Geospatial Assessment of Topographic Control on Soil Physical Properties and Agricultural Suitability in Shanga Local Government Area, Kebbi State, Nigeria

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***Abstract*— Soil spatial variability driven by topography presents significant challenges for agricultural productivity in semi-arid regions. This study integrated geospatial technologies with field-based analysis to assess the influence of topography on soil physical properties and agricultural suitability in Shanga Local Government Area, Kebbi State, Nigeria. The research employed a mixed-methods approach combining remote sensing, Geographic Information Systems (GIS), laboratory soil analysis, and farmer surveys. Twenty soil samples (10 lowland, 10 highland) were analyzed for texture, bulk density, porosity, and moisture content. Spatial analysis utilized SRTM DEM (30m resolution) and Landsat 8 imagery for topographic classification and moisture estimation using the Normalized Difference Moisture Index (NDMI). Statistical analysis included independent samples t-tests and Pearson correlation. Results revealed that significant ($p < 0.05$) topographic differentiation: lowland soils exhibited higher natural moisture content (6.28% vs. 1.39%, $t = 5.74$, $p < 0.001$), greater porosity (0.459 vs. 0.418, $t = 2.21$, $p = 0.040$), and higher silt+clay content (27.88% vs. 17.72%, $t = 2.46$, $p = 0.024$) compared to highland soils. Strong negative correlations were observed between topography and moisture content ($r = -0.81$, $p < 0.001$), porosity ($r = -0.46$, $p = 0.040$), and fine particle content. Perceptions of the farmers (n=383) corroborated these findings, with 63% rating lowland soils as superior and 65% reporting higher yields in these areas. The study concludes that topography is the primary control on soil property distribution, creating a distinct catena with implications for site-specific soil management. While lowland soils are more productive and requires drainage management and fertility enhancement, highland soils necessitate erosion control and water conservation strategies.**

***Index Terms*—Soil Mapping, Toposequence, Soil Catena, Land Management, Agricultural Suitability**

I. INTRODUCTION

Soil, as one of the natural resources is essential for sustaining terrestrial ecosystems and agricultural production on a global scale (FAO, 2020). It is estimated that 95% of the world's food supply depends directly on soil, making its preservation and sustainable management a cornerstone of global food security and environmental stability (Bossio et al., 2020). However, soil degradation driven by deforestation, unsustainable farming, and climate change threatens these vital functions, with the United Nations Sustainable Development Goals particularly SDG 2 (Zero Hunger) and SDG 15 (Life on Land) prioritizing the restoration and sustainable management of soil resources worldwide (United Nations, 2021).

In sub-Saharan Africa, soil variability and fertility decline pose challenges to agricultural productivity and food security. Approximately 70–80% of agricultural land in Nigeria suffers from nutrient depletion due to intensive cultivation, inadequate fertilization, and erosion, severely limiting crop yields and rural livelihoods (Amapu et al., 2012). This regional crisis underscores the need for localized, science-based soil management strategies that account for environmental heterogeneity and socio-economic contexts.

Within Nigeria, the Sudan Savanna region exemplifies these challenges, where diverse topography significantly influences soil formation and agricultural potential. Topography acts as a primary control on soil development by regulating water movement, erosion processes, and sediment redistribution across landscapes (Jenny, 1941; Schaetzl and Anderson, 2005). In this region, distinct soil environments emerge between lowland floodplains and highland uplands, each with unique agricultural constraints and opportunities. Lowland areas, enriched by seasonal flooding, support water-intensive crops like rice but are prone to waterlogging, while highland areas, characterized by steeper slopes, are vulnerable to erosion and more suitable for cultivating drought-tolerant crops such as millet and sorghum (Ojanuga, 2006).

Despite broad recognition of these topographic influences, detailed localized studies quantifying the extent of soil property variation and its agronomic implications remain scarce in northern Nigeria. Such site-specific assessments are critical for developing tailored soil management practices that enhance productivity while promoting sustainability.

Geospatial technologies, including Geographic Information Systems (GIS) and remote sensing, offer powerful tools for assessing spatial variability of soil at landscape scales (Lagacherie and McBratney, 2007; Minasny et al., 2013). These approaches enable the integration of topographic, climatic, and soil data to generate continuous soil property maps and identify management zones. However, their application in data-scarce regions like Nigeria's Sudan Savanna remains underutilized, thereby limiting the potential for precision agriculture and evidence-based land-use planning.

This study addresses these research and application gaps by employing an integrated geospatial and field-based approach in Shanga Local Government Area (LGA), Kebbi State. The research aims to map the spatial distribution of key soil physical properties across lowland and highland areas; statistically compare soil properties between topographic positions; quantify relationships between soil properties and topography; and evaluate soil suitability for agricultural production based on physical characteristics. The findings are intended to contribute to the development of evidence-based, terrain-specific soil management recommendations that support sustainable agricultural development in Sudan Savanna environments and align with broader regional and global sustainability goals.

II. MATERIALS AND METHODS

Study Area

Shanga LGA is located in Kebbi State, northwestern Nigeria, between latitudes 11°12'30"N to 11°13'14"N and longitudes 4°34'43"E to 4°34'51"E (Figure 1). The area covers approximately 1,642 km² with a population of 205,000 (2024 projection). The climate is tropical savanna (Köppen Aw), characterized by distinct wet (May-September) and dry (October-April) seasons, with annual rainfall ranging from 800 mm in highlands to 1,100 mm in lowlands. The vegetation type can be described as Sudan savanna, comprising of species such as Acacia nilotica, Faidherbia albida, and Balanites aegyptiaca. Topography ranges from 132 m in southern riverine zones to 318 m in northern uplands, with the Sokoto-Rima Basin influencing the local hydrology. Agriculture is the dominant livelihood, employing over 80% of the population, with rice, millet, sorghum, maize, and groundnuts as principal crops.

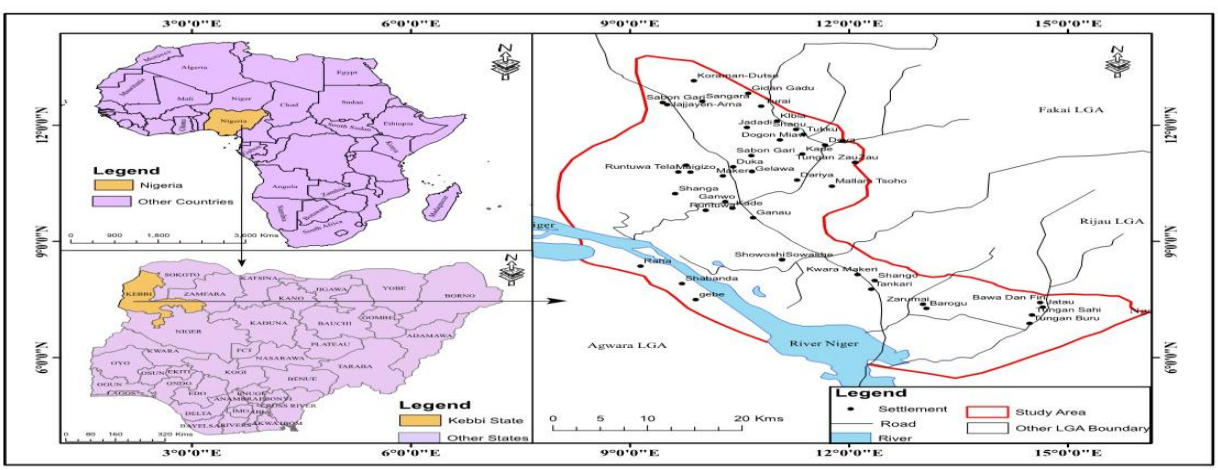

Figure 1: The Study Area

The study employed an applied research design integrating quantitative geospatial analysis with field surveys. Primary data included soil samples collected from 20 representative sites (10 lowland, 10 highland) using systematic random sampling. Other data comprised of Landsat 8 Operational Land Imager (OLI) imagery and a Digital Elevation Model of 30m spatial resolution) were utilized in order to determine suitability locations for agricultural productivity. Farmer perceptions were captured through structured questionnaires administered to 383 respondents, determined using the Krejcie and Morgan (1970) formula for a finite population of 205,000 at 95% confidence level and 5% margin of error.

2.1 Soil Sampling and Laboratory Analysis

Soil samples were collected at 0-15 cm depth during the post-rainy season (October-November) to capture stable soil conditions. Physical properties analyzed included: texture (hydrometer method), bulk density (core sampling method), porosity (calculated from bulk and particle density), and natural moisture content (gravimetric method). Laboratory procedures followed standard methods described by Gee and Bauder (1986) and Blake and Hartge (1986).

2.2 Geospatial Analysis

Geospatial analysis was conducted using ArcGIS10.8. Topographic parameters (elevation, slope, aspect) were derived from SRTM DEM. Highland and lowland areas were classified based on elevation thresholds and slope characteristics. The Normalized Difference Moisture Index (NDMI) was calculated from Landsat 8 imagery using the formula: NDMI = (NIR - SWIR1)/(NIR + SWIR1), where NIR is Band 5 (0.85-0.88 µm) and SWIR1 is Band 6 (1.57-1.65 µm). Spatial interpolation of soil properties was performed using Inverse Distance Weighting (IDW) to generate continuous distribution maps.

2.3 Statistical Analysis

Statistical analysis was conducted using SPSS version 26. Independent samples t-tests compared mean values of soil properties between lowland and highland areas. Pearson correlation analysis quantified relationships between topography (coded as binary variable: lowland=0, highland=1) and soil properties. Descriptive statistics summarized farmer survey data. Significance was evaluated at $p < 0.05$.

III. RESULTS AND DISCUSSION

3.1 Topographic Characteristics and Soil Moisture Patterns

The SRTM DEM analysis revealed a clear topographic gradient in Shanga LGA, with elevations ranging from 132 m in southern floodplains to 318 m in northern uplands (Figure 2). Lowland areas (<150 m) comprised riverine floodplains and valley bottoms, while highland areas (>200 m) included which show plateaus and hillslopes with slopes up to 15°. The NDMI analysis shows pronounced moisture differentiation along this topographic gradient, with lowland areas exhibiting NDMI values ≥ +0.22 (indicating 15-20% higher plant-available moisture) compared to highland values ≤ +0.05. (Figure 3).

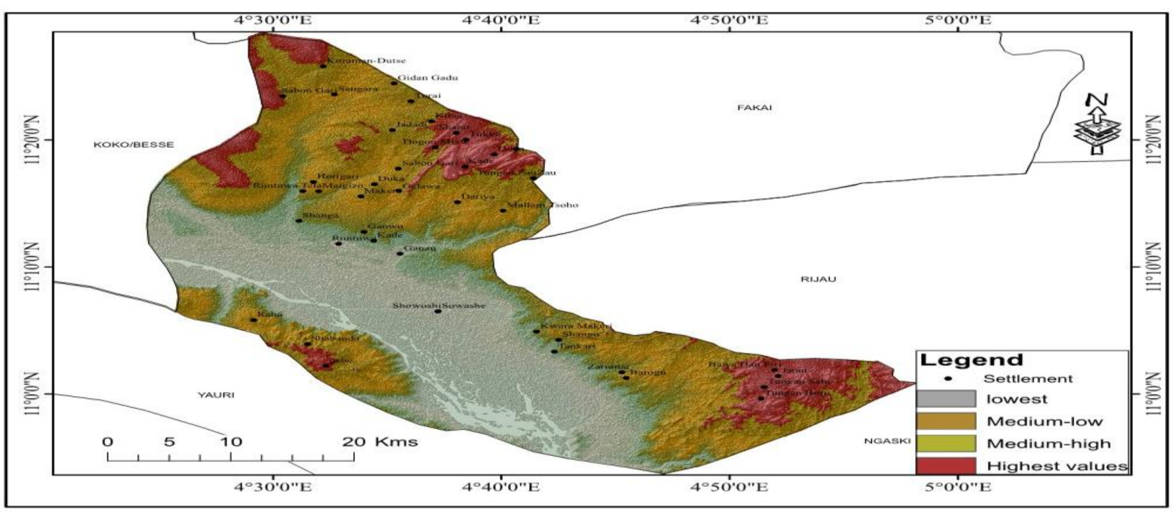

Figure 2: Elevation Map of Shanga LGA

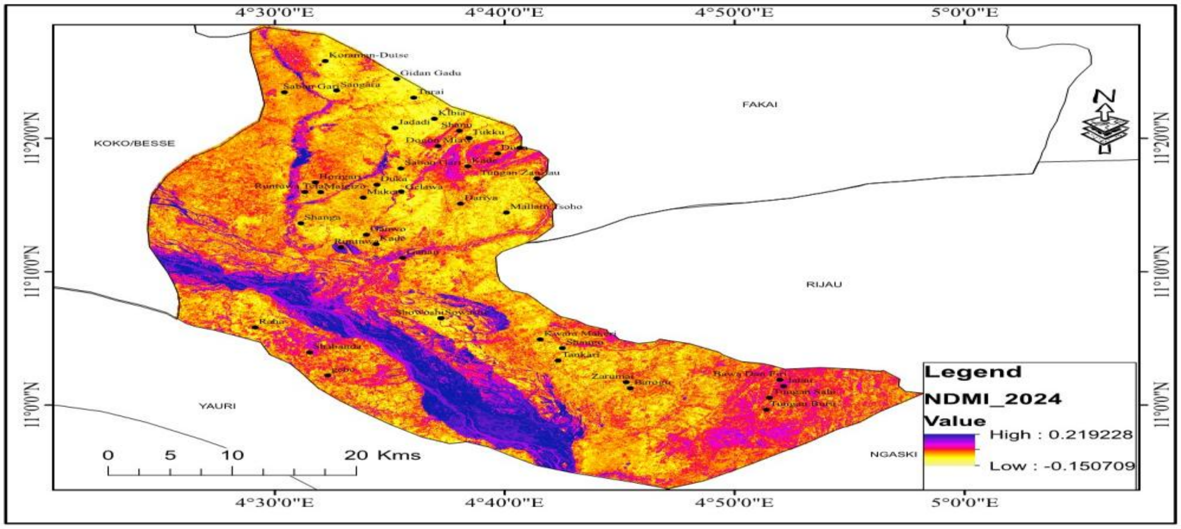

Figure 3: Normalized Difference Moisture Index (NDMI)Map of Shanga LGA

3.2 Spatial Distribution of Soil Physical Properties

Spatial interpolation maps generated using Inverse Distance Weighting (IDW) revealed distinct patterns in soil property distribution (Figure 4 and 5). Lowland areas showed relatively uniform distribution of favorable soil properties, with spatial continuity in higher moisture content, greater porosity, and finer textures. The highland areas within the study area exhibited greater spatial variability, characterized by pockets of coarser textures and lower porosity interspersed with localized areas of better soil conditions.

The transition zones between highland and lowland areas however, show gradual changes in soil properties, reflecting the continuous nature of the catenary sequence. This pattern results from erosional processes on steeper highland slopes, which selectively remove finer particles, leaving coarser sand fractions as Govers et al., (1996) have observed in similar location. These transported fines are subsequently deposited in lowland areas, creating the observed enrichment of silt and clay content in these depositional zones.

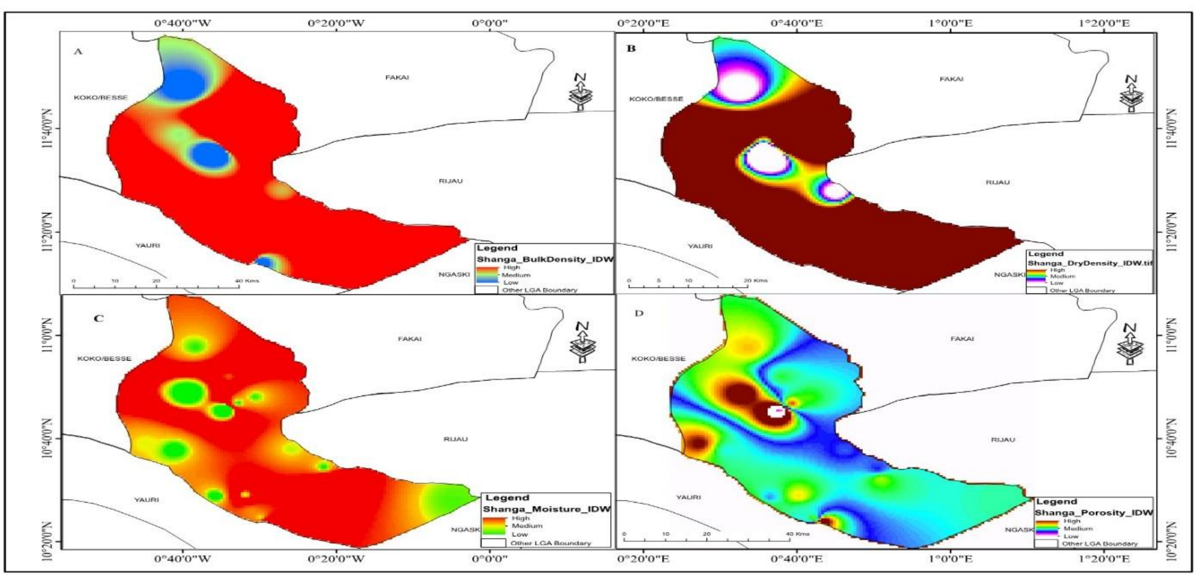

Figure 4: Inverse Distance Weighting (IDW) of physical Soil Properties (bulk density, dry density, moisture content, and porosity)

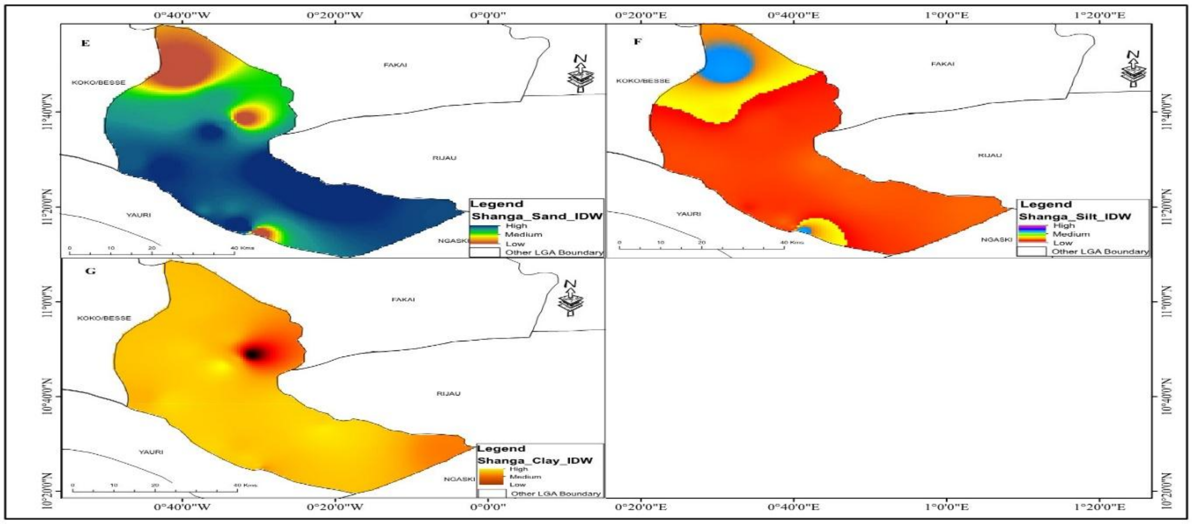

Figure 5: IDW Interpolation of soil textural fractions (sand, silt and clay)

3.3 Statistical Comparison of Soil Properties

Based on the independent samples t-tests there are significant differences in several soil properties between lowland and highland areas (Table 1).

Natural moisture content showed the most pronounced difference, with lowland soils containing 4.5 times more moisture than highland soils (6.28% vs. 1.39%, $t = 5.74$, $p < 0.001$). This substantial divergence underscores the primary role of topography in controlling soil hydrological conditions. Porosity has shown that it significantly higher in lowlands (0.459 vs. 0.418, $t = 2.21$, $p = 0.040$), indicating better soil structure and aeration in these depositional environments.

Table 1. Soil Properties of the Study Area

Soil Property	Lowland Mean	Highland Mean	t-statistic	p-value
Natural Moisture Content (%)	6.28 ± 2.34	1.39 ± 0.73	5.74	<0.001
Porosity (n)	0.459 ± 0.045	0.418 ± 0.033	2.21	0.040
Bulk Density (kg/m³)	1528.30 ± 118.66	1602.60 ± 97.85	-1.47	0.160
Sand Content (%)	72.12 ± 12.56	78.50 ± 11.05	-1.49	0.153
Silt Content (%)	17.92 ± 9.13	11.64 ± 6.17	2.21	0.040
Clay Content (%)	9.96 ± 5.71	6.14 ± 3.73	2.12	0.049
Silt+Clay Content (%)	27.88 ± 12.56	17.72 ± 9.23	2.46	0.024

$p < 0.001$, $p < 0.05$

Source: Researcher's Analysis 2025

The texture analysis on the other hand shows that lowland soils contained significantly higher proportions of silt (17.92% vs. 11.64%), clay (9.96% vs. 6.14%), and combined fines (27.88% vs. 17.72%). The particle size distribution directly results from the selective transport and deposition processes along the topographic gradient.

Notably, bulk density and sand content on the other hand, show no significant differences between topographic positions. This finding contrasts with some previous studies but aligns with research by Salako et al. (2006) in cultivated savanna catenas. The similarity likely stems from comparable land management practices (annual tillage) and uniformly low organic matter levels that mask potential topographic effects on soil compaction.

3.4 Relationships Between Soil Properties and Topography

Pearson correlation analysis revealed strong to moderate relationships between topography and key soil properties is shown in Table 2.

Table 2: Pearson correlation coefficients between topography and soil properties

Soil Property	Correlation Coefficient (r)	p-value	Interpretation
Natural Moisture Content	-0.81	<0.001	Very strong negative
Porosity	-0.46	0.040	Moderate negative

Silt Content	-0.46	0.040	Moderate negative
Clay Content	-0.45	0.049	Moderate negative
Silt+Clay Content	-0.50	0.024	Moderate negative
Bulk Density	0.34	0.160	Weak positive (NS)
Sand Content	0.33	0.153	Weak positive (NS)

NS = Not Significant
Sources: Laboratory Analysis 2025

A very strong negative correlation was observed between topography and moisture content ($r = -0.81$, $p < 0.001$), confirming that soil moisture decreases substantially with increasing elevation and slope. Moderate negative correlations were found with porosity ($r = -0.46$), silt content ($r = -0.46$), clay content ($r = -0.45$), and combined fines ($r = -0.50$).
These correlation patterns demonstrate that favorable soil properties diminish systematically along the topographic gradient from lowland to highland positions. The weak positive correlations between topography and both bulk density ($r = 0.34$) and sand content ($r = 0.33$) were not statistically significant, but further supporting the interpretation that texture and moisture show stronger topographic dependence than compaction in this managed landscape.

Farmer Perceptions and Practices
Shanga Local Government Area (LGA), farmers' perceptions and adaptation strategies reveal a clear prioritization of agricultural practices, figure 6

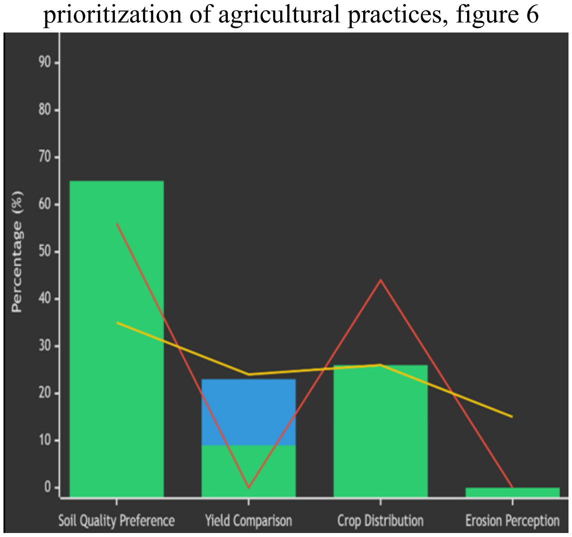

Figure 6: Perception and Adaptation Strategies

In figure 6, crop distribution emerging as the most widely adopted or recognized approach reported by approximately 98% of respondents. This is closely followed by yield comparison at around 86%, indicating that farmers actively assess and compare productivity outcomes. Soil quality preference also registers notable attention at 78%, reflecting farmers' awareness of soil health in cultivation decisions. In contrast, erosion perception ranks significantly lower at about 45%, suggesting that soil erosion is either a less immediate threat, less visible, or afforded lower priority in local adaptation efforts. These insights highlight on immediate agronomic and productivity strategies over longer-term land degradation concerns in the region.
Report from 383 farmers revealed perceptions aligning with measured soil property differences. About 63% of the respondents rated lowland soils as better than highland soils, while only 23% favored highlands. Correspondingly, 65% reported higher crop yields in lowlands, with only 9% reporting higher yields in highlands. Rice cultivation dominated lowlands (56% of crop area), while millet and sorghum were more common in highlands. Farmers identified soil erosion as prevalent in highlands (35% reported erosion only in highlands), with poor soil quality cited as a major challenge by 25% of respondents.

IV. TOPOGRAPHIC CONTROL ON SOIL PROPERTY DISTRIBUTION

The significant differences in soil properties between lowland and highland areas demonstrate the strong influence of topography on pedogenesis in Shanga LGA. The higher moisture content in lowlands results from multiple factors: (1) topographic convergence of surface and subsurface flow, (2) reduced runoff velocity in gentle slopes, (3) proximity to shallow groundwater tables, and (4) periodic flooding from the Sokoto-Rima River system. These findings align with the catena concept (Milne, 1935), which describes systematic soil variation along hillslopes due to differential erosion and deposition processes.
The enrichment of fine particles (silt and clay) in lowland soils reflects downslope transport and deposition through erosion processes. Steeper highland slopes experience greater erosional energy, selectively removing finer particles and leaving

coarser sand fractions (Govers et al., 1996). The deposition of these transported fines in lowland areas enhances water retention capacity and nutrient availability, creating more favorable conditions for plant growth.

The absence of significant differences in bulk density between topographic positions contrasts with some previous studies but aligns with findings by Salako et al. (2006) in cultivated savanna catenas. This similarity likely results from comparable land management practices (annual tillage) and low organic matter levels that mask potential topographic effects on soil compaction.

4.1 Implications for Agricultural Suitability

The soil property differences have direct implications for agricultural suitability and management requirements. Lowland soils, with their higher moisture retention and finer texture, are better suited for water-intensive crops like rice and vegetables. However, their propensity for waterlogging during peak rainfall necessitates drainage management interventions such as raised beds, drainage channels, or controlled irrigation.

Highland soils within the study area characterized by lower moisture retention and coarser texture, are more suitable for drought-tolerant crops like millet, sorghum, and groundnuts. Their vulnerability to erosion requires conservation measures including terracing (on slopes >8%), contour farming (on slopes 3-8%), mulching, and agroforestry. The limited water-holding capacity also suggests potential benefits from water harvesting techniques such as zai pits or micro-catchments.

4.2 Integration of Scientific and Local Knowledge

The alignment between measured soil property differences and farmer perceptions validates the importance of integrating scientific assessment with local knowledge in agricultural development planning. Farmers' preference for lowland cultivation and recognition of highland erosion problems demonstrate practical understanding of landscape-soil relationships developed through generations of observation and experience.

However, gaps remain between awareness and practice, particularly regarding soil conservation. While 60% of farmers were aware of sustainable practices, only 20%of those implemented them, cited financial constraints (40%) as the primary barrier. This highlights the need for policies addressing not only technical aspects of soil management but also economic and institutional barriers to adoption.

4.3 Methodological Considerations

The integrated geospatial-field approach proved effective for characterizing soil spatial variability in a data-scarce region. The combination of remote sensing for landscape classification, GIS for spatial analysis, and field sampling for ground truthing provided a robust framework for soil assessment. However, limitations include the relatively small number of sampling points and potential accessibility constraints in remote areas.

Future research can be strengthened by: (1) increasing sampling density, especially within transitional zones; (2) incorporating soil chemical and biological parameters for a more comprehensive assessment; (3) conducting multi-temporal analyses to account for seasonal variability; and (4) integrating high-resolution satellite imagery or drone-based remote sensing to enable finer-scale characterization.

V. CONCLUSION

This study demonstrates that topography is a primary control on soil physical property distribution in Shanga LGA, creating a distinct catena with lowland areas functioning as depositional zones with favorable soil conditions and highland areas as erosional zones with more limiting soil characteristics. The significant differences in moisture content, texture, and porosity between topographic positions have direct implications for crop suitability and management requirements.

The integration of geospatial technologies with field-based assessment provided an effective approach for soil characterization in this Sudan Savanna environment. The alignment between scientific measurements and farmer perceptions validates local knowledge while providing quantitative evidence to inform management decisions.

For sustainable agricultural development in Shanga LGA, terrain-specific management strategies are essential. Lowland areas should focus on optimizing the use of their favorable soil conditions while managing waterlogging risks through improved drainage and raised bed cultivation. Highland areas require prioritized investment in soil and water conservation measures to mitigate erosion and enhance moisture retention. Bridging the gap between awareness and practice will require addressing financial and institutional barriers through targeted policies, extension services, and farmer support programs. A more robust methodology integrating soil data and DEM in a GIS environment should be undertaken on similar environment

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