statistically significant. Nevertheless, notable spatial trends were evident. The Aguata zone, characterised by relatively higher elevations (60–76 m) as presented in Table 1, generally exhibited improved drainage conditions and lower susceptibility to waterlogging. In contrast, lowland areas within the Onitsha zone (10–17 m elevation) were more likely to experience prolonged moisture retention and seasonal flooding.

These observations demonstrate the importance of topographic position in influencing soil water dynamics. Elevation affects runoff velocity, infiltration opportunity time, and groundwater interactions, thereby shaping local hydrological conditions (Vogel et al., 2019). The integration of elevation data with soil hydraulic measurements, therefore, provides a stronger mechanistic basis for interpreting spatial variability. The lack of significant zonal

differences further confirms that agro-ecological classification alone is insufficient for predicting hydraulic behaviour. Instead, localised soil conditions and topographic variability remain the primary determinants of water movement within rice production systems.

Implications for Climate-Smart Rice Production

Rice production requires carefully regulated water conditions, and both water deficit and prolonged saturation can adversely affect root development, nutrient uptake, and grain yield. Consequently, the contrasting hydraulic behaviour observed across the study area underscores the need for site-specific water management strategies, including tailored irrigation scheduling, improved drainage systems, and organic matter enhancement. Improving soil organic matter content has been identified as a key strategy for increasing water-holding capacity, aggregate stability, and resilience to climatic extremes (Lal et al., 2021). Organic amendments can enhance pore continuity in compacted soils while simultaneously improving moisture retention in coarse-textured soils. Such interventions are particularly important in sub-Saharan Africa, where climate change is expected to intensify rainfall variability and increase production risks (IPCC, 2021).

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