



SPATIAL VARIABILITY AND GEOSTATISTICAL ANALYSIS OF SOIL FERTILITY INDICATORS IN GUSAU LOCAL GOVERNMENT AREA, ZAMFARA STATE, NIGERIA

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ABSTRACT

Soil fertility variability reveal a significant challenge to sustainable agriculture in tropical agroecosystems, particularly in sub-Saharan Africa. This study evaluated the spatial variability and geostatistical characteristics of soil fertility indicators in Gusau, Zamfara State, Nigeria. Using a systematic sampling approach across Wanke and Magami, 80 surface soil samples (0–20 cm) were analyzed for pH, organic carbon (OC), total nitrogen (TN), available phosphorus (AVP), exchangeable potassium (K), and cation exchange capacity (CEC). Descriptive statistics revealed low variability in pH, moderate variability in OC and K, and high variability in AVP, indicating pronounced spatial heterogeneity. Pearson correlation analysis showed weak to moderate relationships among properties, with OC and CEC emerging as primary drivers of nutrient dynamics. Regression analysis confirmed OC and CEC as significant predictors of soil fertility status ($p < 0.001$). Geostatistical analysis, employing semivariogram modeling and ordinary kriging, demonstrated moderate spatial dependence for most properties and revealed distinct spatial patterns across the landscape. Spatial distribution maps characterized the area as having slightly acidic soils, moderate OC, and adequate K availability, but widespread AVP deficiency. These findings underscore the necessity of site-specific nutrient management and the pivotal role of organic matter in stabilizing soil fertility. To enhance agricultural productivity and sustainability in the Sudan savanna region, the study recommends integrated soil fertility management practices, specifically prioritizing organic amendments and targeted phosphorus fertilization to address identified deficiencies. This research provides a critical and comprehensive framework for precision nutrient application to mitigate the negative effects of uneven soil conditions in northern Nigerian agroecosystems.

Keywords: Spatial variability, geostatistics, Soil fertility indicators; Available phosphorus; Soil organic carbon

INTRODUCTION

Soil fertility is a key factor influencing agricultural productivity and environmental sustainability, particularly in tropical agroecosystems where crop production largely depends on the nutrient-supplying capacity of soils. In many parts of sub-Saharan Africa, declining soil fertility has emerged as a major constraint to sustainable agricultural production due to continuous cultivation, nutrient mining, and inadequate nutrient replenishment. These challenges are often intensified by population pressure and land-use intensification, which place increasing demands on already fragile soil resources. As a result, maintaining soil fertility has become a major concern for ensuring food security and sustainable land management in many developing regions (Lal, 2018; Vanlauwe et al., 2019). In addition to nutrient depletion, soils within agricultural landscapes often exhibit considerable spatial variability in their physical and chemical properties. Soil variability arises from the combined effects of soil forming factors such as parent material, climate, topography, and biological activity, as well as land management practices including cultivation, fertilization, and residue management.

This spatial heterogeneity influences nutrient availability and crop productivity across agricultural fields. Understanding the spatial distribution of soil fertility indicators is therefore essential for improving nutrient management and optimizing agricultural production (Chivenge et al., 2021; FAO, 2022). Traditional soil fertility assessments often rely on point-based measurements that assume uniform soil conditions across large areas. However, such approaches may fail to capture the inherent spatial variability of soil properties, leading to inefficient fertilizer application and suboptimal crop

management practices. In recent years, geostatistical techniques have become increasingly important tools for analyzing spatial patterns of soil properties and for generating predictive maps of soil fertility indicators. Methods such as semivariogram analysis and kriging interpolation allow researchers to quantify spatial dependence and produce continuous surface maps that describe the spatial distribution of soil nutrients across landscapes (Webster & Oliver, 2007; Chivenge et al., 2021). Geostatistical analysis provides valuable information for site-specific nutrient management and precision agriculture, enabling farmers and land managers to apply inputs according to spatial variability within fields. This approach improves fertilizer efficiency, reduces production costs, and minimizes environmental impacts associated with excessive nutrient application. Consequently, spatial analysis of soil fertility indicators has become an important component of modern soil management strategies aimed at enhancing agricultural productivity and sustainability (Vanlauwe et al., 2019; FAO, 2022).

The Gusau Local Government Area of Zamfara State lies within the Sudan savanna agro-ecological zone of northwestern Nigeria, where agriculture constitutes the primary livelihood for rural communities. Major crops cultivated in the area include maize, sorghum, millet, groundnut, and cowpea. Despite the importance of agriculture in the region, detailed information on the spatial variability and distribution of soil fertility indicators remains limited. Such information is crucial for identifying nutrient deficiencies and developing appropriate soil management strategies for sustainable crop production. Therefore, this study aimed to evaluate the spatial variability and geostatistical characteristics of selected soil fertility indicators

in agricultural soils of the Gusau Local Government Area, Zamfara State, Nigeria. Specifically, the study assesses the spatial distribution of key soil chemical properties and applies geostatistical techniques to generate spatial maps that can support improved soil fertility management and sustainable agricultural practices in the study area.

MATERIALS AND METHODS

Study Area Description

The study was conducted in the Gusau Local Government Area, located in the northwestern part of Zamfara State. The area lies approximately between latitudes 12°00'–12°15' N and longitudes 6°30'–6°45' E and falls within the Sudan savanna agro-ecological zone of northern Nigeria. The climate of the region is characterized by distinct wet and dry seasons controlled by the movement of the intertropical convergence zone (ITCZ). Annual rainfall ranges between 700 and 900 mm, with the rainy season extending from May to September, while the dry season occurs from October to April. Mean annual temperatures range between 27 and 34°C. The vegetation of the area is dominated by typical Sudan savanna species consisting of scattered shrubs, grasses, and drought-tolerant trees. Agriculture represents the primary economic activity of the local population, with major crops including maize (*Zea mays*), sorghum (*Sorghum bicolor*), millet (*Pennisetum glaucum*), groundnut (*Arachis hypogaea*), and cowpea (*Vigna unguiculata*). The soils of the area are mainly derived from basement complex parent materials and are generally characterized by sandy loam to loamy sand textures, reflecting the dominance of coarse soil particles common in savanna environments.

Soil Sampling Design

A systematic soil sampling survey was conducted across representative agricultural fields within the study area to capture spatial variability of soil fertility indicators. Soil samples were collected from two agricultural locations within the Gusau Local Government Area, namely Wanke and Magami, which represent major cultivated areas within the region. At each location, forty (40) sampling points were established using a systematic sampling approach to adequately represent spatial variation across the cultivated fields. Soil samples were collected at two depth intervals: 0–20 cm (surface soil) and 20–50 cm (subsurface soil).

These depths represent the active root zone and the underlying soil layer influencing nutrient dynamics within the soil profile. At each sampling point, soil samples were collected using a hand auger at a depth of 0–20 cm, representing the surface soil layer where most crop roots and nutrient transformations occur. The surface soil was selected for the spatial variability analysis because it is the layer most influenced by agricultural management practices and plays a critical role in crop nutrient uptake. The collected samples were placed in labeled polyethylene bags indicating the sampling location and sample identification number. In total, 80 surface soil samples were collected across the two locations for laboratory analysis and geostatistical evaluation of soil fertility indicators. The soil samples were transported to the laboratory where they were air-dried, gently crushed, and passed through a 2-mm sieve to remove plant residues and coarse fragments prior to laboratory analysis.

Laboratory Analysis

The collected soil samples were air-dried at room temperature, gently crushed to break aggregates, and passed through a 2-mm sieve to remove coarse fragments, roots, and plant residues prior to laboratory analysis. The prepared soil

samples were analyzed for selected soil chemical properties relevant to soil fertility evaluation using standard analytical procedures widely adopted in soil science research.

Soil pH was determined potentiometrically in a 1:2.5 soil-to-distilled water suspension using a digital pH meter. Soil organic carbon (SOC) was determined using the Walkley–Black wet oxidation method, which involves oxidation of organic carbon with potassium dichromate and sulfuric acid followed by titration of the residual dichromate. Soil total nitrogen (TN) was determined using the macro-Kjeldahl digestion, distillation, and titration method, which measures the nitrogen present in organic forms and ammonium compounds in the soil (Burt, 2018; Hazelton & Murphy, 2019). Available phosphorus (P) was extracted using the Bray and Kurtz No. 1 extraction method, which is commonly applied to acidic and slightly neutral soils in tropical environments. The extracted phosphorus was determined colorimetrically using a spectrophotometer after the development of the phosphomolybdate blue complex. Exchangeable bases, including calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+), were extracted using 1 N ammonium acetate solution at pH 7.0. Calcium and magnesium were determined using atomic absorption spectrophotometry, while potassium and sodium were measured using a flame photometer (Hazelton & Murphy, 2019; FAO, 2022).

Exchangeable acidity, consisting of hydrogen (H^+) and aluminum (Al^{3+}), was extracted using 1 N potassium chloride (KCl) and determined by titration with standardized sodium hydroxide solution. The Effective Cation Exchange Capacity (CEC) was calculated as the sum of exchangeable bases (Ca^{2+} , Mg^{2+} , K^+ , and Na^+) and exchangeable acidity (H^+ and Al^{3+}). This parameter provides an estimate of the soil's ability to retain nutrient cations under natural soil conditions and is widely used in soil fertility evaluation studies (FAO, 2022; Chivenge et al., 2021). These laboratory determinations provided the key soil fertility indicators used for subsequent statistical and geostatistical analyses in the study.

Statistical and Geostatistical Analysis

Descriptive statistical analysis was first performed to evaluate the variability of soil fertility indicators across the study area. Statistical parameters including mean, minimum, maximum, standard deviation, and coefficient of variation (CV) were computed to summarize the distribution of the measured soil properties. The coefficient of variation was used to classify the degree of variability of soil properties into low ($\text{CV} < 15\%$), moderate (15–35%), and high ($>35\%$) variability, which provides an indication of the extent of spatial heterogeneity in the soils. Spatial variability of soil fertility indicators was analyzed using geostatistical techniques.

Experimental semivariograms were computed to determine the spatial dependence of soil properties using the semivariance function: where $\gamma(h)$ represents the semivariance at separation distance h , $N(h)$ is the number of data pairs separated by distance h , and $Z(x_i)$ and $Z(x_i+h)$ represent measured soil property values at locations x_i and x_i+h , respectively. The spatial structure of soil properties was described using semivariogram parameters including nugget (C_0), sill ($C_0 + C$), and range (A_0). The nugget represents unexplained variation caused by measurement errors or micro-scale variability, while the sill indicates the total variance of the variable. The range represents the distance beyond which spatial dependence between observations becomes negligible. Spatial dependence of soil properties was evaluated using the nugget-

to-sill ratio, which was classified as strong (<25%), moderate (25–75%), or weak (>75%) spatial dependence.

This classification helps determine the influence of intrinsic soil-forming factors and management practices on soil variability. Based on the fitted semivariogram models, ordinary kriging interpolation was applied to generate spatial distribution maps of selected soil fertility indicators across the study area. The kriging technique provides the best linear unbiased estimates of soil properties at unsampled locations and allows visualization of nutrient distribution patterns within the agricultural landscape. All statistical and geostatistical analyses were performed using appropriate statistical and GIS software to evaluate the spatial variability of soil fertility indicators in the study area.

RESULTS AND DISCUSSION

Descriptive Statistics and Variability of Soil Properties

Descriptive statistics of soil fertility indicators are presented in Table 1. Statistical measures such as mean, standard deviation, and coefficient of variation (CV) provide a quantitative framework for evaluating the variability and spatial heterogeneity of soil properties within the study area. The coefficient of variation is particularly useful in soil science for comparing the degree of dispersion among different soil attributes (Bünemann et al., 2018).

Soil pH exhibited low variability (CV < 15%), indicating a relatively homogeneous distribution across the study area. This suggests that soil reaction is primarily governed by intrinsic soil-forming factors such as parent material and climatic conditions rather than localized anthropogenic influences. Similar observations have been reported in tropical soils, where pedogenic processes exert dominant control over soil acidity at broader spatial scales (Lal, 2018; Minasny et al., 2019). The relative uniformity of soil pH implies a stable chemical environment, which is critical for nutrient solubility and microbial activity.

However, soil organic carbon (OC) and exchangeable potassium (K) exhibited moderate variability (CV = 15–35%), indicating the combined influence of inherent soil characteristics and management practices. The variability in OC is likely associated with differences in land use systems, vegetation cover, and organic residue management. Spatial differences in carbon inputs and decomposition rates have been widely reported as key drivers of OC variability in tropical agroecosystems (Lehmann et al., 2020; Chivenge et al., 2021). Similarly, the moderate variability observed in exchangeable potassium reflects the dual contribution of mineral weathering and anthropogenic nutrient depletion due

to continuous cultivation and uneven fertilizer application (Fageria et al., 2021).

Available phosphorus (AVP) showed high variability (CV > 35%), indicating pronounced spatial heterogeneity. This is consistent with the behavior of phosphorus in highly weathered tropical soils, where its availability is strongly influenced by fixation reactions with iron and aluminum oxides. Consequently, phosphorus distribution is often patchy and highly responsive to site-specific management practices (Hinsinger et al., 2018; Penn & Camberato, 2019).

Relationships among Soil Fertility Indicators

Beyond variability, understanding the relationships among soil properties is essential for interpreting soil fertility dynamics. Correlation analysis revealed that soil organic carbon exhibited a positive association with available phosphorus and exchangeable potassium, suggesting that organic matter plays a significant role in enhancing nutrient availability. This is attributable to the capacity of organic matter to improve cation exchange capacity (CEC), reduce phosphorus fixation, and enhance nutrient retention.

On the other hand, soil pH showed a moderate influence on nutrient availability, particularly phosphorus, reflecting the pH-dependent solubility of phosphate compounds. Slightly acidic to neutral pH conditions are generally optimal for phosphorus availability in tropical soils, whereas extreme acidity promotes fixation.

Implications for Soil Fertility Management

The observed variability patterns and interrelationships among soil properties highlight the complexity of soil fertility dynamics in the study area. The coexistence of low variability (pH), moderate variability (OC and K), and high variability (AVP) suggests that different soil nutrients respond differently to both pedogenic processes and land management practices. This heterogeneity underscores the need for site-specific nutrient management strategies rather than blanket fertilizer recommendations. In particular: Areas with low phosphorus levels require targeted P fertilization and organic amendments. Management practices that enhance organic matter (e.g., residue retention, manure application) should be prioritized to improve overall soil fertility. Balanced fertilization strategies are essential to address nutrient imbalances and sustain productivity. These findings are consistent with previous studies emphasizing the importance of precision soil fertility management in tropical agroecosystems (Vanlauwe et al., 2019).

Table 1: Descriptive Statistics of Soil Fertility Indicators

Parameter	Min	Max	Mean	Std. Dev	CV (%)	Variability Class
pH	5.6	6.5	6.1	0.25	4.1	Low
OC (%)	0.85	1.48	1.2	0.18	15	Moderate
AVP (mg/kg)	3.2	18.5	9.8	4.2	42.8	High
K (cmol/kg)	0.12	0.45	0.31	0.09	29	Moderate

Field date 2025

Pearson Correlation Matrix of Selected Soil Fertility Properties in Wanke, Study Area

The Pearson correlation matrix (Table 2) revealed predominantly weak to moderate relationships among the measured soil fertility properties, indicating complex interactions typical of tropical soils with sandy loam characteristics.

Soil pH showed weak positive correlations with organic carbon (OC; $r = 0.08$), total nitrogen (TN; $r = 0.07$), and

available phosphorus (AVP; $r = 0.25$), while weak negative relationships were observed with exchangeable potassium (K; $r = -0.02$) and cation exchange capacity (CEC; $r = -0.15$). The weak association between pH and OC/TN suggests that soil organic matter dynamics in the study area are not strongly controlled by soil reaction, which is consistent with findings in tropical soils where rapid mineralization limits organic matter accumulation (Adekiya et al., 2020). The slight positive relationship between pH and AVP indicates that

phosphorus availability may increase marginally with increasing pH, likely due to reduced fixation under near-neutral conditions (Hinsinger et al., 2021).

Organic carbon exhibited a weak positive correlation with total nitrogen ($r = 0.24$), reflecting the close linkage between carbon and nitrogen cycles, as nitrogen is largely stored in soil organic matter pools. This relationship aligns with established soil fertility principles and corroborates reports that soils with higher organic carbon tend to support improved nitrogen availability (Lal, 2020). However, OC showed negligible negative correlations with AVP ($r = -0.04$) and K ($r = -0.04$), and a very weak positive relationship with CEC ($r = 0.03$), suggesting that organic matter content in the study area may be relatively low and insufficient to significantly influence nutrient retention capacity.

Total nitrogen demonstrated a moderate and statistically significant positive correlation with exchangeable K ($r = 0.35^*$), indicating that soils with higher nitrogen content also tend to have higher potassium levels. This may be attributed to shared sources such as organic matter decomposition and fertilizer inputs, or to improved nutrient retention in relatively more fertile microsites. Conversely, TN had weak negative relationships with AVP ($r = -0.08$) and CEC ($r = -0.08$), suggesting that nitrogen availability is not strongly associated with phosphorus dynamics or cation exchange processes in the study area.

Available phosphorus showed a significant negative correlation with exchangeable K ($r = -0.35^*$), implying a potential antagonistic interaction or differential nutrient dynamics. This inverse relationship may reflect competitive adsorption processes or varying fertilizer management

practices influencing nutrient availability (Fageria et al., 2021). The weak positive correlation between AVP and CEC ($r = 0.13$) suggests that soils with slightly higher exchange capacity may retain more phosphorus, although the relationship remains minimal.

Exchangeable potassium exhibited weak and negative correlations with most variables except TN, reinforcing its relative independence from other soil properties in the study area. The negative relationship between K and CEC ($r = -0.06$) is unexpected, as higher CEC soils typically retain more cations; however, this may be due to the dominance of sandy fractions with low clay and organic matter content, limiting cation retention capacity (Brady & Weil, 2022). Cation exchange capacity (CEC) generally showed weak correlations with all variables, including OC ($r = 0.03$), TN ($r = -0.08$), and AVP ($r = 0.13$), indicating that CEC in the study area is likely controlled more by inherent soil texture (sandy loam) than by organic matter content. This observation is consistent with tropical soils where low-activity clays and limited organic matter reduce the influence of SOM on CEC (Six et al., 2019).

General, the dominance of weak correlations suggests limited nutrient interdependence and highlights the inherently low fertility status and poor nutrient retention capacity of the soils in Wanke. The few significant relationships (TN–K and AVP–K) indicate localized interactions that may be influenced by management practices or micro-environmental variability. These findings emphasize the need for integrated soil fertility management strategies, including organic matter amendments and balanced fertilization, to improve nutrient availability and sustain soil productivity in the study area.

Table 2: Pearson Correlation Matrix of Selected Soil Fertility Properties in Wanke, Study Area

Variable	pH	OC	TN	AVP	K	CEC
pH	1	0.08	0.07	0.25	-0.02	-0.15
OC	0.08	1	0.24	-0.04	-0.04	0.03
TN	0.07	0.24	1	-0.08	0.35*	-0.08
AVP	0.25	-0.04	-0.08	1	-0.35*	0.13
K	-0.02	-0.04	0.35*	-0.35*	1	-0.06
CEC	-0.15	0.03	-0.08	0.13	-0.06	1

Field date 2025

Pearson Correlation Matrix of Selected Soil Fertility Properties in Magami, Study Area

The Pearson correlation matrix (Table 3) for Magami revealed a mixture of weak, moderate, and statistically significant relationships among the selected soil fertility parameters, indicating relatively stronger nutrient interactions compared to Wanke. This suggests a more functionally integrated soil system, possibly influenced by variations in organic matter inputs and management practices.

Soil pH exhibited weak positive correlations with organic carbon (OC; $r = 0.21$), available phosphorus (AVP; $r = 0.18$), exchangeable potassium (K; $r = 0.27$), and cation exchange capacity (CEC; $r = 0.05$), while a weak negative relationship was observed with total nitrogen (TN; $r = -0.09$). The generally weak associations indicate that soil reaction has limited direct control over nutrient dynamics in the study area. However, the positive trend with AVP and K suggests that near-neutral pH conditions may slightly enhance nutrient availability, particularly phosphorus solubility and base cation retention (Hinsinger et al., 2021).

Organic carbon demonstrated a moderate and statistically significant positive correlation with available phosphorus ($r = 0.33^*$) and a strong positive correlation with CEC ($r = 0.48^{**}$). The OC–CEC relationship is particularly important,

indicating that soil organic matter contributes substantially to the cation exchange capacity in Magami soils. This aligns with established findings that organic matter enhances charge development and nutrient retention, especially in tropical soils with low-activity clays (Lal, 2020; Brady & Weil, 2022). The positive OC–AVP relationship further suggests that organic matter mineralization may be contributing to phosphorus availability through organic P release and reduced fixation (Adekiya et al., 2020).

Total nitrogen showed a significant negative correlation with available phosphorus ($r = -0.36^*$), indicating a possible antagonistic relationship between nitrogen and phosphorus in the study area. This may be attributed to differential nutrient uptake by plants, microbial immobilization, or imbalanced fertilizer application, where increased nitrogen availability does not correspond with phosphorus supply (Fageria et al., 2021). TN also exhibited weak negative correlations with K ($r = -0.22$) and CEC ($r = -0.03$), suggesting limited association with exchange processes and base cation dynamics.

Available phosphorus displayed a significant positive relationship with OC ($r = 0.33^*$) and moderate positive correlations with K ($r = 0.21$) and CEC ($r = 0.29$). The positive association with CEC indicates that soils with higher

exchange capacity may retain more phosphorus, likely through adsorption onto clay and organic matter surfaces. This supports the role of soil organic matter and colloidal fractions in regulating phosphorus availability (Hinsinger et al., 2021).

Exchangeable potassium showed weak to moderate positive correlations with pH ($r = 0.27$), AVP ($r = 0.21$), and CEC ($r = 0.12$), but negative relationships with OC ($r = -0.07$) and TN ($r = -0.22$). The positive association with pH suggests that K availability may increase under less acidic conditions due to reduced leaching and improved retention. However, the weak relationships overall indicate that potassium dynamics in the study area may be influenced more by external inputs and soil mineralogy than by organic matter.

Cation exchange capacity (CEC) exhibited its strongest relationship with organic carbon ($r = 0.48^{**}$), confirming that organic matter is a major contributor to the soil's exchange capacity in Magami. Weak positive correlations with AVP (r

$= 0.29$) and K ($r = 0.12$) further suggest that higher CEC enhances nutrient retention, although these relationships are not statistically significant. The negligible relationship with TN ($r = -0.03$) indicates that nitrogen availability is less dependent on cation exchange processes, as it is primarily governed by biological transformations.

Overall, the correlation pattern in Magami indicates a more pronounced influence of soil organic matter on nutrient dynamics compared to Wanke. The significant OC–CEC and OC–AVP relationships highlight the central role of organic matter in improving soil fertility through enhanced nutrient retention and availability. Conversely, the negative TN–AVP relationship suggests potential nutrient imbalance, emphasizing the need for integrated nutrient management. These findings underscore the importance of organic amendments, balanced fertilization, and sustainable soil management practices to optimize nutrient interactions and improve soil productivity in the study area.

Table 3: Pearson Correlation Matrix of Selected Soil Fertility Properties in Magami, Study Area

Variable	pH	OC	TN	AVP	K	CEC
pH	1	0.21	-0.09	0.18	0.27	0.05
OC	0.21	1	0.17	0.33*	-0.07	0.48**
TN	-0.09	0.17	1	-0.36*	-0.22	-0.03
AVP	0.18	0.33*	-0.36*	1	0.21	0.29
K	0.27	-0.07	-0.22	0.21	1	0.12
CEC	0.05	0.48**	-0.03	0.29	0.12	1

Field date 2025

Regression Analysis of Selected Soil Fertility Properties in Wanke and Magami Study Area

The regression analysis (Table 4) evaluated the influence of selected soil fertility variables on the dependent variable (Soil Fertility Index, SFI). The model identified organic carbon (OC) and cation exchange capacity (CEC) as significant predictors, while bulk density (BulkD) and the intercept were not statistically significant at $p < 0.05$.

Organic carbon (OC) exhibited a strong positive and highly significant effect on SFI ($\beta = 0.39733$; $F = 53.81$; $p < 0.0001$). This indicates that increases in soil organic carbon significantly enhance soil fertility status in the study areas. The high Type II sum of squares (90.64) further confirms that OC explains a substantial proportion of the variability in soil fertility. This finding underscores the central role of soil organic matter as a key driver of soil productivity through its influence on nutrient supply, microbial activity, and soil structure. Similar results have been widely reported in tropical soils, where organic carbon is considered the backbone of soil fertility due to its role in nutrient cycling and retention (Lal, 2020; Adekiya et al., 2020).

Cation exchange capacity (CEC) also showed a significant positive contribution to soil fertility ($\beta = 0.25264$; $F = 29.81$; $p < 0.0001$). The relatively high Type II SS (50.22) indicates that CEC is another major determinant of SFI in the study area. This relationship reflects the ability of soils with higher exchange capacity to retain essential cations such as Ca^{2+} , Mg^{2+} , and K^{+} , thereby enhancing nutrient availability and reducing leaching losses. The significance of CEC in this model is consistent with established soil science theory, which identifies CEC as a critical indicator of soil nutrient-holding capacity, particularly in tropical soils with variable charge characteristics (Brady & Weil, 2022).

Bulk density (BulkD) had a negative but non-significant effect on soil fertility ($\beta = -1.52362$; $F = 2.43$; $p = 0.1214$). Although the negative coefficient suggests that increasing soil compaction may reduce soil fertility, the lack of statistical significance indicates that BulkD does not strongly influence SFI within the observed range of values. This may be due to relatively uniform soil texture (sandy loam) across the study sites, which limits variability in bulk density and its impact on root growth and water movement. Nevertheless, the negative trend aligns with previous findings that higher bulk density can restrict root penetration, reduce aeration, and limit microbial activity (Hamza & Anderson, 2021).

The intercept ($\beta = 3.18537$; $p = 0.0716$) was not statistically significant, suggesting that the baseline soil fertility level without the contribution of the explanatory variables is not substantially different from zero within the model context.

Overall, the regression results indicate that soil organic carbon and cation exchange capacity are the dominant factors controlling soil fertility in Wanke and Magami. The stronger influence of OC compared to CEC suggests that improving organic matter content should be the primary management focus. The findings highlight the importance of organic amendments, residue retention, and conservation practices in enhancing soil fertility. Furthermore, the combined significance of OC and CEC demonstrates the interdependence of soil organic matter and nutrient retention mechanisms in sustaining soil productivity.

From a management perspective, these results support the adoption of integrated soil fertility management (ISFM) practices, including the use of organic manures, compost, and cover crops alongside inorganic fertilizers. Such approaches can simultaneously improve soil organic carbon levels and enhance cation exchange capacity, thereby optimizing nutrient availability and long-term soil health.

Table 4: Regression Analysis of Selected Soil Fertility Properties of the Study Area

Variable	Parameter	Standard	Type II SS	F Value	Pr > F
	Estimate	Error			
Intercept	3.18537	1.75529	5.54694	3.29	0.0716
OC	0.39733	0.05416	90.63814	53.81	<.0001
CEC	0.25264	0.04627	50.21798	29.81	<.0001
BulkD	-1.52362	0.97784	4.08928	2.43	0.1214

Field date 2025

Spatial Distribution

The spatial analysis of soil fertility indicators across Gusau Local Government Area (LGA) (figures 1 to 4) revealed marked heterogeneity in soil pH, organic carbon (OC), available phosphorus (AVP), and exchangeable potassium (K), reflecting the combined influence of soil-forming factors, climatic conditions, and land management practices. The integration of kriging-based spatial interpolation with soil fertility parameters provided a robust framework for understanding nutrient distribution patterns and their implications for sustainable agricultural production in the Sudan savanna agro-ecological zone. Soil pH across the study area ranged from moderately acidic (5.60–6.00) to slightly acidic (6.10–6.50), with slightly acidic conditions dominating most parts of the landscape, particularly in the central, southern, and eastern regions. The spatial continuity of slightly acidic pH values suggests a relatively stable soil chemical environment across large portions of the study area. However, the occurrence of moderately acidic zones, particularly in the northern region, indicates areas subjected to more intense leaching and base cation depletion. Under such conditions, essential nutrients such as calcium and magnesium are removed from the soil profile, while exchangeable aluminum becomes more dominant, potentially leading to reduced nutrient availability and toxicity effects on plant roots. This pattern is consistent with the behavior of tropical savanna soils, where high rainfall intensity and sandy loam texture promote leaching processes that influence soil reaction and nutrient dynamics (Lal, 2018; Minasny et al., 2019). The moderate spatial dependence observed in soil pH further suggests that both intrinsic factors (such as parent material and mineralogy) and extrinsic factors (including land use practices and fertilizer application) contribute to its spatial variability. Topographic variation may also play a role, as elevated landscape positions are

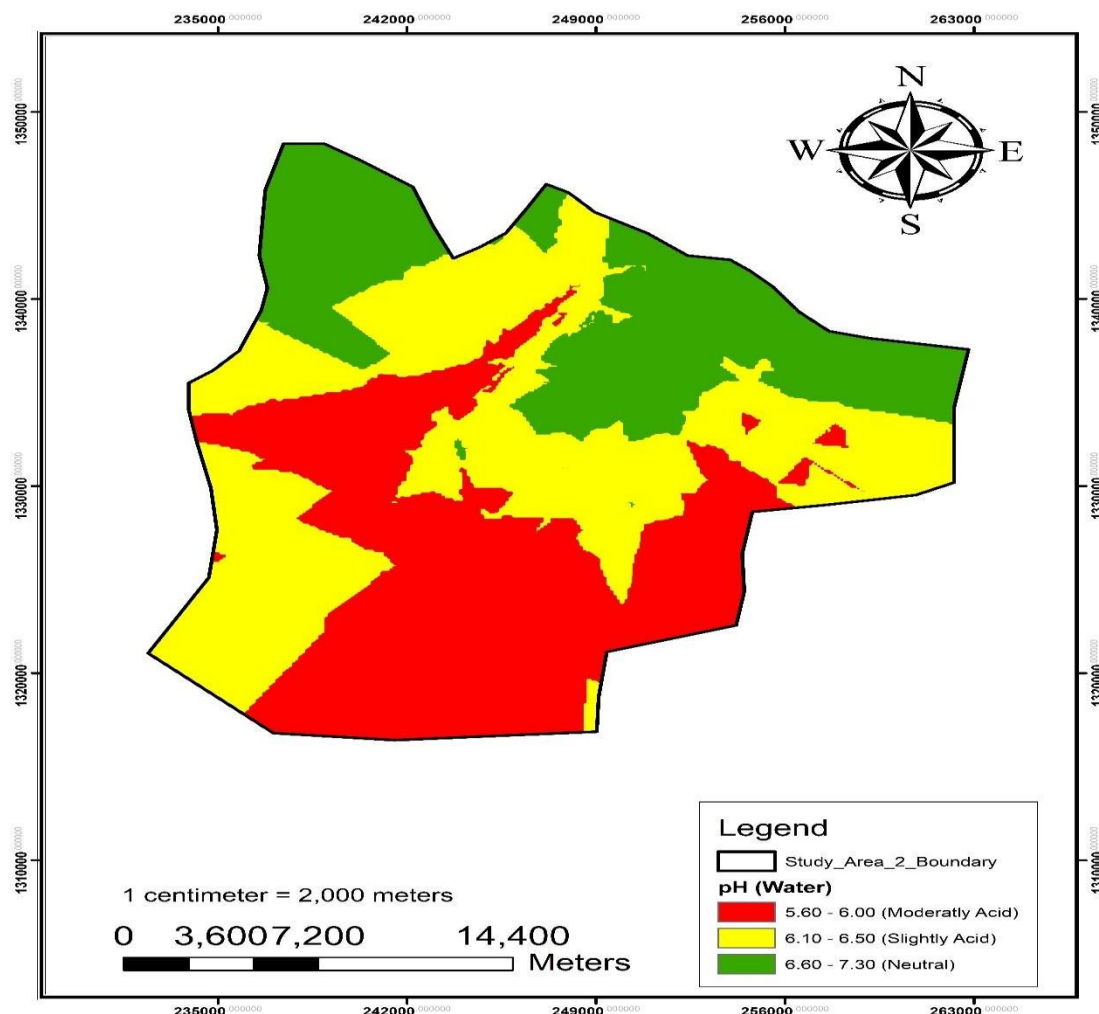


Figure 1: Soil Reaction (pH) Distribution of the Study Area

Typically more prone to leaching, while lower positions may accumulate base cations. Soil organic carbon (OC) exhibited a relatively uniform spatial distribution, with medium OC levels (1.00–1.50%) dominating the study area and localized pockets of low OC (<1.00%) occurring in the northern, southeastern, and southwestern regions. The predominance of moderate OC levels suggests that the soils maintain a baseline level of organic matter input, likely derived from crop residues and natural vegetation. However, the presence of low OC zones highlights areas where organic matter depletion has occurred, possibly due to continuous cultivation, residue removal, and limited organic input. Organic carbon is a critical component of soil fertility, influencing nutrient cycling, soil aggregation, water retention, and microbial activity. In tropical environments, however, OC levels are often constrained by rapid decomposition rates driven by high temperatures and moisture availability (Lehmann et al., 2020). The spatial variability of OC observed in this study reflects the interaction between climatic conditions and land management practices, particularly the intensity of cultivation and organic matter management. Areas with reduced OC are likely associated with nutrient mining and soil degradation, a common phenomenon in sub-Saharan Africa (Vanlauwe et al., 2019; Chivenge et al., 2021). Available phosphorus (AVP) displayed pronounced spatial variability, with low concentrations (0–10 mg kg⁻¹) dominating most of the study area and medium levels (10–20 mg kg⁻¹) confined to localized zones, particularly in the southwestern and northwestern regions. This distribution clearly indicates that phosphorus is the primary limiting nutrient in the soils of Gusau LGA. The persistence of low phosphorus levels despite moderately favorable pH and OC conditions suggests that phosphorus availability is not solely controlled by soil reaction or organic

matter content but is strongly influenced by fixation processes. In tropical soils, phosphorus is often immobilized through adsorption onto iron and aluminum oxides, forming stable compounds that are not readily available for plant uptake (Hinsinger et al., 2018; Penn & Camberato, 2019). This explains the observed mismatch between relatively favorable pH conditions and low phosphorus availability in the study area. The moderate to strong spatial structure of AVP further indicates that soil mineralogy and localized management practices play significant roles in determining phosphorus distribution. Exchangeable potassium (K), in contrast, exhibited generally adequate to high levels, with concentrations exceeding 0.30 cmol kg⁻¹ in large portions of the central and southern regions. Medium levels were observed in transitional zones, while low potassium concentrations occurred as isolated patches. The relatively high potassium status of the soils is likely attributed to the weathering of potassium-bearing minerals such as feldspars and micas, which are common in many tropical soils. The spatial variability of potassium reflects moderate spatial dependence, indicating that its distribution is influenced by both inherent soil properties and management practices. Unlike phosphorus, potassium is less affected by fixation processes and is more readily available in the soil solution, although it can still be depleted through continuous cropping and leaching. The localized zones of low potassium observed in the study area likely represent areas of nutrient depletion due to intensive cultivation and insufficient replenishment. The integrated analysis of soil pH, OC, AVP, and K reveals a coherent pattern of soil fertility dynamics characterized by slightly acidic soil conditions, moderate organic carbon levels,

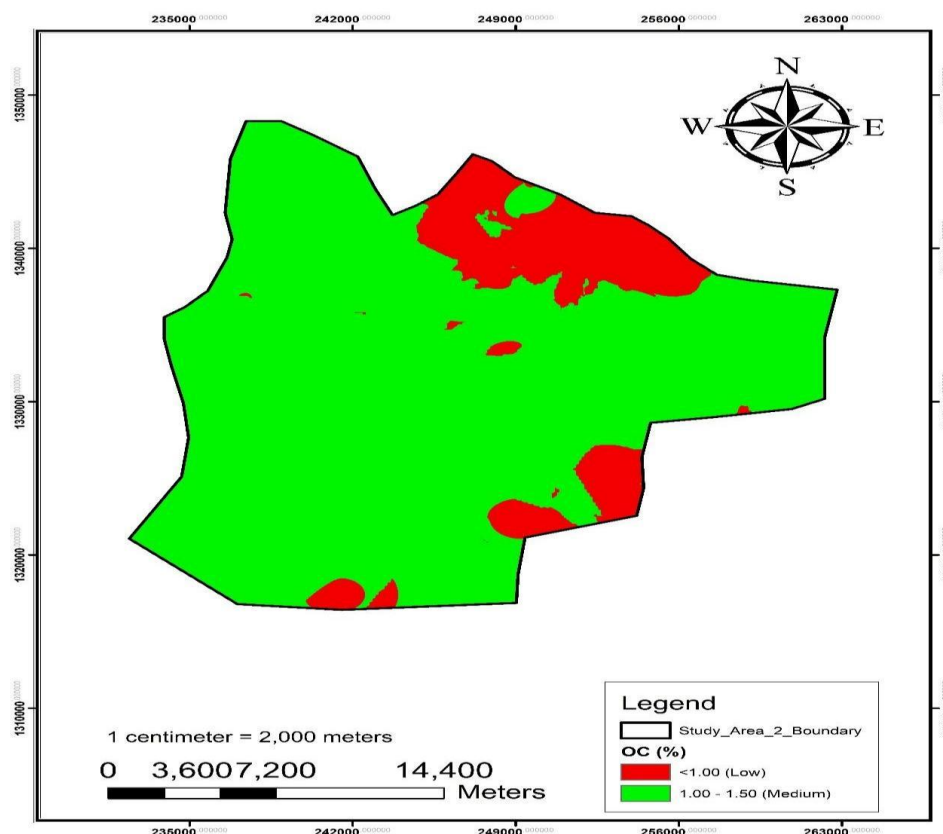


Figure 2: Organic Carbon (OC) Distribution of the Study Area

Adequate potassium availability, and widespread phosphorus deficiency. This pattern is typical of tropical agroecosystems, where phosphorus is often the most limiting nutrient despite the presence of other essential nutrients (Bünemann et al., 2018; Vanlauwe et al., 2019). The spatial association between organic carbon and potassium suggests that organic matter contributes to nutrient retention and cation exchange processes, thereby enhancing soil fertility. However, its influence on phosphorus availability remains limited due to the dominant role of chemical fixation mechanisms in acidic soils. This highlights the complexity of nutrient interactions in tropical soils, where improving one soil property does not necessarily translate into improved availability of all nutrients. From a geostatistical perspective, the moderate spatial dependence observed across all soil properties indicates that both natural soil-forming processes and anthropogenic activities contribute to soil variability. The effectiveness of kriging interpolation in identifying spatial patterns and nutrient zones underscores the importance of geostatistical techniques in soil fertility assessment and precision agriculture. The observed spatial heterogeneity has

important implications for soil fertility management. The widespread phosphorus deficiency necessitates targeted phosphorus fertilization strategies, particularly in areas identified as low AVP zones. In addition, the maintenance and improvement of soil organic carbon through practices such as residue incorporation, cover cropping, and conservation tillage are essential for sustaining soil fertility and enhancing nutrient use efficiency. The generally adequate potassium levels suggest that potassium fertilization may not be required across the entire study area but should instead be focused on localized deficiency zones. This approach aligns with the principles of site-specific nutrient management, which aim to optimize input use, reduce costs, and minimize environmental impacts. Overall, the findings of this study demonstrate that soil fertility in Gusau LGA is constrained more by nutrient imbalance, particularly phosphorus deficiency, than by overall nutrient scarcity. The integration of geostatistical analysis with soil fertility assessment provides a powerful tool for understanding spatial variability and developing targeted management strategies that can enhance agricultural productivity and sustainability in the Sudan savanna region.

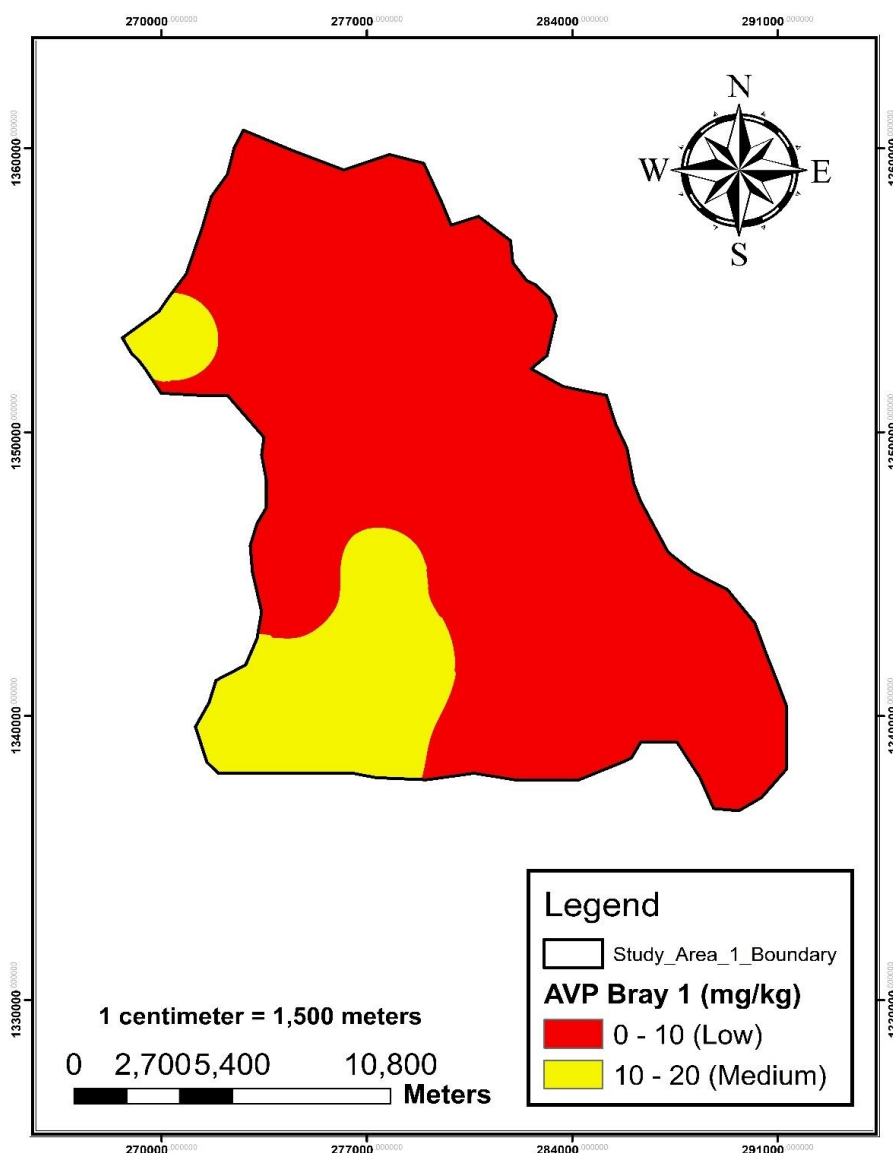


Figure 3: Available Phosphorous (AvP) Distribution of the Study Area

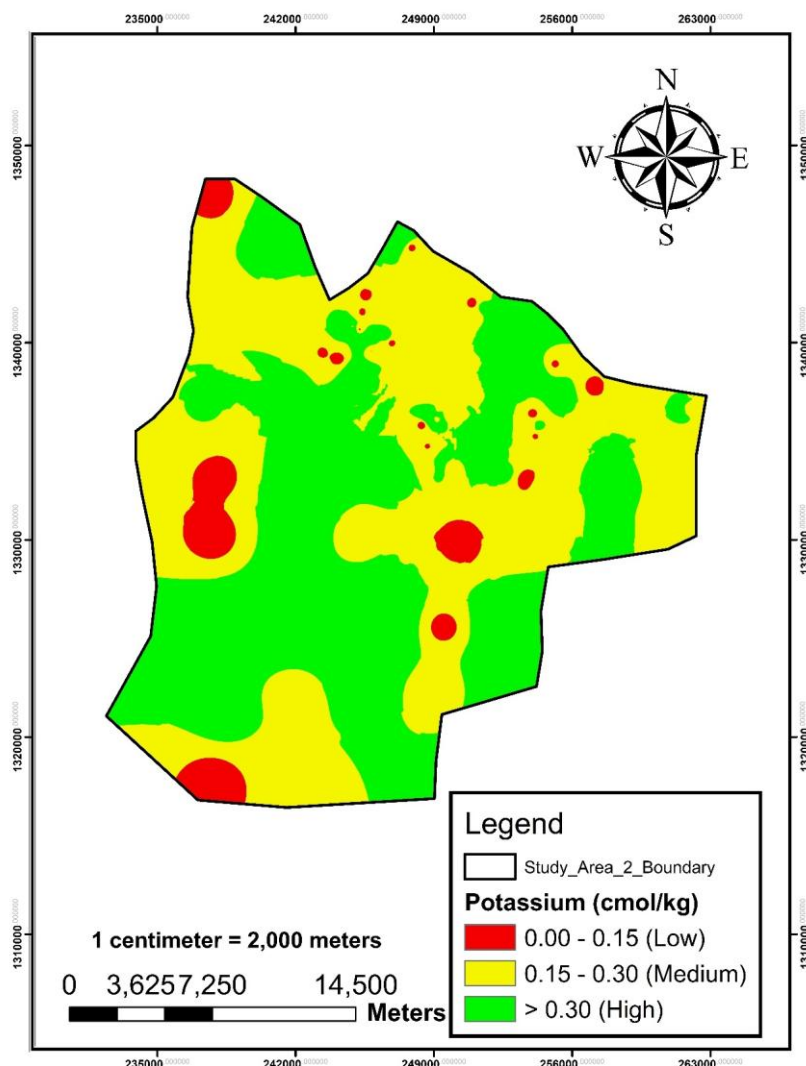


Figure 4: Potassium (K) Distribution of the Study Area

CONCLUSION

This study assessed the spatial variability and geostatistical characteristics of key soil fertility indicators in Gusau Local Government Area, Zamfara State. The results revealed low variability in soil pH, moderate variability in organic carbon and exchangeable potassium, and high variability in available phosphorus, indicating pronounced spatial heterogeneity across the study area.

Correlation analysis showed weak nutrient interactions in Wanke, suggesting low fertility and poor nutrient integration, whereas stronger relationships in Magami—particularly between organic carbon, available phosphorus, and cation exchange capacity—indicate a more functionally active soil system. Regression analysis further identified organic carbon and cation exchange capacity as the most significant determinants of soil fertility, emphasizing the central role of soil organic matter in nutrient dynamics and retention.

Spatial distribution patterns demonstrated that soils are generally slightly acidic, with moderate organic carbon, adequate potassium, and widespread phosphorus deficiency, identifying phosphorus as the primary limiting nutrient. The observed spatial dependence of soil properties confirms the combined influence of soil-forming factors and management practices.

Finally, soil fertility in the study area is affected by nutrient imbalance and low organic matter rather than absolute nutrient deficiency. Therefore, site-specific nutrient management strategies, particularly the use of organic amendments and targeted phosphorus fertilization are essential for improving soil fertility, enhancing crop productivity, and ensuring sustainable land management in the Sudan savanna agro-ecological zone.

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