PRINCIPAL COMPONENT AND CLUSTERING APPROACH TO DELINEATION OF SOIL MANAGEMENT UNIT IN PELLA DISTRICT OF HONG LOCAL GOVERNMENT AREA, ADAMAWA STATE

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ABSTRACT

Principal Component Analysis (PCA) was applied to 29 soil physicochemical parameters to identify the most influential indicators of variability in soils of the Pella district. The first seven principal components (PC1–PC7) explained 96% of the total variance, with strong contributions from Cu, K, Porosity, Clay, Effective Cation Exchange Capacity (ECEC), Fe, and Exchangeable Sodium Percentage (ESP). These variables emerged as key drivers of soil heterogeneity, thereby reducing the set of parameters required for effective soil characterization. The component structure highlighted Cu, ECEC, Fe, AvP, and ESP as dominant contributors across multiple components, underscoring their relevance in soil fertility assessment. Cluster analysis further classified soils from eleven sampling units (Pella, Dzuma, Midila, Zhedinye, Mbulinyi, Dagza, Uding, WuroBokki, Fachi, PellaGwaja, and Holma) into three distinct management zones. Dzuma, Pella, Uding, PellaGwaja, and Holma formed one similarity group; Zhedinye and Dagza clustered together, while WuroBokki, Fachi, Mbulinyi, and Midila constituted a third group. This classification demonstrates that PCA combined with clustering provides a robust framework for delineating site-specific soil management zones, enabling precision agriculture strategies that target variability in soil fertility. By identifying critical soil properties and grouping soils into management units, this study offers a practical basis for improving crop productivity and promoting sustainable land management in the Pella district.

Keywords: Principal Component Analysis, clustering, nutrients, Hong, Adamawa State

INTRODUCTION

Soils of northeastern Nigeria are often characterized as weak, highly weathered, and fragile, with low-activity clays (Adekiya et al., 2022). The occurrence of this low-activity clay, coupled with other climatic factors, has resulted in widespread plant nutrient deficiencies in soils of Adamawa State, with adverse consequences for crop production and soil fertility maintenance (Simon et al., 2025). While soil fertility is not always homogeneous, heterogeneity is influenced by both inherent soil properties and anthropogenic variability across soils with different management practices (Alhassan et al., 2023).

Spatial variability of soil properties is an important aspect of soil fertility evaluation. Soils can vary significantly over short distances due to factors such as topography, land use, and management practices. Tropical soils are characterized by high spatial variability due to the combined effects of intrinsic (e.g., biophysical and chemical processes), and extrinsic factors (e.g., crop management, fertilizer and tillage, among others) operating at different intensities and on different spatiotemporal scales. Spatial variability in soils and the corresponding variability of yield response of various crops to nutrient application have already been observed across Sub-Saharan Africa (Abdulraheem et al., 2022; Akinseye et al., 2020).
The methods and successes in evaluating soil fertility variability have been observed to increase technical knowledge of soil fertility management. The absence of an effective soil fertility evaluation method, therefore, strongly diminishes its predictive values. Some methods for assessing soil properties for soil nutrient determination can be cumbersome and time-consuming. Consequently, low-complexity techniques are employed to select a subset of key variables for spatiotemporal soil assessment. In this context, multivariate analysis, such as principal component analysis (PCA), aims to condense the observed variables into a smaller set of variables (factors) for soil property assessment without losing much of the necessary information from large datasets gathered (Abdel-Fattah et al., 2021). One of the major objectives of cluster analysis is to assign individuals (observations) to homogenous clusters (groups) so that observations within each group are similar to one another with respect to variables or attributes of interest (Alhassan et al., 2023). It is then very important to study the variability of soil properties that are geographically related to develop sustainable site-specific soil management strategies in the study area. Thus, this study was carried out to evaluate soil properties of the Pella district using Principal Component Analysis (PCA) and Clustering Analysis (CA), with the aim of classifying the management units into a dendrogram.

MATERIALS AND METHODS

Study Area

The study was conducted in the Pella district of the Hong Local Government Area, Adamawa State, North-East Nigeria. It lies between latitudes 9^0 58' to 10^0 35' N, longitudes 12^0 35' to 13^0 13'E with an elevation of 305-400m above sea level (Zemba et al., 2020). It has an approximate land area of 328.25 $km^{2,}$ consisting of the Adamawa Mountain with a mixed assemblage of granite outcrops, dissected surface, steep slopes, and plains (Babayi et al., 2012). The soil in this area falls into the lithosol category, with parent material of the undifferentiated basement complex, represented by migmatite-gneisses, schists, quartzites, aplite, medium- and coarse-grained granites, pegmatite, diorite, and amphibolites (Udo, 1970; Ray, 2020).

Soil Sampling and Laboratory Analysis

Eleven units, namely Pella, Dzuma, Midila, Zhedinye, Mbulnyi, Dagza, Uding, WuroBokki, Fachi, PellaGwaja and Holma, were used as sampling units for soil sampling. Eight surface soil samples were collected from each of the eleven mapping units at random, at a depth of 0-20cm. Laboratory analysis was performed on the collected samples. Particle analyses of soils were determined using a Buoyoucous hydrometer method (Jaiswal, 2003). Soil bulk density was determined from soil cores (Gautam et al.,2023). The total porosity was calculated by assuming a particle density of 2.65mg^{-3} using the expression as given by (Childs & Bybordi, 1969). Soil pH and EC were determined in a 1:2 (Soil: Water) suspension using a pH meter and an EC conductivity meter (Gautam et al., 2023). Soil organic carbon was determined using the Wet Oxidation method (Walkley & Black 1934). Organic matter was calculated as the product of the soil's organic carbon content and a factor of 1.724. Total nitrogen was determined by the Kjeldahl wet oxidation method as outlined by Sabah et al. (2022). Available phosphorus was determined using the Bray-1 method (Bray and Kurtz, 1945). Exchangeable cations: Calcium (Ca), Magnesium (Mg), Potassium (K) and Sodium (Na) were determined from the extract of soil treated with neutral normal ammonium acetate (pH 7.0), [1N neutral ammonium acetate (NH_4OAc)]. Calcium and Magnesium were determined by titration, whereas K and Na were determined using a flame photometer (Gautam et al., 2023). Total Exchangeable Acidity (TEA) was determined by extracting soil samples with 1N KCl and titrating the extract with 1N Sodium hydroxide (Jaiswal, 2003). Effective Cation Exchange Capacity (ECEC) was determined by summing the exchangeable cations (Ca, Mg, K, and Na) and exchangeable Al and H (Jaiswal, 2003*)*. Percentage base saturation was calculated by dividing the sum of exchangeable bases by the soil's ECEC and expressed as a percentage (Gautam et al., 2023). Exchangeable sodium percentage (ESP) was calculated as the proportion of ECEC (NH_4OAc) occupied by sodium cations, i.e., dividing the exchangeable sodium content of the soil by the ECEC (soil) expressed as a percentage (Gautam et al., 2023). Micro nutrients (Cu, Fe, Mn, Zn, S, and Mo) were extracted using perchloric acid/Nitric acid and digested on a hot plate at about 200-225^{0}C until the mixture turned yellow or white. The digest was then dissolved in 0.1M HCl and filtered. Determination of Cu, Fe, Mn and Zn was carried out by an Atomic Absorption Spectrophotometer. Sulphur (S) was extracted with $CaCl_2$ and determined turbidimetrically using a spectrophotometer, while Molybdenum (Mo) was extracted with ammonium oxalate and determined by the calorimetric method (Gautam et al., 2023).

Statistical Analysis

Data were analyzed using descriptive statistics with SAS (2015). Variability levels were interpreted using coefficient of variation (CV) classes as described by Tabi & Ogunkunle (2007): most variable (CV > 35%), moderately variable (CV 15–35%), and least variable (CV < 15%). The suitability of the dataset for factor analysis was confirmed by the Kaiser-Meyer-Olkin (KMO) statistic, which exceeded the recommended threshold, indicating sampling adequacy. Principal Component Analysis (PCA) was then used to reduce the dataset. Cluster analysis was performed using Euclidean distance and Ward’s method to group soils from eleven samples.

RESULTS AND DISCUSSION

Soil Physical Properties

The results of the soil physical properties analyzed are presented in Table 1. Most of the units have high sand percentages, ranging from 62.42 to 69.90%, with a low coefficient of variability (13.39%). Silt has a moderate CV of 31.39%, with a range of 16.48 to 20.39%, while the clay fraction has a higher coefficient of variability (40.42%), with a range of 12.53 to 20.01%. The highest variability in clay may result from deposition via erosion and eluviation (Ray, 2020). The soil bulk densities of the entire unit were low, ranging from 1.46 to 1.54 g/cm^{-3}; these values are characteristic of loam and clay loam soils. According to Nam et al. (2021), soils with a bulk density of less than 2.5 g/cm3 are assessed to have high humus content. The percentage soil porosity ranged from 41.88 to 44.50 %; these values indicate moderate porosity. According to Afriawan et al. (2021), soil porosity should be above 50% because it improves plant growth conditions and boosts soil respiration and microbial activity. Similar findings to those reported in this study were recorded by Ahmed et al. (2013) in Mubi, South of Adamawa State, Nigeria.

Table 1: Soil Physical Properties of the Study Area. (0-20cm depth) Pella District

Units	Sand	Silt	Clay	BD	Porosity
		%		(g/cm^3)	(%)
Dagza	66.11	18.53	15.36	1.51	43.12
Dzuma	68.61	16.89	14.50	1.52	42.75
Fachi	62.42	17.57	20.01	1.46	44.50
Holma	68.38	18.98	12.64	1.53	42.25
Mbulinye	65.70	18.74	15.56	1.50	43.50
Midila	69.35	17.22	13.43	1.53	42.38
Pella	69.90	17.57	12.53	1.54	41.88
Pella gwaja	69.27	16.48	14.25	1.53	42.12
Uding	68.86	17.75	13.39	1.53	42.50
Wrobokki	66.53	17.64	15.83	1.51	43.12
Zhedinye	63.91	20.39	15.70	1.50	43.75
SE	4.50	2.81	3.00	0.04	1.33
CV (%)	13.39	31.22	40.42	4.82	6.21

Soil Chemical Properties of the Study Area: Pella District

The mean chemical properties of the study soils are presented in Table 2. The pH in all units was slightly acidic to neutral, with values ranging from 6.18 to 7.0 and a coefficient of variation (CV) of 4.63%. Low soil pH may be due to cation depletion during long cultivation and to high use of inorganic fertilizers (Mulat et al., 2021). Similar, slightly acidic values were also recorded by Maunde et al. (2016) while evaluating the soil fertility status of the Song Local Government of Adamawa State, Nigeria. Mean electrical conductivity (EC) values across all units were low, ranging from 0.027 to 0.975 ds/m, with a very high CV (86.11%). The lower EC values recorded in the area may be attributed to leaching of salt to much lower horizons, given the light-textured nature of the soil in the study area.

A similar result was also reported in the soils of Loko, Adamawa State, by Musa (2015). The low EC value may also be due to cation depletion during prolonged cultivation (Mulat et al., 2021). Low mean values of soil organic carbon and organic matter were recorded, with ranges of 0.01 to 1.10 % and 1.38 to 1.91 %, respectively, and moderate variation (26.29%) for organic carbon and (26.18%) for organic matter. These low values could be attributed to the sandy-to-sandy loam texture of the soil, which might facilitate high runoff and depletion of organic materials by rainfall in the area. The low organic matter can also be linked to a high rate of organic matter oxidation (Mulat et al., 2021). Mean value of available phosphorus ranged from 7.88 to 11.55 mg/kg and varied within the units (16.2%). These low-to-medium available phosphorus values could be related to low organic matter recorded in the area. A similar result, with a lower Available Phosphorus value, was reported by Jamala & Oke (2013) in soils from some parts of Adamawa State, Nigeria, and attributed to land use and the region's inherent P deficiency. Low value of Total Nitrogen was also recorded, which could also be attributed to low organic matter content of the soils and their sandy nature, which can facilitate high infiltration that can leach down nitrogen (Brady & Weil, 2008).

Table 2 Soil Chemical Properties of the Study Area (0-20cm depth) Pella District

Units	**pH**	**EC**	**Org. C**	**Org. M**	**TN**	**Av N**	**AvP**	**S**
		(dS/m)	**%**				**mg/kg**	**mg/kg**
Dagza	6.3	0.0275	0.89	1.54	0.075	0.0008	11.52	6.32
Dzuma	6.64	0.0513	1.10	1.91	0.093	0.0006	10.42	5.56
Fachi	6.93	0.0338	0.93	1.60	0.078	0.0009	9.41	4.72
Holma	6.6	0.0325	0.97	1.67	0.083	0.0010	9.82	6.33
Mbulinye	6.18	0.0375	0.79	1.38	0.068	0.0007	7.88	6.53
Midila	6.83	0.0975	1.03	1.79	0.085	0.0008	9.88	6.75
Pella	6.77	0.0413	0.81	1.39	0.069	0.0007	10.00	5.14
Pella gwaja	7.00	0.0287	1.08	1.87	0.090	0.0008	10.35	4.60
Uding	6.42	0.0437	0.98	1.70	0.083	0.0007	11.48	5.97
Wurobokki	6.5	0.0400	1.01	1.75	0.084	0.0012	9.65	5.46
Zhedinye	6.54	0.0275	1.02	1.77	0.085	0.0008	11.55	5.36
SE	0.153	0.018	0.127	0.218	0.011	0.0002	0.825	0.76
CV (%)	4.63	86.11	26.29	26.18	26.81	42.44	16.2	26.66

Soil Micronutrients of the Study Area, Pella District

The results for soil micronutrients in the study area are presented in Table 3. Mean molybdenum values ranged from 0.29 to 0.71 mg/kg, with the minimum in the Zhendinye unit and the maximum in the Holma unit. Slightly lower values were reported by Bapetel et al. (2013) for some soils in Adamawa State. The low to medium content of Mo in the soil might be a result of nutrient interaction with soil pH; the mean values of copper (Cu) ranged from 0.30 to 0.92 mg/kg, with the least value recorded in Zhedinye unit and the highest mean value at the Holma unit, with a high coefficient of variability (64.00 %). The iron Fe values ranged from 3.59 to 6.80mg/kg, with a high coefficient of variability of 42.93%.

Table 3: Soil Micronutrients of the Study area (0-20cm depth) Pella District

Units	Mo	Cu	Fe	Mn	Zn
			mg/kg		
Dagza	0.46	0.59	4.82	1.04	1.42
Dzuma	0.41	0.48	4.74	0.63	1.35
Fachi	0.50	0.59	6.80	3.14	1.49
Holma	0.71	0.92	4.82	0.59	1.31
Mbulinye	0.49	0.42	5.57	4.11	1.30
Midila	0.37	0.66	3.59	1.35	1.16
Pella	0.35	0.69	5.62	2.29	1.40
Pella gwaja	0.45	0.53	5.07	3.34	0.80
Uding	0.50	0.70	4.09	0.57	1.73
Wurobokki	0.41	0.89	4.08	1.78	1.53
Zhedinye	0.29	0.30	4.21	1.68	1.00
SE	0.13	0.20	1.04	0.60	0.33
CV (%)	57.57	64.00	42.93	63.88	50.14

Alhassan (2019) also reported adequate levels of Fe in soils of Bade Local Government Area, North-Eastern Nigeria. The mean manganese (Mn) concentration ranged from 0.57 to 4.11 mg/kg, with a high coefficient of variation (63.88). About 30% of the values fell within the low rating, while medium and high concentrations had 35% each. High Mn concentrations found could also be attributed to the slight acidity of the soils in these areas. The soils should therefore be closely monitored to avoid Mn toxicity. The mean zinc (Zn) concentration ranged from 0.80 to 1.73 mg/kg, with a high coefficient of variation (50.1%). Most units had medium Zn concentrations, except at Uding and Wurobokki, which showed high concentrations. Lower values were equally recorded in the Pellagwaja unit. Specific fertilization in these low Zn-rated areas may be required for crops such as corn, beans, and some deciduous fruit trees. Low Zn concentrations were also reported by Alhassan (2019) in soils of the Bade Local Government Area, North-Eastern Nigeria.

Exchangeable Bases and Acidity, Percent Base Saturation and Exchangeable Sodium Percentage of the Soils, Pella District.

Table 4 presents the mean exchangeable bases, acidity, percentage base saturation, and exchangeable sodium. Mean calcium across all units ranged from 5.3 to 66.12 cmol/kg, with slight variation (CV = 11.75%) that did not differ significantly between units. The recorded medium calcium value might result from calcium-containing weathered rocks and minerals such as calcite, apatite, and dolomite, which are dominant in the study area (Ray, 2020). The values of Magnesium (Mg) ranged from 2.04 to 2.73 cmol/kg, with moderate CV (15.68%), while Potassium (K) and Sodium (Na) had moderate CV of (19.5) and 22.34% respectively, these values may be attributed to presence of potassium rich clay mineral like illite and feldspar as opined by Amadi et al. (2019) that granitic rocks domiciled in Pella Hong local government showed quartz, feldspar, mica and some accessory minerals. Total exchangeable bases (TEB) ranged from 8.88 to 9.82cmol/kg, with the minimum value found in the Midila unit and the maximum mean value at the Wurobokki unit. The TEB varied slightly across the units (CV 8.49). However, total exchangeable acidity (TEA) values range from 1.09 to 2,30cmol/kg, with a moderate coefficient of variability (33.68%). Mean values of effective cation exchange capacity (ECEC) also ranged from 10.11 to 12.02 cmol/kg with a slight coefficient of variability (8.44%), this low ECEC values may be attributed to the low clay and organic matter contents of the soils (Adamu et al., 2014). The percentage base saturation (PBS) values were higher across all units, ranging from 80.41 to 87.96%, with a slight coefficient of variability (5.07%). which might be due to a slight, near-neutral pH recorded in the area. Values of ESP also ranged from 4.53 to 6.39%, with moderate variation across sampled locations (21.39%). This shows that the sodium content in the soils is minimal, with the least possibility of developing into a sodic soil.

Principal Component Analysis (PCA)

Tables 5 and 5a present the principal component matrix and component structure summary of the study area, which identified seven (7) factors that explain the major variations in the soil. The Seven (7) principal components (PCs) were obtained with eigenvalues greater than 1. The scree plot shows a sharp drop after PC3–PC4, then a gradual flattening. That indicates that the first three to five components capture most of the meaningful variance, while later ones contribute little (Fig. 1). PC1–PC3 explain 66.7% of total variance, PC1–PC5 explain 85.7%, PC1–PC7 explain 96.0% (Table 5a). PC1 reflects soil texture and cation properties (Sand, Clay, K, Cu, Porosity); PC2 captures exchangeable bases (OrgC, TN, Ca, Na, ECEC); PC3 relates to fertility and micronutrients (Fe, Mn, Mo, EC); PC4 highlights soil acidity and nutrient balance (S, Ca, Mn, Na, pH); while PC5 emphasizes Phosphorus and soil reaction (AvP, EC, Mg, PBS). However, this number was reduced to the first five (5) axes, as they explained at least 5% of the variance (Martín-Sanz et al., 2022).

Table 4: Exchangeable Cations, Total Exchangeable Bases and Acidity, Percent Base Saturation and Exchangeable Sodium Percentage of the Soils (0-20cm depth), Pella District.

Units	Ca	Mg	Na	K	TEB	Al	H	TEA	ECEC	PBS	ESP
	cmol/kg									(%)	
Dagza	5.88	2.67	0.561	0.604	9.71	1.29	1.01	2.30	12.02	80.87	4.66
Dzuma	5.65	2.69	0.534	0.626	9.51	1.32	0.98	2.30	11.81	80.41	4.53
Fachi	5.87	2.51	0.618	0.654	9.65	0.70	0.67	1.37	11.02	87.65	5.62
Holma	5.65	2.37	0.641	0.733	9.39	0.67	0.64	1.31	10.71	87.84	5.99
Mbulinye	5.64	2.53	0.638	0.561	9.38	0.56	0.53	1.09	10.48	89.61	6.14
Midila	5.31	2.35	0.641	0.573	8.88	0.63	0.60	1.23	10.11	87.96	6.39
Pella	5.62	2.68	0.549	0.585	9.43	0.95	0.67	1.62	11.06	85.22	4.97
Pella gwaja	5.82	2.04	0.484	0.555	8.89	0.79	0.76	1.54	10.44	85.38	4.60
Uding	6.12	2.28	0.549	0.643	9.60	0.59	0.56	1.16	10.75	89.21	5.09
Wurobokki	5.88	2.73	0.543	0.656	9.82	0.90	0.87	1.78	11.59	85.16	4.73
Zhedinye	5.79	2.39	0.569	0.661	9.41	1.32	0.73	2.05	11.46	82.03	4.96
CV (%)	11.75	15.68	22.34	19.5	8.49	35.34	41.13	33.68	8.44	5.07	21.39

The results in Table 5 showed that the seven principal components (PC1, PC2, PC3, PC4, PC5, PC6, and PC7) accounted for 96% of the total variation in the selected soil properties with Eigenvalues greater than one. Among the 29 soil properties examined, the first principal component (PC1) captured 25.8% of the total variation between the units. This component included potassium (K), total porosity, clay content, hydrogen (H), total exchangeable acidity (TEA), and aluminum (Al), and on a lighter note, silt fraction, indicating their significant contributions to the observed variation. The second principal component (PC2) accounted for 23.6% of the total variation between units. It consisted of soil effective cation exchange capacity (ECEC), total exchangeable bases (TEB), calcium (Ca), total nitrogen (TN), organic matter (OM), organic carbon (OC) and magnesium (Mg), suggesting their influence on the observed variation.

The third principal component (PC3) accounted for 17.2% of the total variation between units. It consisted of iron content (Fe), electrical conductivity (EC), manganese (Mn) and clay content. The fourth principal component (PC4) accounted for 10.6% of the total variation between units. It consisted of soil Sulphur concentration (S) and sodium (Na) on a lighter note. The fifth principal component (PC5) accounted for 8.5% of the total variation between units. The variance was mainly due to electric conductivity (EC). The sixth principal component (PC6) accounted for 5.9% of the total variation between units. It consisted of soil available nitrogen (AN) content. The seventh principal component (PC7) accounted for 4.4% of the total variation between units. It consisted, to a lesser extent, of soil available nitrogen (AN) content, potassium (K), molybdenum (Mo), and zinc (Zn). The principal component analysis (PCA) has shown that soil properties can be reduced from 29 to 7 components. This should guide the farmer in managing the soil of the Pella district. The analysis accounts for about 96% of the variability and identifies PC1 as the variable with the highest eigenvalue (7.49), followed by PC2 (6.84), PC3 (5.00), PC4 (3.06), PC5 (2.46), PC6 (1.70), and PC7 (1.28), indicating the relative importance of these elements in managing the soil of the Pella district. A similar PCA analysis was conducted by Menge et al. (2024) on the mean values of soil chemical properties.

Table 5: Principal Components Matrix.

	Components						
Variables	**PC1**	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**
Sand	-.84	-.33	-.05	-.27	.31	.06	.06
Silt	.40	-.02	-.85	.01	-.17	-.22	.08
Clay	.68	.36	.50	.28	-.24	.05	-.11
BD	-.72	-.40	-.36	-.34	.26	-.03	.07
Porosity	.72	.37	.41	.33	-.25	00	-.06
PH	.26	.42	.26	-.26	-.53	.44	-.10
EC	.10	.31	.75	.19	.52	-.05	-.04
OC	.55	.62	-.13	.38	.05	.35	.05
TN	-.56	-.63	-.11	.39	.06	.34	-.05
Av N	-.24	-.22	-.22	00	-.14	.72	.43
Av P	-.26	-.05	-.6	.15	-.64	.18	-.02
Ca	-.41	.64	.29	-.53	-.07	.12	.02
Mg	.27	.59	-.14	.37	-.50	.04	.33
Na	.28	-.72	.22	.42	.12	-.10	.33
K	.79	.03	.27	.15	.33	00	.41
TEB	-.19	.81	.26	-.30	-.25	.15	.23
Al	.54	.44	-.47	-.37	.26	-.07	.29
H	.68	.33	-.10	-.09	.34	-.40	-.28
TEA	.67	.44	-.35	-.28	.33	.15	.05
ECEC	.12	.87	.08	.38	-.08	-.06	.22
PBS	-.71	.12	.44	.20	-.46	-.12	.02
ESP	.13	-.86	.12	.43	.10	-.08	.09
S	-.58	.15	.14	.56	.37	-.12	.15
Mo	-.37	.38	.66	.22	.11	.06	.41
Cu	-.87	.18	.24	-.33	.04	-.13	.12
Fe	.08	-.09	.89	-.32	-.09	-.13	-.12
Mn	.17	-.32	.64	-.49	-.21	.40	-.15
Zn	.07	-.75	.25	-.12	-.02	.25	.40

Values>0.5 represent chosen parameters for the variations

Table 5b: Component Structure Summary

PC 1	PC 2	PC 3	PC 4	PC 5
Cu	ECEC	Fe	S	AvP
Sand	ESP	Silt	Ca	pH
K	TEB	EC	Mn	EC
Porosity	Zn	Mo	ESP	Mg
BD	Na	Mn	Na	PBS
PBS	Ca	AvP		
H	TN	Clay		
Clay	OC	Al		
TEA	Mg	PBS		
S	TEA	Porosity		
TN	Al			
OC	pH			
Al				
Ca				
Silt				

Scree Plot

Figure 1 presents the scree plot, showing the percentage of variance explained by each principal component plotted against the eigenvalues. Any eigenvalues not up to 1 either did not contribute or contributed less to the variability of the data. As shown in the scree plot (Graphical visualization of Eigenvalues), PC1 has 7.49, PC2 has 6.84, PC3 has 5.00, PC4 has 3.06, PC5 has 2.46, PC6 has 1.70, PC7 has 1.28, and zero for PC8, respectively. The percentage of variance explained by each principal component, as shown in the graph between eigenvalues and principal components, accounts for the major portion. Principal components with eigenvalues larger than 1 are more informative than the original variable. Thus, from the graph, the maximum variation was observed for PC1, which decreased gradually compared to the other PCs. At PC 8, the eigenvalue is almost less than 1, therefore contributing less to the component's variability.

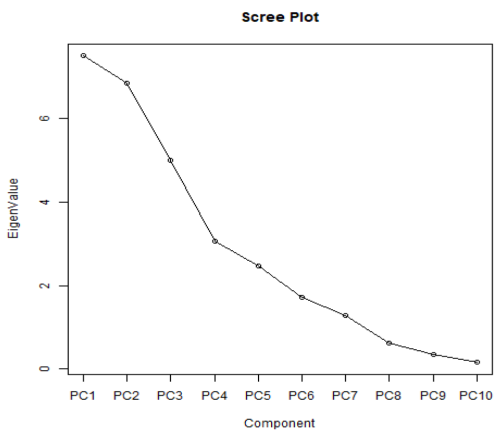

Fig 1: Scree Plot of eigenvalues and principal components.

Clustering

Cluster analysis of 29 soil physicochemical parameters across eleven sampling units in the Pella district revealed three distinct management zones. The dendrogram grouped Dzuma, Pella, Uding, Pella Gwaja, and Holma into Cluster 1, Zhedinye and Dagza into Cluster 2, and Wuro Bokki, Fachi, Mbulinyi, and Midila into Cluster 3. These clusters reflect spatial variability in soil properties, consistent with the dimensional reduction achieved through Principal Component Analysis (PCA), where the first seven components explained 96% of the total variance. The variability among clusters was driven by different sets of soil parameters. Cluster 1 was characterized by Sand, Clay, Bulk Density (BD), Porosity, Mg, K, Al, H, TEA, PBS, and Cu, indicating that soil texture and cation exchange properties are critical for management in these units. Cluster 2 was influenced by Silt, pH, Electrical Conductivity (EC), Organic Carbon (OrgC), Total Nitrogen (TN), Available Phosphorus (AvP), Sulfur (S), Mo, Fe, Mn, and Zn, highlighting the importance of nutrient availability and organic matter dynamics. Cluster 3 was defined by Ca, Na, Total Exchangeable Bases (TEB), Effective Cation Exchange Capacity (ECEC), and Exchangeable Sodium Percentage (ESP), suggesting that base cation balance and sodicity are the dominant factors. These findings underscore the utility of PCA and clustering in simplifying complex soil datasets and identifying site-specific drivers of fertility. By delineating management zones, the study provides a framework for precision agriculture strategies that tailor nutrient inputs to localized soil conditions. Similar approaches have been reported by Alhassan et al. (2023) in Yobe State, Nigeria, and by Menge et al. (2024), who demonstrated the effectiveness of PCA in identifying significant contributors to soil variability and establishing nutrient management zones. Collectively, these results reinforce the role of multivariate statistical tools in guiding sustainable land management and improving crop productivity.

Units

Figure 2: Classification of 3 Management Zones in a Dendrogram.

CONCLUSION

Spatial variability in some soil properties was observed across units within the study sites. These variations were contributed by variables such as sand, clay, BD, porosity, Mg, K, Al, H, TEA, PBS, and Cu, and are considered likely indicators of the different soil groupings in the study area. PC1 to PC7 explained 96% of the total variance of soil physico-chemical properties. Clustering analysis showed that Cluster 1 includes: Dzuma, Pella, Uding, Pella gwaja and Holma units, Cluster 2 includes Zhedinye and Dagza, and Cluster 3 includes Wuro bokki, Fachi, Mbulinye and Midilla. Cluster 1 is strongly influenced by copper (Cu), potassium (K), porosity, clay, TEA, and OrgC. Management in this zone should focus on improving organic matter retention with organic amendments such as compost or manure. Copper levels should be carefully monitored to avoid toxicity, and Porosity can be enhanced and bulk density reduced through conservation tillage. Cluster 2 is driven by effective cation exchange capacity (ECEC), calcium (Ca), sodium (Na), exchangeable sodium percentage (ESP), and zinc (Zn). Management practices here should address sodicity by applying gypsum or organic amendments to improve soil structure and help stabilize nutrient retention. Cluster 3 is characterized by iron (Fe), manganese (Mn), available phosphorus (AvP), sulfur (S), magnesium (Mg), and soil pH. Management in this cluster should prioritize correcting soil acidity with lime application where needed to optimize nutrient uptake. Phosphorus availability can be improved through localized fertilization. Drainage improvements and pH control are critical in this regard. Finally, sulfur and magnesium inputs should be balanced to support crop nutrition effectively.

REFERENCES

Abdel-Fattah, M.K., Mohamed, E.S., Wagdi, E. M., Shahin, S., Aldosari, A.A., Lasaponara, R. and Alnaimy, M.A. (2021). Quantitative evaluation of soil quality using principal component analysis: The case study of El-Fayoum depression Egypt. *Sustainability,* 13*: 1824. Available:https://doi.org/10.3390/su13041 24.*

Abdulraheem, M. I., Abbas Naqvi, S. M. Z., Li, L., Ahmed, S., Wei, W., Rui, S., *et al.* (2022). Soil Fertility Management: Issues and Challenges in Tropical Areas of Nigeria. In: H. S. Jatav and V. D. Rajput (Eds). Agriculture Issues and Policies: Ecosystem Services Types, Management and Benefits. p313 – 326. *https*://doi.org/10.52305PFZ A6988.

Adekiya, A. O., Adegbite, K. A., Aremu, C., Adebiyi, O. T., Alori, E. T., Ayorinde, B. B., et al. (2022). Land Use Capability and Suitability Classifications of a Plinthic Alfisol of a Derived Savannah Ecology of Nigeria. *The Open Agriculture Journal, 16: 1-12.* DOI: 10.2174/18743315-v16-e2204220.

Adamu, U.K., Muhammad, A. and Adam, I.A. (2014). Evaluation of Soil Reaction Exchangeable Acidity and Cation Exchange Capacity of Soils from Kano University of Science and Technology Wudil Teaching, Research and Commercial Farm, Gaya. *Bayero Journal of Pure and Applied Sciences,* 7(1): 52–55.

Afriawan, A., Ahmad, A. and Gusli, S. (2021). Analysis of plant root properties, texture and porosity that affects landslides in Tangka sub-Watershed. *IOP Conf. Ser. Earth Environ Sci.,*886(1)*, 012093.doi:10.1088/1755-1315/886/1/012093.*

Ahmadi, A., Tukur, A., Maspalma, S., Okunlola, A., Unuevho, C. and Ameh, M. (2019). Comparative Geological study and physico-chemical parameters of Groundwater in Hong and Zango Settlements in Northern Nigeria. 44. 292-300.

Ahmed, M., Zata, A.I. and Abubakar, M.S. (2013). Effects of Disc ploughing on the morphological and physical properties of soils in Mubi south local government area, Adamawa state, Nigeria. *International Journal of Agricultural Science and Bioresource Engineering Research,* 2 (2):. 27-34. *http://www.ijasber.com ISSN 2315 – 6775.*

Alhassan I. (2019). Status of available micronutrients and their correlation with some soil properties in Bade local Government Area North eastern Nigeria. *Azarian J. Agric. Vol. (6) issue* 42019 106-111 http://dx.doi.org110.29252/azarij.014.

Alhassan, I., Dogo, S., Abdu, H., Muhmud, S &Hegarty J.P. (2023). Determination of soil nutrient management zone using principal component and clustering analysis in Bade local Government Area Yobe State Nigeria. *Journal of Research in Environmental and Earth Sciences,* 9(4) :68-74.

Akinseye, F. M., Hakeem, A. A., Kamara, A. Y., Elijah, A. A., Anthony, M. W. (2022) Understanding the response of sorghum cultivars to nitrogen applications in the semi-arid Nigeria using the agricultural production systems simulator. *Journal of Plant Nutrition, 43: 834–850.*

Babayi, A.U., Hong, A.H., Tashiwa Y.I., Umaru B.G., Buba S. Y & Abdullahi, A.S. (2012). Extend and remedy on gully erosion in Banshika Area Adamawa State Nigeria. *Academic Research international.www.journal.savap.org.pk.*

Bapetel, U., Sandabe, M. K, & Yakubu, H. (2013). Molybdenum availability and some physico-chemical properties of soils of different parent materials in Adamawa State, Nigeria. Journal *of Agric. and Envi.Vol.9 No1 and 2. 91-100.*

Brady, N.C. & Weil, R. R. (2008). The nature and properties of soils. 14th Ed. Prentice Hall Upper Saddle River, pp.960.

Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil science, 59(1), 39-46`*

Childs, E.C & Bybordi C. (1969). The vertical movement of water in a stratified porous material.1. Infiltration. *J. Water resource Research.5-(2)446-459.doi.org.*

Gautam, M.K., Sachan, R., Singh, D & Kumar, A. (2023). Fundamentals of soil science (laboratory manual) on soil analysis. Bhavyya books (BET) pub. New Dhelhi. www.bhavyabook.com.

Jaiswal, P.C. (2003). Soil, plant and water analysis. Kalyani publishers Ludhiana, New Delhi-Norda Hyderabad, India. pp 1-399.

Jamaila, G.Y & Oke, D.O. (2013). Soil Profile Characteristics as Affected by Land Use Systems in the Southeastern Adamawa State. *Nigeria Journal of Agriculture and Veterinary Science*. V6 Issue 4. PP 04-11 www.iosrjournals.org.

Martín-Sanz, J.P., Martín. A., Valverde-Asenj. D., Quintana-Nie to, J.R., Huecas, C.G & Lopez-Lafuente, A. L. (2022). Comparison of soil quality indexes calculated by network and principal component analysis for carbonated soils under different uses. J. *Ecological Indicators www.elsevier.com/locate/ecolind.ecological indicator 143(2022) 109374. 1470-160X/© 2022*https://doi.org/10.1016/j.ecolind.2022.109374

Maunde, M.M., Saddiq, A.M., Alhassan, I., Usman, B.H. & Ibrahim, A. (2016). Variability of Soil Properties in Song Local Government Area of Adamawa State, Northeast Nigeria. *Research Journali's Journal of Agriculture,* 3(6): 1–8.

Menge. D.M., Musila. R.N., Kagito. S., Bii, L., Gichuki, J., Gichuhi, E., Kundu, C.A., Murori, R., Ismail, A and Panchbhai, A. (2024). Using Principal Component Analysis to Assess Soil Chemical Properties in the Mwea Irrigation Scheme, Kenya: Implications for Rice Agronomic Management. *International Journal of Plant and Soil Science Volume,* 36(5): 106-126.

Mulat, Y., Tsehai, K., Bedadi, B., & Yusuf, M. (2021). Soil quality evaluation under different land use types in Kersa sub-watershed, Eastern Ethiopia. *Environ. Syst. Res. 10.doi.1186/s40068-021-00224-6.*

Musa, H. (2015). Catenary soil variability and its management implication along Loko toposequence, Northeastern Nigeria. *International Journal of Science, Environment and Technology,* (4)5:1279-1288.www.ijset.net.

Nam, T.S., Khanh, H.C., Thao, H. V, & Thuan, N.C. (2021). Physical and chemical characteristics of soil inside and outside the full-dyke systems in Phu Tan district, An Giang province. *Can Tho University Journal of science,* 57,. https://doi.org/10.22144/ctu.jsi.2021.033.

Ray, A.A. (2020). Soils and Soil Management. In Adebayo A.A., Tukur A.L and Zemba A. A. (Eds). *Adamawa state in map*. Second edition. Paraclete publishers Yola-Nigeria.

Sabah, G., Pitchamuthu, S., Rengaraji, M., Chinnathambi, R. & Rajendran S.D. (2022). *Hand book of analytical method in soil science*. Iterative Inter.publ. Sefypage Developer Pvt ltd Karmataka.

SAS. (2015). SAS 9.4 in-database products: User's guide, fifth edition.

Simon, B., Osuji, L., Obafemi, A., & Lawal, O. (2025). Assessing the Vulnerability of soil nutrient to climate stressors in Adamawa State, Nigeria. *Journal of global ecology and environment 21(4),125-138. Doi.org.*

Tabi, F.O. & Ogunkunle, A.O. (2007). Spatial variation of some soil physico-chemical properties of an Alfisol in southwestern Nigeria. *Nigerian Journal of Soil and Environmental Resources,* 7:82-91.

Udo, R.K. (1970). Geographical Regions of Nigeria. (1st ed). Heinemann London.

Walkley, A. & Black, C.A. (1934). An Examination of the Different Method of Determining Soil Organic Matter via Chronic-Acid Titration Method. *Soil Science Society America Journal, 37: 29-39.*

Zemba, A.A., Tukur, A.L & Ezra, A. (2020). Basic Geographic information on local government area. In Adebayo A. A., Tukur, A. L and Zemba, A.A.(Eds). Adamawa state in map. Second edition. Paraclete publishers Yola-Nigeria.