International Journal of Sustainable Agricultural Research
2025 Vol. 12, No. 2, pp. 128-146
ISSN(e): 2312-6477
ISSN(p): 2313-0393
DOI: 10.18488/ijsar.v12i2.4363

Assessment of agronomic potential of land resources within the Gadana watershed in Northeast Nigeria, based on the analysis of soil and physiographic attributes

Alhaji Maigana Chiroma[1+]
Ibrahim Adamu[2]
Abubakar Abdullahi Lawal[3]
Ibrahim Baba Goni[4]
Yusuf Ibrahim[5]

[1,2]*Department of Soil Science, University of Maiduguri, Nigeria.*
[1]*Email:* amchiroma@unimaid.edu.ng
[2]*Email:* iadurkwa@gmail.com
[3]*Department of Agricultural and Environmental Resources Engineering, University of Maiduguri, Nigeria.*
[3]*Email:* abubakar.lawal@unimaid.edu.ng
[4,5]*Department of Geology, University of Maiduguri, Nigeria.*
[4]*Email:* ibgoni@yahoo.com
[5]*Email:* yusufibra012@gmail.com

(+ Corresponding author)

Article History
Received: 30 May 2025
Revised: 1 August 2025
Accepted: 7 August 2025
Published: 15 August 2025

Keywords
Agriculture
Crop productivity
Crop productivity
Irrigation
Land evaluation
North-east Nigeria
Soil fertility
Sustainability
Watershed.

ABSTRACT

This research aimed to evaluate the potential of land resources within the Gadana watershed for their suitability to support intensive agriculture. Land suitability assessments for surface irrigation and rain-fed cropping were conducted using topography and soil physical and chemical properties as primary evaluation criteria. Surface soil samples from the potentially irrigable segment of the watershed were collected and analyzed for selected physical and chemical properties using standard analytical methods. The results showed highly variable soil textures, ranging from sandy loam to clay loam. The soil pH values ranged from 5.4 to 6.2; electrical conductivity (ECe) from 0.03 to 0.14 dS/m^{-1}; organic carbon (OC) from 0.27 to 0.82%; total nitrogen (TN) from 0.10 to 0.22%; available phosphorus (AP) from 0.70 to 4.55 mg/kg; and cation exchange capacity (CEC) from 4.42 to 8.81 cmol (+) kg^{-1}. Results revealed that a significant portion of the watershed, measuring up to 687.0 ha and 700.8 ha, falls under flat (47.19%) and gentle (48.14%) slopes, respectively, which are considered suitable for surface irrigation. The identified textural classes include sandy loam (SL) covering 174.74 ha (36.41%), sandy clay loam (SCL) covering 7.89 ha (1.60%), and clay loam (CL) covering 297.40 ha (61.98%). Only a small portion of the watershed was marginally suitable or unsuitable for intensive cropping. Therefore, the soils of the study area would require careful management to enable sustainable cropping. The main limitations are slope, soil texture, and fertility, which can be addressed through nutrient recycling and proper soil management practices.

Contribution/Originality: The study evaluated the potential of the Gadana watershed in northeastern Nigeria to support intensive, year-round cultivation of both rain-fed and irrigated crops. Favorable segments of the watershed were identified based on topographical criteria and selected soil physicochemical properties. The findings underscored the importance of climate-smart soil and water conservation strategies to address challenges related to slope, soil texture, and fertility.

1. INTRODUCTION

Yobe State, which is located within the Lake Chad basin's catchment area, has experienced over a decade of conflict, leading to the large-scale displacement of people, significant human, social, and economic losses, and high levels of food insecurity. The armed conflict between the Nigerian government and Boko Haram insurgents has severely impacted local and regional food security by destroying agricultural production and food trade, reducing investments, and causing deterioration of land and infrastructure (Chiroma & Alhassan, 2021; Food and Agriculture

Organization of the United Nations, 1985). The crisis is intensifying the challenges faced by vulnerable farmers, who are increasingly exposed to natural hazards associated with climate variability, including recurrent dry spells and floods over the past decades. This variability leads to frequent crop failures and food insecurity in the region. The impacts of climate change in the drier northern areas are alarming and pose life-threatening risks, as many farming households have abandoned agriculture and shifted to non-farming activities due to declining crop yields caused by adverse environmental conditions (Akomolafe, Awoyemi, & Babatunde, 2018; Apata, Ogunyinka, Sanusi, & Ogunwande, 2010). A World Bank report indicated that the overall impact of the conflict on agriculture is estimated at USD 3.7 billion (Food and Agriculture Organization of the United Nations, 2018). Many affected populations face severe restrictions on access to their farmlands. In contrast, the few who gain access often lose their farm products to terrorists, who, on many occasions, set them ablaze, killing farmers and destroying their crops (Babagana et al., 2018).

Yobe State, located in northeastern Nigeria, is characterized by arid and semi-arid climates with low and variable rainfall amounts, averaging 300 mm per year (Abdullahi, Fullen, & Oloke, 2016). Analysis of long-term climatic data from 1981 to 2016 in this state has revealed anomalies in rainfall, temperature, and evaporation, particularly in the northern and eastern regions of the state (FAO-ICRISAT, 2019). The assessment indicates an upward trend in average annual rainfall, accompanied by higher average temperatures between 1999 and 2016 in the Potiskum area, located in the eastern part of the state where the present study was conducted. These changing climatic events have significant implications for crop and pasture production within the state and other parts of the sub-region (Nigerian Meteorological Agency (NIMET), 2017). In Yobe State and other parts of the sub-region, the consequences of climate change trigger a series of adverse outcomes, including the loss of crops due to drought and bushfires, uncontrolled deforestation, land degradation, and insecurity, all leading to declining agricultural yields (FAO-ICRISAT, 2019). Despite these challenges, Yobe State places a high premium on developing its agricultural potential. The state is blessed with a total land area of approximately 47,153 km^2. Of this land, about 70%, or roughly 33,007.1 km^2, is classified as arable land. Additionally, 10% of the land is covered by forests, 11.9% is under permanent crop production, and 3.15% consists of permanent meadows (FAO-ICRISAT, 2019). The climatic condition in the state is conducive for both lowland and upland rain-fed cultivation of various crops such as maize, sorghum, cowpea, groundnut, rice, and soybean (FAO-ICRISAT, 2019) and diverse types of vegetables.

In recognition of the numerous challenges posed by climate change to agriculture and food security, the federal government of Nigeria has implemented several policies and strategies aimed at addressing key issues in agricultural development within the country. One notable policy initiative is the introduction of the National Fadama Project, which is funded by the World Bank. The Fadama project aligns with the Government's Agricultural Transformation Agenda (ATA) and has been implemented in several northeastern states, including Yobe State. It was initially introduced on a pilot scale in 1993 to assist Nigerian rural farmers by providing necessary funds to enhance their agricultural productivity. The implementation of the project in selected beneficiary states was coordinated through the Agricultural Development Programmes (ADPs), supported by the World Bank, in various states. The services provided to farmers include, among others, access to finance for small-scale farmers to drill shallow tube wells, credit facilities, marketing support, and other essential services (Khan, 2020). The project specifically targets the development of irrigation for small-scale farmers, especially in low-lying areas. It has witnessed spectacular successes by increasing productivity, income, and living standards for many rural farmers who earn their livelihood through Fadama farming (Khan, 2020). In this and other similar areas in Sub-Saharan Africa (SSA), where the threat of climate change is most pronounced, steps towards prioritizing irrigation development are key to attaining food security. The establishment of small and medium irrigation schemes, particularly in those parts of the region characterized by extreme weather variability, will, besides helping farmers to stabilize yields, also help create jobs for the growing population, especially the youth (Chiroma & Alhassan, 2021). The history of irrigation practices in northern Nigeria dates back to a time when it was realized that, in many areas characterized by low rainfall and high evaporation rates, rain-fed cultivation of crops is no longer sustainable in the absence of supplementary irrigation. (Shanono, Nasidi, & Usman, 2022).

North-eastern Nigeria, where Yobe State is situated, has a river system network that drains the region. Notable among them are Kumadugu Yobe, Kumadugu Gana, River Yedzeram, River Ngadda, River ElBeid, River Hawul, and River Ngeji. These rivers and their tributaries have large or small floodplains supporting all-year-round cereals, pulses, and vegetable cultivation. These floodplains, locally called Fadama in northern Nigeria, refer to low-lying, relatively flat areas either in streamless depressions or adjacent to seasonally or perennially flowing streams/rivers (Garba & Amir, 2019). They are primarily found in lowland areas underlain by shallow aquifers, often along major river systems. The floodplains in this region have diverse soil types characterized by a range of properties, varying from medium to fine texture with reasonably good hydraulic properties, thus providing farmers with several options for cultivating different types of crops (Graham, 2000). Despite the potential of these important soil resources, information regarding their productive potential and constraints to management is limited. Apart from a few preliminary localized studies, no other major characterization of this region's soil resources, particularly the eastern part of the state where the present study was cited, has been carried out. It is, therefore, essential to conduct detailed scientific investigations of the soil resources of the potentially irrigable floodplains in Gadana, Yobe State, to fill the information gap. The output of such investigations allows the identification of major limiting factors for agricultural production. Additionally, it enables decision-makers to support the development and implementation of management strategies that facilitate the sustainable exploitation of scarce environmental resources for increased crop productivity. On this premise, a soil survey of the potentially irrigable segments of the floodplains in Gadana, Yobe State, was undertaken to assess their productive potentials and constraints for growing upland and irrigated crops.

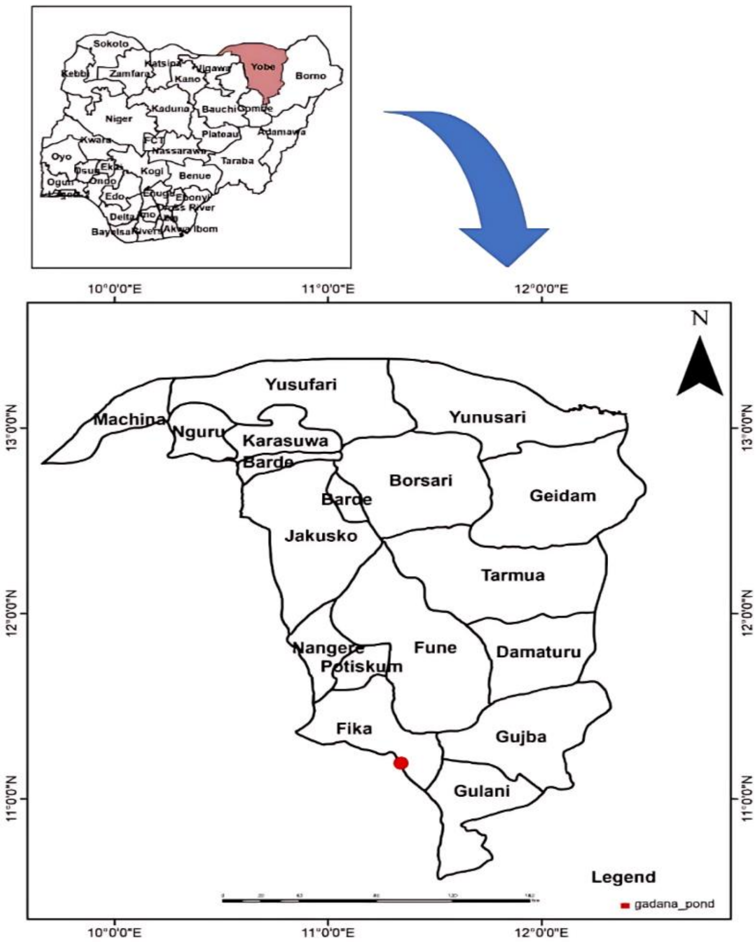

Figure 1. A map showing the location of the study area.

2. MATERIALS AND METHODS

2.1. Description of the Study Area

This study was conducted in Gadana village, Nangere Local Government Area Council of Yobe State, Nigeria. The area lies within the geographical bounds of 11.19° and 11.34°, with an altitude of 288 meters above mean sea level (Figure 1). The climate of the area is characterized by three distinct seasons: the cool, dry harmattan season (November to February), the hot, dry season (March to May), and the rainy season (June to October). The region is generally hot and dry for most of the year, although the southern part experiences slightly milder conditions. The rainy season varies geographically, lasting from June to September in the north and from May to October in the south, with relative humidity ranging from 45% to 50%. The annual mean temperature is approximately 37°C, peaking around April, while minimum temperatures are typically recorded from November to February. Rainfall in this region is generally low and variable, with annual totals ranging from 400 mm to 600 mm. Droughts are common, and the dry harmattan winds, which carry dust from the north, exacerbate the desiccating effects of high temperatures during the long dry season. The main soil types in the Gadana watershed include Entisols, Inceptisols, and Alfisols. Small-scale farmers in this area cultivate a diverse range of crops, with maize, sorghum, cowpea, and groundnut being the primary crops grown during the rainy season. Additionally, crops such as rice, tomato, pepper, and onion are cultivated with irrigation.

2.2. Data Source

Research data for this study were obtained from both primary and secondary sources. Primary data were collected directly from the field during the survey, and locations for field observations and data collection points were georeferenced using the Global Positioning System (GPS) instrument. Secondary data, such as satellite images, were obtained from United States Geological Survey (USGS) sources for use in analyzing the slope and elevation of the watershed.

2.3. Study Methods

2.3.1. Soil Survey Methods

Satellite images and Digital Elevation Model (DEM) data were analyzed to define the catchment size of the Gadana watershed.

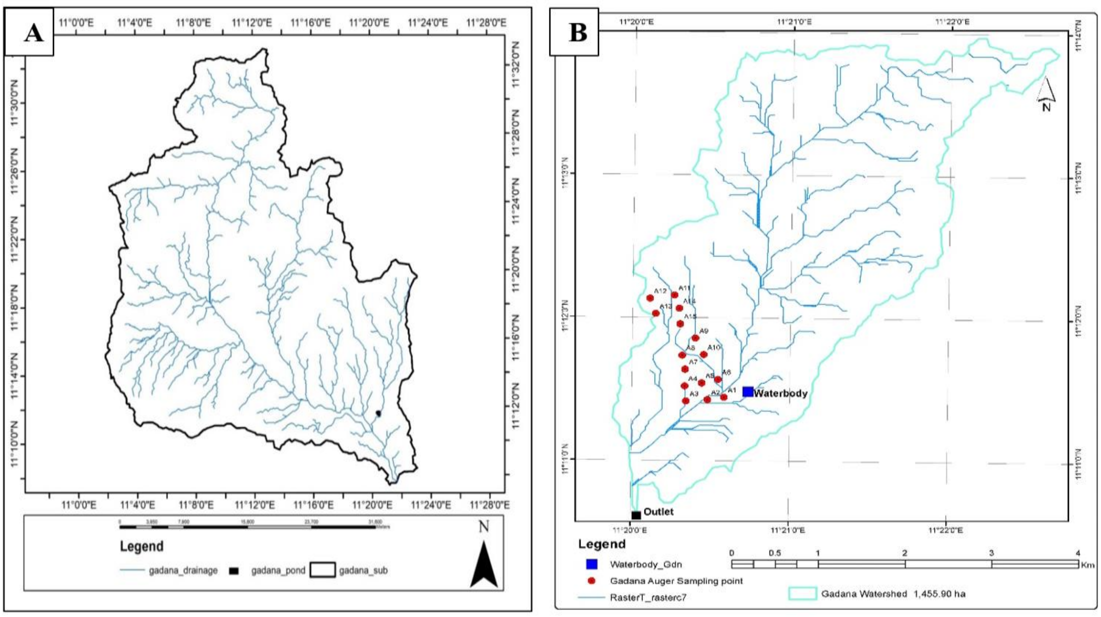

Figure 2. Map showing the Gadana watershed (A) and sub-watershed (B) of the catchment area.

The watershed delineation showed that the Gadana sub-watershed covers a total area of 1,455.9 ha (Figure 2). Satellite imageries with a resolution of 30 m were used to derive the DEM of the area, which was later utilized as input data in ArcGIS to delineate watersheds and to generate a slope map of the study area for irrigation suitability analysis (Mideksa & Temesgen, 2020; Winchell, Srinivasan, Di Luzio, & Arnold, 2008). The slope map of the watershed was derived using the "Spatial Analysis" tool in ArcGIS. The slope derived from the DEM was classified based on the classification system of FAO (1996) using the "Reclassification" tool, an attribute generalization technique in ArcGIS. The data on soil texture was generated based on field data. Field investigations were carried out for ground truthing to verify satellite image interpretations, in-situ measurements, and soil sampling for laboratory analyses.

2.3.2. Soil Sampling and Laboratory Analytical Methods

A hand-held Garmin GPS was used to geo-code the samples. A total of 15 soil samples were collected from a depth of 0-30 cm in a regular grid of 150 m. In each grid cell, a composite of multiple random samples was collected in a zigzag pattern using a 5 cm diameter auger. One composite sample covered a minimum of 2.25 ha. The cores were thoroughly mixed, and a 1 kg sub-sample was returned to the laboratory for analysis. Soil samples were analyzed for particle size distribution (PSD), soil pH, organic carbon (OC), total nitrogen (TN), available phosphorus (AP), exchangeable bases (Ca, Mg, K, and Na), and cation exchange capacity (CEC) at the Department of Soil Science, University of Maiduguri, Borno State, Nigeria. Following the sieving of the air-dried soil samples using a 2 mm mesh, particle-size fractions were determined using the Bouyoucos hydrometer method (Gee & Bauder, 1986). Soil pH and electrical conductivity (ECe) were determined potentiometrically with a digital pH-EC meter in a 1:2.5 (soil: water) supernatant suspension, as described by Van Reeuwijk (2006). Soil organic carbon (OC) content was determined by the wet digestion method as described by Nelson and Sommers (1982). Total nitrogen (TN) was analyzed using the Macro-Kjeldahl method, following digestion, distillation, and titration procedures described by Bremner and Mulvaney (1982). Soil available phosphorus was determined by the Bray 1 method as outlined by Page, Miller, and Keeney (1982). Exchangeable bases were extracted with 1 M NH_4OAc at a pH of 7.0. The contents of calcium and magnesium in the ammonium acetate were determined titrimetrically. Simultaneously, the exchangeable potassium (K) and sodium (Na) in the extract were measured using a Flame Photometer. Cation exchange capacity (CEC) was estimated by the summation method, while exchangeable sodium percentage (ESP) was calculated as the proportion of the CEC (NH_4OAc) occupied by exchangeable sodium, using the formula: ESP = (exchangeable sodium × 100) / CEC (NH_4OAc).

2.4. Statistical Analysis

Statistical parameters such as mean and coefficient of variation, generally considered indicators of central tendency, were analyzed using SAS statistical software (SAS Institute Inc., 1991). The Pearson correlation coefficients were estimated for paired combinations of selected response variables to measure the strength and direction of their relationships. These statistical parameters were calculated using Excel® 2007 and SPSS 15.0.

3. RESULTS AND DISCUSSION

3.1. Watershed Analysis

The total Gadana watershed catchment area is estimated at 175,400 ha (Figure 2) based on USGS satellite imagery with 30 m resolution. ALOS Palsar Digital Elevation Model with 12.5 m spatial resolution satellite imagery was used to demarcate a sub-watershed of 1,455.9 ha, which was used for a more detailed analysis. A linear model (Audu, 1999) was used to estimate an average annual runoff of the Gadana watershed catchment at 206 mm, which yields an estimated 361,324,000 m^3 volume of water over the whole watershed and 1,528,520 m^3 volume of water over the sub-watershed. These water volumes can be harvested for both human and agricultural development. Therefore, when the entire watershed is considered, an estimated 69,086 ha of maize and 64,753 ha of tomato can be irrigated comfortably. Similarly, if only the sub-watershed is considered, only an estimated 292 ha of maize and 274 ha of tomato can be irrigated, based on their modeled crop water requirements of 523 mm and 558 mm for maize and tomato crops, respectively.

3.2. Particle Size Distribution (PSD) of Soils of the Study Area

Considerable variation was observed in the PSD of the surface soils from the study area (Table 1). The texture of the topsoil varied from sandy loam to clay across the sections of the study area. The sand and silt size fractions dominated up to 66.6% of the sampling locations. The sorting of soil materials initiated by biological activities, downward clay movement, water runoff, and erosion or a combination of the aforementioned pedological processes were among the factors often cited as being responsible for the dominance of coarse-size fractions of sand and silt in the soil of Northern Nigeria (Malgwi, Ojanuga, Chude, Kparmwang, & Raji, 2000; Voncir, Mustapha, Tenebe, Kumo, & Kushwaha, 2008). The predominance of coarse-size fractions in some of the soils also implies ease of leaching of nutrients as well as susceptibility to erosion by wind and water (Ihem et al., 2014; Onweremadu, 2008) especially considering the low organic matter contents of these soils (<2%) (Figure 4a). The short-duration high-intensity rainfall events characteristic of the study area can also increase the risk of surface crusting, thereby resulting in reduced infiltration and accelerated runoff and soil erosion (Ekwue, 1994). The resulting increase in runoff and soil erosion caused by such intense rainstorms.

Table 1. Physical properties of the surface 0-30 cm soil samples at Gadana.

Auger sample ID	Particle size distribution (%)			Textural class
	Sand	Silt	Clay	
A 1	49.90	25.70	24.40	SCL
A 2	47.40	20.70	31.90	SCL
A 3	22.40	45.70	31.90	CL
A 4	22.40	45.70	31.90	CL
A 5	42.40	20.70	36.90	CL
A 6	27.40	45.70	26.90	CL
A 7	32.40	40.70	26.90	CL
A 8	42.40	20.70	36.90	CL
A 9	37.40	28.20	34.40	CL
A 10	67.90	16.20	15.90	SL
A 11	58.40	22.20	19.40	SL
A 12	62.40	20.70	16.90	SL
A 13	58.40	22.20	19.40	SL
A 14	52.40	28.20	19.40	SL
A 15	52.40	28.20	19.40	SL
Mean	45.07	28.77	26.17	-
CV	41.09	37.75	27.52	-

Note: CV = Coefficient of variation; SL = Sandy loam; SCL = Sandy clay loam; CL = Clay loam.

This, in turn, negatively impacts important soil chemical properties such as pH, organic matter, and soil nutrients (Lal, 1990; Pieri & Steiner, 1997).

3.3. Soil Reaction (pH) and Electrical Conductivity (ECe)

Soil reaction (usually expressed as pH value) affects important soil and crop attributes such as nutrient availability and toxicity, microbial activity, and root growth. Thus, it is considered one of the most important chemical attributes of the soil solution since higher plants and microorganisms markedly respond to their chemical environment. The pH of the surface soil samples from the study area varied markedly, ranging from 5.4 to 6.2, with a mean of 5.8 (Figure 3a). Based on the ratings of soil pH, these soils are classified as strongly acidic to slightly acidic in pH. The lower soil pH observed in the present study may indirectly affect plant growth by influencing vital processes such as transformation, solubility, and the availability of essential plant nutrients (Bolan, Adriano, & Curtin, 2003; Tiruneh et al., 2023). Elements such as iron, aluminium, and manganese may become toxic to some plants' growth. Some sections of the field, representing up to 26% of the total land area, were strongly acidic, which may be attributed to several factors, including nutrient mining, loss of buffering capacity arising from the loss of soil organic matter, leaching of plant nutrients, and the loss of soil through wind erosion as suggested in similar studies (Bielders, Bielders, & Bationo, 2002; Elias, 2017; Yeneneh, Elias, & Feyisa, 2022). Other reasons often cited in related studies include the nature of the soil mineralogy (Hlaing, Mar, Lwin, Oo, & Ngwe, 2021; Rawal, Acharya, Bam, & Acharya, 2018) and frequent soil disturbance from tillage coupled with indiscriminate use of inorganic nitrogenous fertilizers (Tellen & Yerima, 2018). ECe values ranged from 0.03 to 0.14 dS m^{-1} (Figure 3b), which is far lower than the critical limit for soil salinity (< 4 dS m^{-1}) per the rating of Landon (2014). The low ECe values obtained in this study align with the findings of Egwu, Okunola, and Ugwoke (2018) and Salem, Ibrahim, and Sani (2020). The observed low EC content of these soils is characteristic of most coarse-textured soils with low organic carbon, as is the case in the study area, which indicates a low level of nutrients and the non-saline nature of the soils (Alhassan, Dogo, Abdu, Mahmud, & Hegarty, 2023; Chaudhari, Desai, Chaudhari, & Rabari, 2018). The soil properties' variability in pH and ECe was 9.14% and 154.59%, respectively. These values are rated low (CV ≤ 15%) and high (CV > 75%) according to the guidelines provided by Warrick (1954) for the variability of soil properties. Other researchers have also documented minor variation in soil pH compared to other soil properties (Khan, Islam, Salam, & Ray, 2021; Prieto-Méndez, Prieto-Méndez, Prieto-García, Acevedo-Sandoval, & Aquino-Torres, 2021). This may be attributed to the fact that pH values are a logarithmic scale of proton concentration in soil solution; there would be much greater variability if soil acidity were directly expressed in terms of proton concentration (Reza, Baruah, Sarkar, & Singh, 2016).

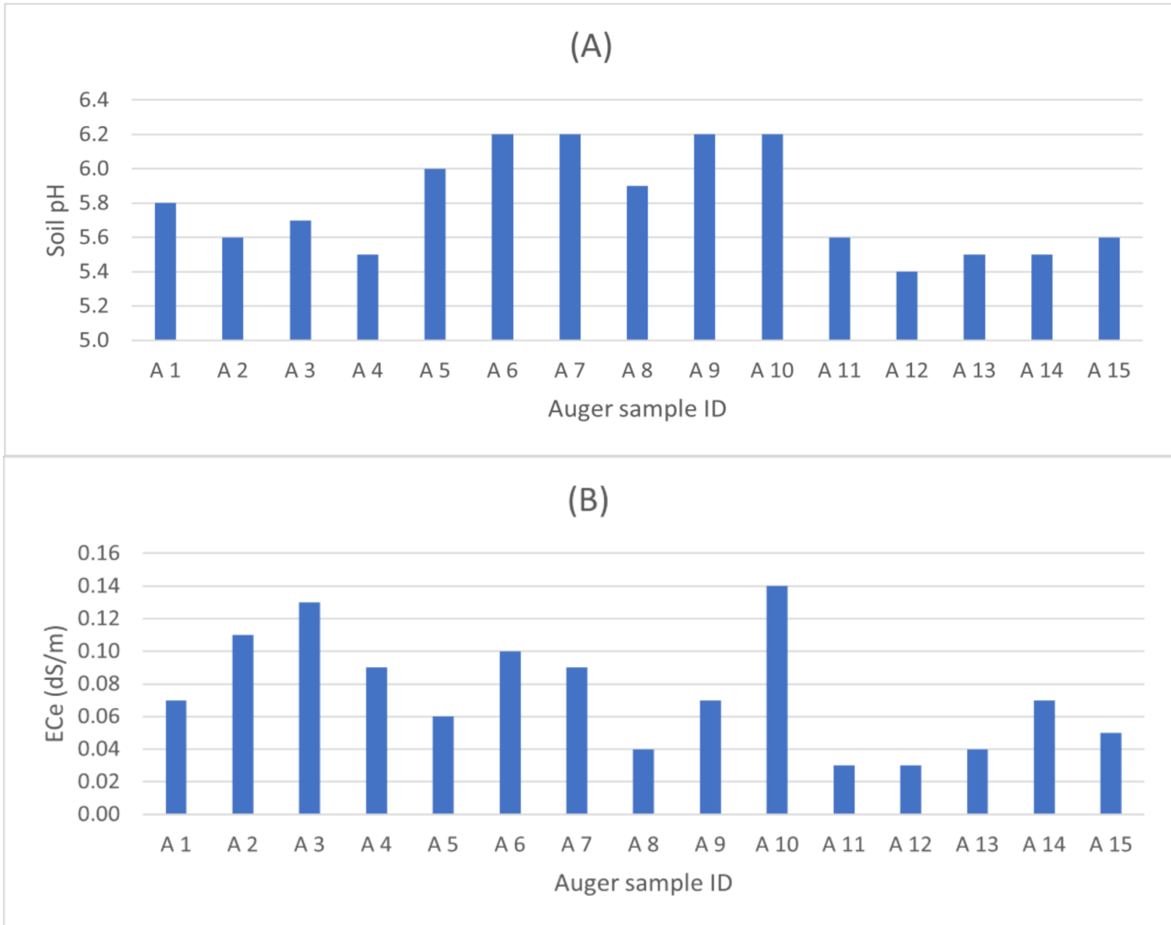

Figure 3. Distribution of soil pH (A) and electrical conductivity ECe (B) in the surface 0-30 cm depth at Gadana.

3.4. Organic Carbon (OC) Total Nitrogen (TN) and Available Phosphorus (AP)

The total amount of organic carbon (OC) in the soil, often regarded as a measure of stored organic matter, reflects the net balance between ongoing accumulation and decomposition processes in the soil. It is thus greatly influenced by crop management and productivity. The contents of OC, total nitrogen (TN), and available phosphorus (AP) in the soils of the study sites are presented in Figure 4 a, b, c. Significant variation was observed in the content of these three important soil fertility indicators. The content of OC (Figure 4a) in the study area falls under a very low category, ranging from 0.27% to 0.82%. The lower organic matter content in these soils can be attributed to poor management practices such as intensive cropping, the complete removal of crop residues, and the lack of addition of organic fertilizer sources (Gebreselassie, 2002; Hlaing et al., 2021). Other reasons include the removal of the top fertile soil, limited application of fertilizers, faster organic matter mineralization, and the shortage of nutrients (Laekemariam, Kibret, Mamo, & Gebrekidan, 2016; Panday, Maharjan, Chalise, Shrestha, & Twanabasu, 2018). The declining trend in soil organic matter can be reversed through the adoption of good agronomic practices such as reduced frequency of cultivation, better cropping patterns that include growing cover crops, mulching, and incorporation of plant and animal sources of manure (Tiruneh et al., 2023).

The results indicate a variable distribution of soil total nitrogen, ranging from low (0.10%) to medium (0.22%). The majority of the soils, representing about 73% of the total area, were low in total nitrogen content (0.05% - 0.15%) (Figure 4b). Similar previous studies have reported low levels of total soil nitrogen in some soils of the Sudan Savanna region of northeastern Nigeria (Egwu et al., 2018; Salem et al., 2020; Salem, Musa, & Askira, 2017). The low nitrogen levels in most areas could be a result of continuous cereal-based cropping, lower external organic-N inputs (such as plant residues, animal manures, etc.), and nitrate ion leaching, as suggested in numerous previous studies Patil, Patil, and Al-Gaadi (2011) and Salem et al. (2020).

Soil TN followed the pattern of soil OC distribution in all studied soils. This is because most of the nitrogen is organic and becomes part of the soil organic matter (Alemu, Mulugeta, & Tadese, 2017; Yeneneh et al., 2022). The results of the correlation analysis showed that OC is positively correlated with TN ($r = 0.93$). A similar study in the same region also showed a strong positive correlation between TN and soil OC (Chiroma, Folorunso, & Alhassan, 2006a). The existence of similarity in the distribution pattern between TN and OC implies that the OM is the primary source of total N in the soils investigated, thus emphasizing the importance of soil organic matter in improving the fertility status of these coarse-textured soils. This result also indicates a variable distribution of soil-available phosphorus, ranging from very low (0.70 mg/kg) to low (4.55 mg/kg). In general, the entire study area is deficient in phosphorus (Figure 4c).

The reason for low soil phosphorus levels may be due to several factors, including intensive cropping systems, low pH (acidic) soils, use of imbalanced fertilizers, and nutrient mining (Hlaing et al., 2021). Others attributed the low phosphorus content of intensely cultivated soils to organic matter's intense uptake and mineralization (Hlaing et al., 2021; Tiruneh et al., 2023).

In general, the low fertility level of the soils could be explained by the nature of the farming system, which is characterized by intensive cultivation, total removal of crop residues for use as animal feed, and limited use of manures and fertilizers. Other workers in the same region have also observed a progressive decline in soil quality following continuous cropping in the absence of organic amendment input (Bielders et al., 2002; Chiroma et al., 2021). This underscored the need to restore the productive potentials of the fragile soils for optimum and sustainable crop production in the area.

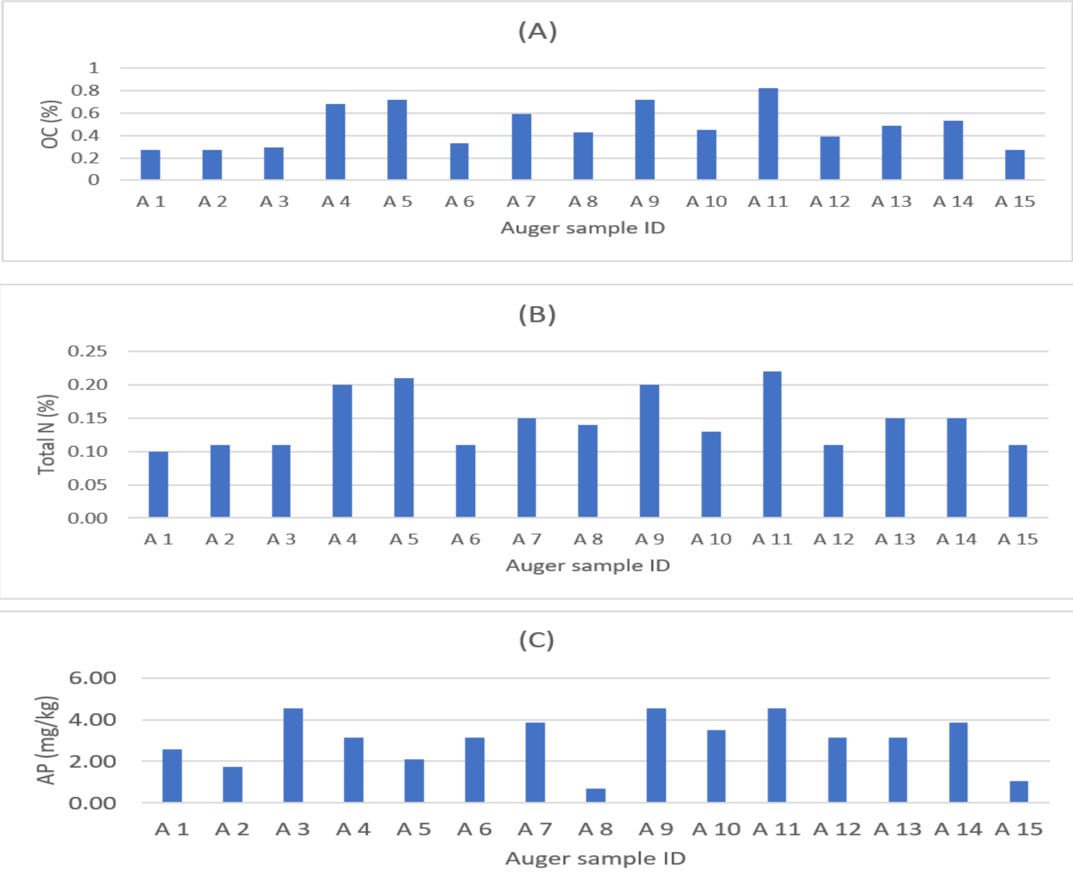

Figure 4. Distribution of soil organic carbon (OC), total nitrogen (TN), and available phosphorus (AP) in the surface 0-30 cm depth at Gadana.

3.5. Exchangeable Bases, Exchangeable Sodium Percentage (ESP) and Cation Exchange Capacity (CEC)

The distribution of exchangeable bases (Table 2) ranged from very low to low (1.80 to 4.80 cmol (+) kg^{-1}) for Ca, low to high (0.60 to 3.80 cmol (+) kg^{-1}) for Mg, very low to high (0.09 to 0.74 cmol (+) kg^{-1}) for K, and low to medium (0.11 to 0.52 cmol (+) kg^{-1}) for Na. This variability in exchangeable bases could be attributed to differences in texture, mineralogy, and pH.

Table 2. Chemical properties of the surface 0-30 cm soil samples at Gadana.

Auger sample ID	Exchangeable bases (cmol (+) kg^{-1})				CEC (cmol (+) kg^{-1}) $^{\pm}$	ESP
	Ca	Mg	K	Na		
A 1	3.80	1.20	0.09	0.11	5.20	2.12
A 2	4.00	2.40	0.10	0.17	6.67	2.55
A 3	3.40	0.60	0.19	0.43	4.62	9.31
A 4	2.60	2.40	0.51	0.20	5.71	3.50
A 5	1.80	5.20	0.28	0.21	7.44	2.82
A 6	2.20	2.80	0.61	0.52	6.13	8.48
A 7	3.40	0.60	0.22	0.20	4.42	4.52
A 8	3.60	1.60	0.26	0.20	5.66	3.53
A 9	2.60	2.60	0.49	0.38	6.67	5.70
A 10	4.20	3.60	0.24	0.20	8.24	2.43
A 11	2.00	3.00	0.50	0.43	5.93	7.25
A 12	2.20	1.20	0.60	0.48	4.48	10.71
A 13	2.40	3.80	0.77	0.61	7.58	8.05
A 14	4.80	2.80	0.69	0.52	8.81	5.90
A 15	3.20	3.80	0.74	0.52	8.26	6.30
Mean	3.08	2.51	0.42	0.35	6.39	5.54
CV	29.23	51.96	55.83	47.97	22.45	49.74

Note: $^{\pm}$CEC = Cation exchange capacity; ESP = Exchangeable sodium percentage, CV = Coefficient of variation.

In general, the low content of exchangeable bases in most sections of the study area might be due to excessive leaching of these basic cations from the surface soil, favored by the high-intensity rainfall characteristic of the study area. Firm soil acidity in the study area does not favor the retention of exchangeable bases in the soil exchangeable complex (Yeneneh et al., 2022). This study's results agree with that of Uzoho and Ekeh (2014), who reported that the nature of parent materials, land use systems, types of fertilizer applied, and their leaching rate determine the availability and distribution of soil nutrients in soils. The Na content is found to be low to medium, with ESP less than 15, which is usually taken as the critical limit for the classification of sodic soils (Brady & Weil, 2013). This finding suggests that sodicity is not a potential problem in these soils. The CEC in these soils ranged from 4.42 to 8.81 cmol (+) kg^{-1}, with a mean of 7.59 cmol (+) kg^{-1}. Landon (2014) states that this range is below the satisfactory value (15 to 25 cmol kg^{-1}) for agricultural lands. The low CEC values of these soils indicate their poor potential to retain plant nutrients. These soils could be made productive by the combined use of nutrient-rich organic manures and mineral fertilizers. Regular additions of organic materials such as animal manures and crop residues to soils can reduce erosion and nutrient runoff losses, improve soil structure, increase water-holding capacity, lower soil temperatures, and provide a source of plant nutrients (Alhassan, Chiroma, Kundiri, Bababe, & Tekwa, 2021).

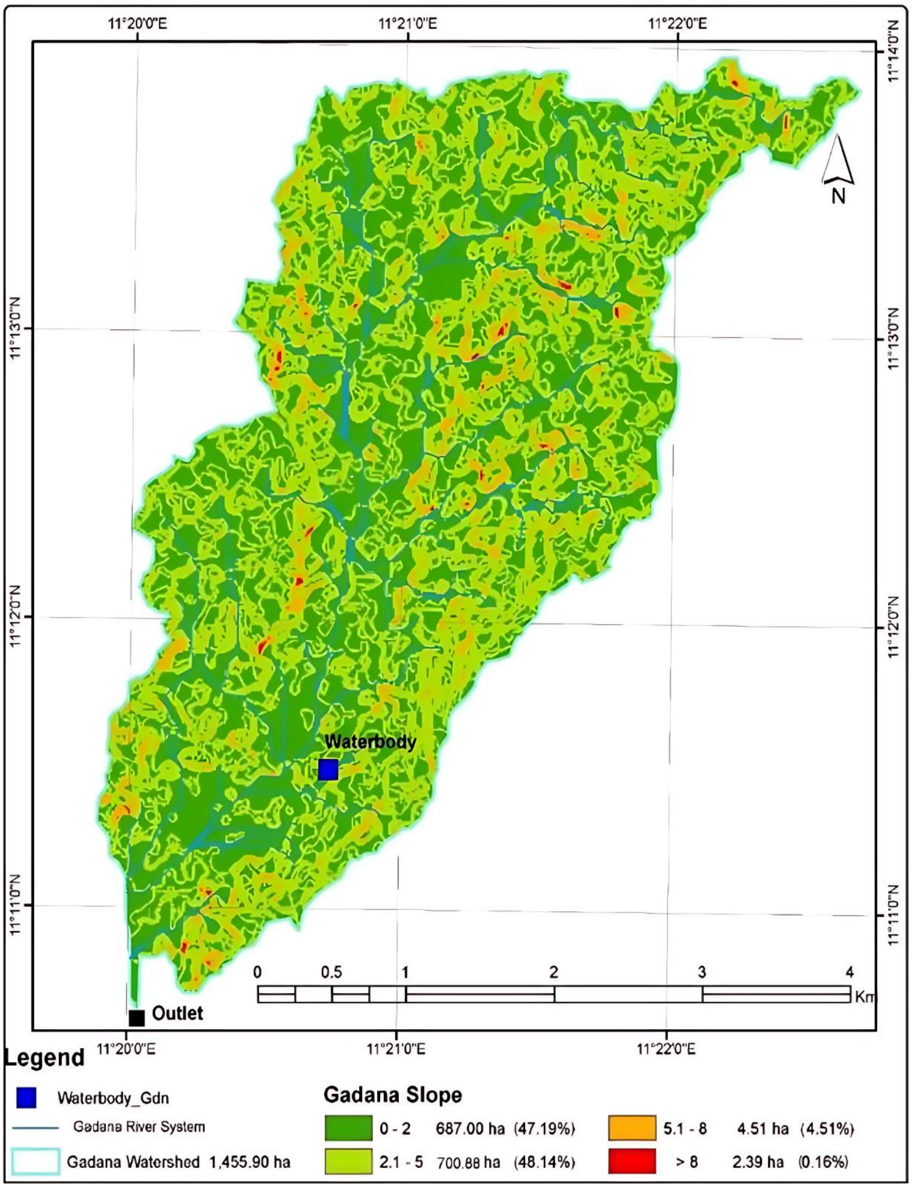

Figure 5. Slope map of Gadana watershed.

3.6. Land Suitability Evaluation

3.6.1. Slope Evaluation for Surface Irrigation

The slope has been considered one of the evaluation parameters for land suitability for irrigation purposes. A higher slope gradient is known to cause less infiltration of rainwater and higher water runoff, leading to less water entering the topsoil to recharge the groundwater (Mohammad, Jahan, Arefin, & Mazumder, 2017). Elevation is another important criterion for predicting the rate and magnitude of erosion in a given area. The interactions of elevation with precipitation and lithology type profoundly affect rainfall erosivity and runoff erosivity, the two most important determinants of water erosion (Jiang, Gao, Yang, Wu, & Dai, 2021). Different slope ranges also impact soil quality factors, such as depth, moisture, texture, and nutrients (Sathiyamurthi, Sivasakthi, Saravanan, Gobi, & Karuppannan, 2024). Studies have shown that as slope steepness increases, the use of machinery to carry out field operations becomes more challenging, and establishment and management costs increase as more erosion prevention measures become necessary (Wong, 1986). Generally, slopes less than 8% are considered suitable for irrigation development (Labiso & Yagaso, 2021). Based on the slope derived from DEM 30-meter resolution by Arc GIS 10.2 spatial analyst tool, the slope of the study area was classified into four categories for surface irrigation (FAO, 1996): 0-2% is highly suitable (S1) 2-5% is moderately suitable (S2), 5-8% is marginally suitable (S3) and >8% is not suitable (N 2) (Figure 5, Table 3). The slope map of the watershed derived from the DEM using GPS was analyzed to evaluate the watershed for surface irrigation. Based on this analysis, a significant portion of the watershed measuring up to 687.0 ha and 48.14 ha, fell under the category of flat (92.5%) and gentle (6.57%) slopes, respectively, and can be classified as a suitable category for surface irrigation (Ibrahim, Ibrahim, Elhag, & Dafalla, 2015; Weldeabzgi, Ketema, Gashu, & Deressa, 2021). Areas with slopes ranging from 0 to 2% and 2 to 5% were considered highly suitable (S1) and moderately suitable (S2) classes because they effectively infiltrate water to reach the crop root zone. Areas with slope percentages greater than 8% were deemed unsuitable because they tend to run off rather than reach the crop root zone. Only an area covering 4.51 ha (0.61%) and 2.39 ha (0.32%) are classified as marginally suitable and not suitable for irrigation farming in the entire Gadana watershed, respectively (Table 3).

Table 3. Slope class of Gadana watershed and rating for surface irrigation.

Area (ha)	Percent of total area	Slope class (%)	Definition	Rating
687.00	49.2	0-2.0	Highly suitable	S1
700.88	50.3	2.1-5.0	Moderately suitable	S2
4.51	0.42	5.1-8.0	Marginally suitable	S3
2.39	0.17	> 8.1	Not suitable	N2

Table 4. Criteria (Reclassification) for land suitability rating of field crops in Gadana watershed.

Crop type	Land	Suitability class				Source
		Highly suitable (S1)	Moderately Suitable (S2)	Marginally suitable (S3)	Not suitable (N)	
Maize	Slope (%)	0-2	4-8	8-16	>16	Ahukaemere, Ekpe, and Unachukwu (2015) and Kefas et al. (2020)
	Soil texture	SCL*, CL, L,	SL, LS	LCS	CS	
Sorghum	Slope (%)	0-3	3-8	8-16	>16	Tadesse and Negese (2020)
	Soil texture	SiCL, SCL, CL	SiC, C	SL, LS	S	Wen (1997) and Tadesse and Negese (2020)
Cowpea	Slope (%)	0-4	4-8	8-12	>12	Ogunwale, Udo, Ibia, Ano, and Esu (2009)
	Soil texture	LS, SL	SC	SCL	Any	Igomu and Idoga (2017)
Groundnut	Slope (%)	0-2	2-5	5-8	>8	Ahukaemere et al. (2015)
	Soil texture	SL, SiL, LS	CL, SiCL	S, SC, SiC	C	

Note: *CL = Clay loam, L = Loam, SL = sandy loam, LS = Loamy sand, LCS = Loamy coarse sand, CS = Coarse sand, SCL = Sandy clay loam, SiCL = Silty clay loam, S = Sand, C = Clay.

3.6.2. Slope Evaluation for Field Crops

The slope, just like other environmental factors such as climate, soil, temperature, etc., places a limit on which a given crop thrives in a given landscape. Topography and slopes generally impact the overall characteristics of agricultural land in various ways, including the soil's ability to retain moisture, susceptibility to erosion, ease of machinery deployment, and intercultural operations (Ahukaemere et al., 2015; Nguyen, Chou, Chen, Hoang, & Tran, 2021). Rain-fed agriculture is the predominant agricultural activity in the study area. The major crops grown in and around the Gadana watershed catchment include maize, sorghum, cowpea, and groundnut, with very little rice and vegetable cultivation by farmers near the river. Based on the analysis of the slope of the study area, these crops were evaluated for suitability for rain-fed agriculture. The results presented in Table 4 show that up to 99.8% of the Gadana watershed fell under the slope category (0-8%) rated as highly suitable to moderately suitable for growing maize, sorghum, cowpea and groundnut. The remaining area of 0.16% (2.39 ha) is rated marginally suitable to unsuitable (N) for producing the field crops evaluated in the present study. Ramamurthy, Reddy, and Kumar (2020) reported that higher slopes with shallow soil depth have a low rate of suitability for cereal crops, especially maize. Many studies have shown that the risk of erosion hazard associated with cultivation on higher slope positions can be overcome by planting cover crops with specific characteristics, such as shrub species that are fast-growing, resistant to pests and diseases, and tolerant to various soil types, as well as preserving biodiversity (Komariah, Ariyanto, & Rachmawati, 2020; Suheri, Mujiyo, & Widijanto, 2018). Bench terracing is often recommended for much higher slope categories, such as 20-30% slope (Marhendi, 2014).

3.7. Soil Texture Suitability Evaluation

3.7.1. Soil Texture Evaluation for Surface Irrigation

Soil texture is among the most important land characteristics for determining the optimum land management practices, such as irrigation and fertilizers (Sathiyamurthi et al., 2024).

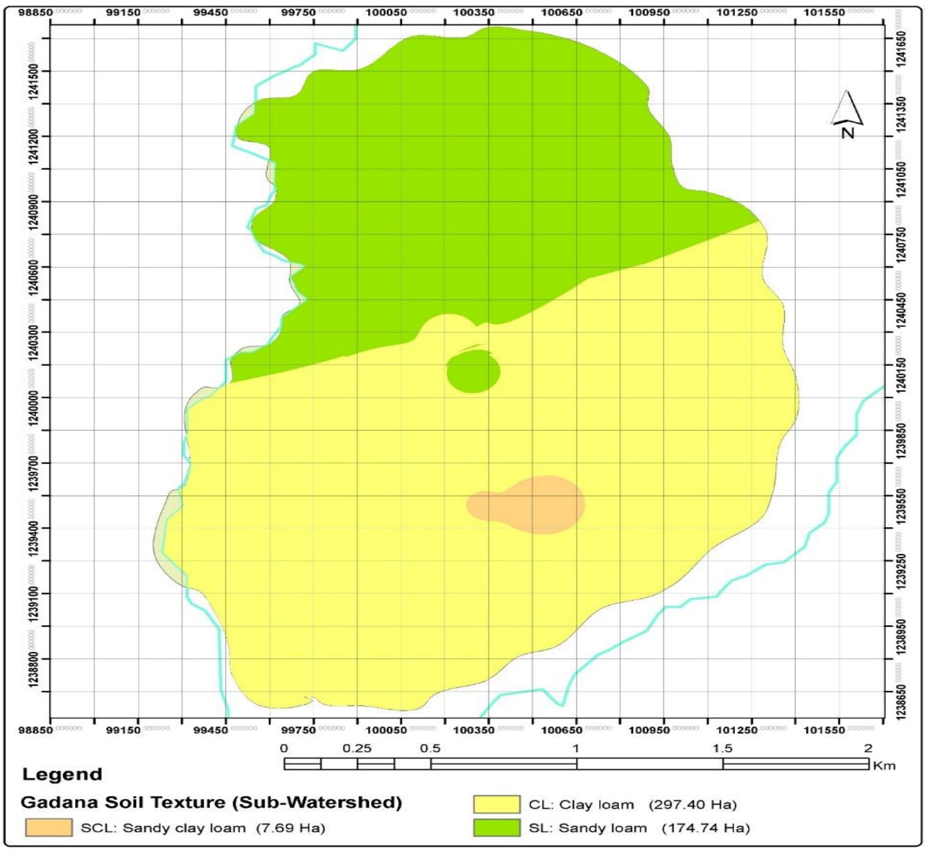

Figure 6. Soil texture map of Gadana watershed.

The texture of the plough layer, 0-30 cm depth where disturbance by tillage is most pronounced, was determined to assess its suitability for surface irrigation. The findings of this study showed that the soil texture of the watershed in Gadana comprises sandy loam, sandy clay loam, and clay loam covering 174.74 ha (36.41%), 7.89 ha (1.60%), and 297.40 ha (61.98%), respectively (Figure 6). Areas with sandy clay loam and clay loam topsoil textures that are deep and fall under the slope category of 0-2% are rated highly suitable for surface irrigation as per the Food and Agriculture Organization of the United Nations (1976) guideline. However, a significant portion of the sub-watershed is covered by a sandy loam texture (174.74 ha), representing approximately 36.4% of the total land area. This section of the watershed was rated moderately suitable for surface irrigation due to the loose nature of the soils. The high sand content of the topsoil in this section of the watershed indicates that illuviation has occurred over time, reducing the level of fine particles in the soil and leaving them susceptible to erosion and disaggregation (Agbai, 2022). Improving the suitability of these soils for surface irrigation would require adopting land management practices that prioritize organic matter addition, green manuring, mulching, and cover crops to enhance the soil's water-holding capacity, soil structure, and aggregate stability.

3.7.2. Soil Texture Evaluation for Field Crops

The three dominant soil textural classes identified in the study area were evaluated for their suitability for growing major crops commonly cultivated in the locality. These crops include maize, sorghum, cowpea, and groundnut. The two soil textural classes with the most extensive coverage are sandy loam and clay loam. Findings from previous studies indicate that sandy loam texture is highly suitable for the production of cowpea and groundnut and moderately suitable for maize production (Table 4). Groundnuts are exceptionally well suited to light-textured soil (Sathiyamurthi et al., 2024).

Nevertheless, similar studies indicate that soils with higher amounts of coarser size fractions, such as loamy sand and sandy loam, are classified as moderately suitable (S2) for maize cultivation (Kefas et al., 2020). The significant limitations of coarse-textured soils like sandy loam, as they relate to cereal production particularly maize are that these soils are inherently low in available water-holding capacity and, consequently, are prone to drying out quickly at the onset of the dry season (Nketia, Adjadeh, & Adiku, 2018). On the other hand, clay loam is highly suitable for producing maize and sorghum, but they are moderately suitable for producing groundnut. Sandy clay loam texture is highly suitable for producing maize and sorghum, but it is marginally suitable for producing cowpeas. Overall, the study revealed that only an insignificant portion of the Gadana watershed was marginally suitable or unsuitable for cultivating the four selected crop species. The limiting factors for some of the land mapping units were slope, soil texture, and fertility, which can be remedied through nutrient recycling.

3.8. Policy Implication of the Study

Sustainable crop production in the Nigerian Sudan Savanna agroecological zone requires a good understanding of the soil's fertility status to develop appropriate nutrient management strategies (Shehu, Jibrin, & Samndi, 2015). The region has a large expanse of arable land with enormous potential for producing a wide range of grain crops such as maize, sorghum, millet, cowpea, groundnut, rice, and wheat (FFD, 2012). However, farmers in this region perceived a steady decline in crop yields over the last few decades due mainly to edaphic and climatic constraints (Chiroma, Folorunso, & Alhassan, 2006b). In this region, low and variable rainfall coupled with high evaporative demand caused by supra-optimal temperatures often exposes plants to varying degrees of stress even during normal rainfall (Chiroma et al., 2006b; ICRISAT, 1987). In addition to climatic constraints, soil nutrient depletion and degradation have been reported as among the most bio-geophysical constraints to agricultural productivity in SSA, including Nigeria's Savanna Zone (Henao & Baanante, 2006). According to an FAO report, soil degradation in SSA is expanding at an alarming rate, accompanied by the lowest agriculture and livestock yields of any region in the world (FAO, 2015) and unless the process of soil degradation is controlled, many parts of the continent will suffer increasingly from food insecurity (Lal, 1990; UNEP, 1982). The threat to food security in this region is further heightened by climate change. If the present pace of climate change continues unabated in the coming years, an estimated reduction in the global yield of crops like maize and wheat will occur by 3.8% and 5.5%, respectively (Yadav, Hegde, Habibi, Dia, & Verma, 2019). It has been widely acknowledged that to ensure future food security with minimal adverse environmental outcomes, there is an urgent need to consider the impact of global climate change together with the degree to which food production systems can adapt (Raj, Roodbar, Brinkley, & Wolfe, 2022; Subhash et al., 2023; Yadav et al., 2014).

The problem of soil degradation in SSA, including northeast Nigeria, is further accentuated by inappropriate management of agroecosystems, thereby making the already fragile natural resource base increasingly vulnerable and prone to rapid degradation. To reduce capital outflows from the economy, the Federal Government of Nigeria, through the Agricultural Transformation Agenda, called for increased crop production by resource-poor farmers by bringing in more floodplains under cultivation. Despite the potential of these floodplains to support yields of arable crops, the soil morpho-physico-chemical dynamics of most floodplain soils in Nigeria are poorly understood, which has limited their use and productivity (Ande et al., 2016). Thus, as a first step toward sound land use planning, the present study sought to characterize the soils of the Gadana watershed to identify their potential and constraints to management. The results showed that soil chemical properties are mostly below their threshold values in all studied soil samples in this area. Findings from the study also revealed that the studied samples were free from salt deposits, and therefore, neither salinity nor sodicity is a potential constraint to cropping for now. The results also suggest a trend toward a progressive decline in soil quality across the study area. Hence, to ensure sustainable crop production, there is a need to consider site-specific soil management strategies, primarily focusing on improving the content of soil organic matter and addressing the problems of soil acidity. The evaluation of land suitability for cropping has long been recognized as critical for effective resource management through sound policies and planning, which eventually lead to improvements in long-term land resource management (Hagos et al., 2022).

4. CONCLUSION

This study assessed the agronomic potential of land resources within the Gadana watershed in north-east Nigeria. Based on the soil physico-chemical and topographical attributes of the study area, the study highlights the potential suitability of the Gadana watershed for both surface irrigation and rain-fed cropping of selected cereal crops. Findings from the study revealed that a large segment of the watershed area, particularly those on flat and gentle slopes, provides a conducive environment for the sustainable cultivation of crops such as maize, sorghum, cowpea, and groundnut. Besides the texture of the soils in the watershed being variable, ranging from sandy loam to clay loam, the fertility status also exhibits some variability, and these can be effectively exploited by implementing appropriate soil and water conservation practices, including nutrient recycling, to enhance sustainability. The study also emphasizes the need for climate-smart practices that effectively address the identified potential limitations, such as slope, soil texture, and fertility, all of which can impact the success of long-term agricultural productivity in the study area. Overall, the Gadana watershed presents a vast potential for intensifying agricultural activities, provided that the identified challenges are adequately addressed through sustainable land management practices.

Funding: This research is supported by the North East Development Commission (NEDC), Nigeria through the Multi-Sectoral Crises Recovery Project (MCRP) (Grant number: NEDC/MCRP/RESEARCH/UNIMAID/CLIMATE/16).
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

REFERENCES

Abdullahi, H. G., Fullen, M. A., & Oloke, D. (2016). Socio-economic effects of drought in the semi-arid Sahel: A review. *International Journal of Advances in Science, Engineering and Technology, 1*(1), 95–99.

Agbai, W. (2022). Surface irrigation suitability assessment of some soils in Akoko Edo Local Government Area of Edo State, Nigeria. *Plant Physiology and Soil Chemistry, 2*(1), 12-15.

Ahukaemere, C., Ekpe, I., & Unachukwu, I. (2015). Suitability evaluation of soils derived from dissimilar lithological materials for maize and groundnut production in Owerri agricultural zone, southeastern Nigeria. *Malaysian Journal of Soil Science, 19*, 73-82.

Akomolafe, K., Awoyemi, O., & Babatunde, A. (2018). Climate change and its effects on agricultural outputs in Nigeria. *Asian Journal of Agricultural Extension, Economics and Sociology, 25*(2), 1-11. https://doi.org/10.9734/AJAEES/2018/37136

Alemu, T., Mulugeta, E., & Tadese, M. (2017). Determination of physicochemical parameters of "Hora" natural mineral water and soil in Senkele Kebele, Oromia Region, Ethiopia. *Cogent Chemistry, 3*(1), 1354800. https://doi.org/10.1080/23312009.2017.1354800

Alhassan, A., Chiroma, A., Kundiri, A., Bababe, B., & Tekwa, I. (2021). Decline in agricultural activity around Lake Chad: Any prospect for restoration? A Review. *ATBU Journal of Environmental Technology (AZOJETE), 17*(2), 221-230.

Alhassan, I., Dogo, S., Abdu, H., Mahmud, S., & Hegarty, J. P. (2023). Determination of soil nutrients management zones using principal component and clustering analysis in Bade LGA, Yobe State, Nigeria. *Quest Journals Journal of Research in Environmental and Earth Sciences, 9*(4), 68-74.

Ande, O., Are, K., Adeyolanu, O., Ojo, O., Oke, A., Adelana, A., . . . Oluwatosin, G. (2016). Characterization of floodplain soils in Southern Guinea Savanna of North Central Nigeria. *Catena, 139*, 19-27. https://doi.org/10.1016/j.catena.2015.12.002

Apata, T. G., Ogunyinka, A., Sanusi, R. A., & Ogunwande, S. (2010). *Effects of global climate change on Nigerian agriculture: An empirical analysis*. Paper presented at the 84th Annual Conference of Agricultural Economic Society held in Edinburgh, Scotland.

Babagana, M., Ismail, M., Mohammed, B., Dilala, M., Hussaini, I., & Zangoma, I. (2018). Impacts of boko haram insurgency on agricultural activities in Gujba Local Government Area, Yobe State, Nigeria. *International Journal of Contemporary Research and Review, 9*(12), 20268-20282. https://doi.org/10.15520/ijcrr.v9i12.631

Bielders, C. L., Bielders, M. K., & Bationo, A. (2002). On-farm evaluation of ridging and residue management options in a Sahelian millet-cowpea intercrop. 1. Soil quality changes. *Soil Use and Management, 18*(3), 216-222.

Bolan, N. S., Adriano, D. C., & Curtin, D. (2003). Soil acidification and liming interactions with nutrient and heavy metal transformation and bioavailability. *Advances in Agronomy, 78*, 215–272.

Brady, N. C., & Weil, R. C. (2013). The nature and properties of soils, Dorlin Kindersley (India) PVT LTD. In (15th ed., pp. 381–387). India: Pearson Printice-Hall Inc

Bremner, J. M., & Mulvaney, C. S. (1982). Total nitrogen. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties. In (2nd ed., pp. 595–624). Madison, WI: American Society of Agronomy and Soil Science Society of America

Chaudhari, P., Desai, N., Chaudhari, P., & Rabari, K. (2018). Status of chemical properties and available major nutrients in soils of Patan district of Gujarat, India. *Crop Research, 53*((3&4)), 147-153.

Chiroma, A., Alhassan, A., Usman, K., Bababe, B., Kundiri, A., & Tekwa, I. (2021). Effects of ridge tillage and organic manure treatment on growth, leaf nutrient concentration and pearl millet (Pennisetum glaucum) stover yield in semi-arid northeast Nigeria. *Journal of Agricultural Economics, Environment and Social Sciences, 7*(2), 108-127.

Chiroma, A., Folorunso, O., & Alhassan, A. (2006a). The effects of land configuration and wood-shavings mulch on the properties of a sandy loam soil in northeast Nigeria. 1. Changes in chemical properties. *Tropicultura, 24*(3), 129-134.

Chiroma, A., Folorunso, O., & Alhassan, A. (2006b). Soil water conservation, growth, yield and water use efficiency of sorghum as affected by land configuration and wood-shavings mulch in semi-arid northeast Nigeria. *Experimental Agriculture, 42*(2), 199-216.

Chiroma, A. M., & Alhassan, A. B. (2021). An overview of agricultural development under an insecure situation: The Borno State experience. In D. Balami & A. A. Niran (Eds.), Exploring the effects of insurgency in Borno State. In (pp. 132–152). Nigeria: Department of Economics, University of Maiduguri

Egwu, G., Okunola, O., & Ugwoke, K. (2018). Evaluation of some heavy metals in wetland soils of Uguru, Yobe State, Nigeria. *Journal of Applied Sciences and Environmental Management*, *22*(6), 987-992.

Ekwue, E. (1994). A simple technique for measuring soil infiltration rates during simulated rainfall. *Journal of Arid Agriculture*, *3*(7), 95-104.

Elias, E. (2017). Characteristics of Nitisol profiles as affected by land use type and slope class in some Ethiopian highlands. *Environmental Systems Research*, *6*, 1-15. https://doi.org/10.1186/s40068-017-0097-2

FAO-ICRISAT. (2019). Climate-smart agriculture in the Yobe State of Nigeria. CSA country profiles for Africa series. International Center for Tropical Agriculture (CIAT); International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). In (pp. 22). Rome, Italy: Food and Agriculture Organization of the United Nations (FAO)

FAO. (1996). *Land husbandry: Components and strategy (by Roose, Eri). FAO Soils Bulletin No. 70.* Rome: Food and Agriculture Organization of the United Nations.

FAO. (2015). *FAOSTAT*. Rome: FAO.

FFD. (2012). *Fertilizer use and management practices for Nigeria.* Abuja, Nigeria: Federal Fertilizer Department, Federal Ministry of Agriculture and Rural Development.

Food and Agriculture Organization of the United Nations. (1976). *A framework for land evaluation.* Rome, Italy: FAO.

Food and Agriculture Organization of the United Nations. (1985). *Guidelines: Land evaluation for irrigated agriculture (FAO Soils Bulletin No. 55).* FAO: Rome, Italy.

Food and Agriculture Organization of the United Nations. (2018). North-eastern Nigeria: Adamawa, Borno and Yobe situation report – July 2018. In. Rome, Italy: FAO

Garba, A. K., & Amir, A. (2019). Properties and fertility potentials of alluvial fadama soils of Kano State of Northern Nigeria. *Journal of Soil Salinity and Water Quality*, *11*(2), 152-160.

Gebreselassie, Y. (2002). Selected chemical and physical characteristics of soils of Adet Research Center and its testing sites in north-western Ethiopia. *Ethiopian Journal of Natural Resources*, *4*(2), 199–215.

Gee, G., & Bauder, J. W. (1986). Bauder particle size analysis. In: A Klute (ed). Method of soil analysis. In (2nd ed.). United States: American Society of Agronomy, Soil Science Society of America

Graham, W. (2000). Characterization of the soils in the Birnin Kebbi area. 3. Physical and hydraulic properties of the soils of the Sokoto and Shella river floodplains. *Nigerian Journal of Basic and Applied Sciences*, *9*(2), 209-216.

Hagos, Y. G., Mengie, M. A., Andualem, T. G., Yibeltal, M., Linh, N. T. T., Tenagashaw, D. Y., & Hewa, G. (2022). Land suitability assessment for surface irrigation development at Ethiopian highlands using geospatial technology. *Applied Water Science*, *12*(5), 98. https://doi.org/10.1007/s13201-022-01618-2

Henao, J., & Baanante, C. (2006). *Agricultural production and soil nutrient mining in Africa: Implication for resource conservation and policy development. Technical Bulletin No. IFDC T-72.* Muscle Shoals, USA: International Fertilizer Development Center.

Hlaing, T. T., Mar, S. S., Lwin, C. S., Oo, H. H., & Ngwe, K. (2021). Spatial variability and mapping of soil properties using GIS-based geostatistics in Myanmar. *IJERD–International Journal of Environmental and Rural Development*, *12*(1), 15-21. https://doi.org/10.32115/ijerd.12.1_15

Ibrahim, M., Ibrahim, S., Elhag, A., & Dafalla, M. (2015). Surface irrigation suitability assessment of the soils of Almanaqil Ridge, Gezira State, Sudan. *International Journal of Emerging Trends in Science and Technology*, *2*(07), 2803-2814.

ICRISAT. (1987). *Pearl millet in African agriculture.* Paper presented at the International Pearl Millet Workshop, 7-11 April, 1986. ICRISAT Centre, India Patencheru, A. P. 502324, India ICRISAT.

Igomu, E. A., & Idoga, S. (2017). Evaluation of soils for cowpea (Vigna unguiculata L.) production: A case study of Siwes Farms of University of Agriculture Makurdi. *International Journal of Plant & Soil Science*, *15*(3), 1–8.

Ihem, E., Ahukemere, C., Nkwopara, U., Chris-Emenyonu, C., Okoli, N., & Osisi, A. (2014). Differences in particle size distribution of soils of northern Niger delta of Nigeria as affected by crude oil pollution. *International Journal of Research in Agriculture and Forestry*, *1*(1), 16-20.

Jiang, Y., Gao, J., Yang, L., Wu, S., & Dai, E. (2021). The interactive effects of elevation, precipitation and lithology on karst rainfall and runoff erosivity. *Catena*, *207*, 105588. https://doi.org/10.1016/j.catena.2021.105588

Kefas, P., Maigida, E., Ezeaku, V., Ofem, K., Akwoga, J., & Ezeaku, P. (2020). Land suitability evaluation for maize production and taxonomic classification of soils overlying undifferentiated basement complex in northeast Nigeria. *Nigerian Journal of Soil Science*, *30*(1), 42–52.

Khan, B. (2020). The impact of the second national fadama development project on poverty reduction in the Geidam Local Government of Yobe State, Nigeria. *Journal of Advanced Research in Economics and Administrative Sciences*, *1*(2), 30-44. https://doi.org/10.47631/jareas.v1i2.32

Khan, M. Z., Islam, M. R., Salam, A. B. A., & Ray, T. (2021). Spatial variability and geostatistical analysis of soil properties in the diversified cropping regions of Bangladesh using geographic information system techniques. *Applied and Environmental Soil Science*, *2021*(1), 6639180. https://doi.org/10.1155/2021/6639180

Komariah, D., Ariyanto, P., & Rachmawati, V. A. (2020). Land suitability evaluation for sorghum (Sorghum bicolor L.) at Gunungkidul, Yogyakarta, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *724*(1), 012032. https://doi.org/10.1088/1755-1315/724/1/012032

Labiso, T. T., & Yagaso, Z. S. (2021). Land suitability analysis for surface irrigation in Humbo woreda, wolaita zone, Southern Ethiopia: Land suitability analysis. *EQA-International Journal of Environmental Quality*, *44*, 32-43. https://doi.org/10.6092/issn.2281-4485/12727

Laekemariam, F., Kibret, K., Mamo, T., & Gebrekidan, H. (2016). Soil–plant nutrient status and their relations in maize-growing fields of Wolaita Zone, Southern Ethiopia. *Communications in Soil Science and Plant Analysis*, *47*(11), 1343-1356.

Lal, R. (1990). Ridge-tillage. *Soil and Tillage Research*, *18*, 107–111. https://doi.org/10.1016/0167-1987(90)90053-G

Landon, J. R. (2014). *Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics*. New York: Routledge.

Malgwi, W. B., Ojanuga, A. G., Chude, V. O., Kparmwang, T., & Raji, B. A. (2000). Morphological and physical properties of some soil at Samaru, Zaria, Nigeria. *Nigerian Journal of Soil Research*, *1*, 58-64.

Marhendi, T. (2014). Land erosion control technology. *Techno (Journal of the Faculty of Engineering, Muhammadiyah University of Purwokerto)*, *15*(1), 50–64.

Mideksa, G., & Temesgen, T. (2020). Irrigation water potential and land suitability assessment in Kurfa Chele-Girawa Watershed, Wabe Shebelle River Basin, Ethiopia. *Turkish Journal of Agriculture, Food Science and Technology*, *8*(1), 139-146. https://doi.org/10.24925/turjaf.v8i1.139-146.2863

Mohammad, R. F., Jahan, C. S., Arefin, R., & Mazumder, Q. H. (2017). Morphometric analysis of major watersheds in Barind Tract, Bangladesh: A remote sensing and GIS-based approach for water resource management. *Hydrology*, *5*(6), 86-95.

Nelson, D. W., & Sommers, L. E. (1982). Total Carbon, Organic Carbon and Organic Matter. In: Page, A.L., Miller, R.H. and Kenney, D.R., Eds., Methods of Soil Analysis, Part 2. In (pp. 539-579). Madison: American Society of Agronomy

Nguyen, D., Chou, T., Chen, M., Hoang, T., & Tran, T. (2021). A GIS-based multicriteria analysis of land suitability for groundnut crop in Nghe An province, Vietnam. *International Journal of Geoinformatics*, *17*(6), 85-95. https://doi.org/10.52939/ijg.v17i6.2071

Nigerian Meteorological Agency (NIMET). (2017). *2017 seasonal rainfall prediction and socio-economic implications for Nigeria*. Abuja, Nigeria: Nigerian Meteorological Agency.

Nketia, K., Adjadeh, T., & Adiku, S. (2018). Evaluation of suitability of some soils in the forest-savanna transition and the Guinea savanna zones of Ghana for maize production. *West African Journal of Applied Ecology*, *26*(1), 61-73.

Ogunwale, J. A., Udo, E. J., Ibia, T. O., Ano, A. A., & Esu, I. E. (2009). Manual of soil, plant and water analyses. In (pp. 31–33). Lagos, Nigeria: Sibon Books Limited

Onweremadu, E. U. (2008). Physico-chemical characterization of a farmland affected by wastewater in relation to heavy metals. *Journal of Zhejiang University Science*, *9*(3), 366-372.

Page, A. L., Miller, R. H., & Keeney, D. R. (1982). *In: Methods of soil analysis part 2. (Chemical and mineralogical properties). Agronomy Monograph No 9*. Madison WI: ASA-SSSA.

Panday, D., Maharjan, B., Chalise, D., Shrestha, R. K., & Twanabasu, B. (2018). Digital soil mapping in the Bara district of Nepal using Kriging tool in ArcGIS. *PloS one*, *13*(10), e0206350. https://doi.org/10.1371/journal.pone.0206350

Patil, S., Patil, V., & Al-Gaadi, K. (2011). Spatial variability in fertility status of surface soils. *World Applied Sciences Journal*, *14*(7), 1020-1024.

Pieri, C., & Steiner, K. G. (1997). The role of soil fertility in sustainable agriculture with special reference to Sub-Saharan Africa. *Agriculture and Rural Development*, *4*, 22-25.

Prieto-Méndez, J., Prieto-Méndez, F., Prieto-García, O. A., Acevedo-Sandoval, E., & Aquino-Torres, E. (2021). *Spatial variability of physical, chemical, and biological properties of agricultural soils in Hidalgo State*. Mexico: Agro Productividad.

Raj, S., Roodbar, S., Brinkley, C., & Wolfe, D. W. (2022). Food security and climate change: Differences in impacts and adaptation strategies for rural communities in the global south and north. *Frontiers in Sustainable Food Systems*, *5*, 691191. https://doi.org/10.3389/fsufs.2021.691191

Ramamurthy, V., Reddy, G. O., & Kumar, N. (2020). Assessment of land suitability for maize (Zea mays L) in semi-arid ecosystem of southern India using integrated AHP and GIS approach. *Computers and Electronics in Agriculture*, *179*, 105806. https://doi.org/10.1016/j.compag.2020.105806

Rawal, N., Acharya, K. K., Bam, C. R., & Acharya, K. (2018). Soil fertility mapping of different VDCs of Sunsari District, Nepal using GIS. *International Journal of Applied Sciences and Biotechnology*, *6*(2), 142-151.

Reza, S., Baruah, U., Sarkar, D., & Singh, S. (2016). Spatial variability of soil properties using geostatistical method: A case study of lower Brahmaputra plains, India. *Arabian Journal of Geosciences*, *9*, 1-8.

Salem, A., Ibrahim, A., & Sani, I. (2020). Spatial variability in the fertility and salinity/sodicity status of fadama soils of Baure, Yamaltu Deba Local Government Area, Gombe State, Nigeria. *Nigerian Journal of Agriculture, Food and Environment*, *16*(4), 119-128.

Salem, A., Musa, H., & Askira, M. (2017). The study of soil profile characteristics under different land use in Fufore Local Government, Adamawa State, Nigeria. *Nigerian Journal of Engineering, Sciences and Technological Research*, *3*(2), 80-91.

Sathiyamurthi, S., Sivasakthi, M., Saravanan, S., Gobi, R., & Karuppannan, S. (2024). Assessment of crop suitability analysis using AHP-TOPSIS and geospatial techniques: A case study of Krishnagiri District, India. *Environmental and Sustainability Indicators*, *24*, 100466. https://doi.org/10.1016/j.indic.2024.100466

Shanono, N. J., Nasidi, N. M., & Usman, N. Y. (2022). Appraising the current state of irrigation schemes in northern Nigeria using sustainability pillars. *Environmental Research and Technology*, *5*(4), 305-314. https://doi.org/10.35208/ert.1097795

Shehu, B., Jibrin, J. M., & Samndi, A. (2015). Fertility status of selected soils in the Sudan Savanna Biome of Northern Nigeria. *International Journal of Soil Science*, *10*(2), 74-83. https://doi.org/10.3923/ijss.2015.74.83

Subhash, B., Singh, R., Avasthe, R., Kumar, S., Rathore, S. S., Singh, V. K., . . . Petrosillo, I. (2023). Soil carbon dynamics under organic farming: Impact of tillage and cropping diversity. *Ecological Indicators*, *147*, 109940. https://doi.org/10.1016/j.ecolind.2023.109940

Suheri, N. A., Mujiyo, M., & Widijanto, H. (2018). Land suitability evaluation for upland rice in Tirtomoyo District, Wonogiri Regency, Indonesia. *SAINS TANAH-Journal of Soil Science and Agroclimatology*, *15*(1), 46-53.

Tadesse, M., & Negese, A. (2020). Land suitability evaluation for sorghum crop by using GIS and AHP techniques in Agamsa sub-watershed, Ethiopia. *Cogent Food & Agriculture*, *6*(1), 1743624.

Tellen, V. A., & Yerima, B. P. (2018). Effects of land use change on soil physicochemical properties in selected areas in the North West region of Cameroon. *Environmental Systems Research*, *7*(1), 1-29.

Tiruneh, G. A., Alemayehu, T. Y., Meshesha, D. T., Adgo, E., Tiruneh, G. A., & Reichert, J. M. (2023). Variability modeling and mapping of soil properties for improved management in Ethiopia. *Agrosystems, Geosciences & Environment, 6*(1), e20357. https://doi.org/10.1002/agg2.20357

UNEP. (1982). *World soil policy*. Nairobi, Kenya: United Nations Environment Programme.

Van Reeuwijk, L. P. (2006). Procedures for soil analysis. *Wageningen: ISRIC–World Soil Information Centre. Technical Reports, 9*, 1–150.

Voncir, N., Mustapha, S., Tenebe, V., Kumo, A., & Kushwaha, S. (2008). Content and profile distribution of extractable zinc (Zn) and some physicochemical properties of soil along a toposequence at Bauchi, Northern Guinea savanna of Nigeria. *International Journal of Soil Science, 3*(1), 62–68. https://doi.org/10.3923/ijss.2008.62.68

Warrick, A. W. (1954). Spatial variability. In: Hillel D (ed.) Environmental soil physics. In (pp. 655–675). Cambridge, MA, USA: Academic Press

Weldeabzgi, G., Ketema, T., Gashu, G., & Deressa, S. (2021). Land suitability evaluation for surface irrigation development using parametric evaluation approach: The case of Gudina Wacho watershed, Western Ethiopia. *Journal of Agricultural Science and Food Technology, 7*(3), 302-309. https://doi.org/10.17352/2455-815X.000124

Wen, T. T. (1997). *Crop requirement tables for Yemen (Field Document No. 3)*. Dhamar, Yemen: ERARLUP Project, GCP/YEM/021/NET, Agricultural Research and Extension.

Winchell, M., Srinivasan, R., Di Luzio, M., & Arnold, J. (2008). *ArcSWAT2: Interface for SWAT 2005—User manual*. United States: Blackland Research and Extension Center, Texas A&M University.

Wong, I. F. (1986). *Soil-Crop suitability classification for peninsular Malaysia*. Malaysia: Ministry of Agriculture Malaysia.

Yadav, D., Singh, D., Babu, S., Madegowda, M., Singh, D., Mandal, D., . . . Kumawat, A. (2014). Intensified cropping reduces soil erosion and improves rainfall partitioning and soil properties in the marginal land of the Indian Himalayas. *International Soil and Water Conservation Research, 12*(3), 521-533.

Yadav, S. S., Hegde, V. S., Habibi, A. B., Dia, M., & Verma, S. (2019). Climate change, agriculture and food security. In: Yadav SS, Redden R.J. et al. (Eds). Food security and climate change. In (1st ed., pp. 1-23). United Kingdom: John Wiley and Sons Ltd

Yeneneh, N., Elias, E., & Feyisa, G. L. (2022). Assessment of the spatial variability of selected soil chemical properties using geostatistical analysis in the north-western highlands of Ethiopia. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science, 72*(1), 1009-1019.