

Determinants of Soil Nutrient Dynamics Under Cashew Cultivation in the Sudan Savanna Zone of Nigeria.

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abstract

Due to the poor management practices, and prolonged cultivation of farmlands by local farmers who were unable to identify the key soil nutrients needed to counter the declining cashew yield, this study assessed the main determinants of soil nutrient dynamics under cashew (*Anacardium occidentale*) in part of the Sudan Savanna, Nigeria. Soil samples were collected from eight 20 x 20 m quadrats at a depth of 0-30 cm in cashew cultivated field. Standard laboratory techniques were used for the determination of particle size distribution, OM, TN, soil pH, EA, Ca²⁺, Mg²⁺, NA⁺, K⁺, AP, CEC, and BS. Principal Component Analysis (PCA) identified the main determinants of soil properties influencing nutrient dynamics under the cashew crops. The results showed only the first two components accounting for 74.6% were retained to explain the variables. The first component named nutrient supply, featured six fertility-related variables with the highest loadings: EA (0.953), BS (-0.944), K⁺ (0.943), pH (0.923), CEC (0.923), and OM (-0.890), and AP (0.750). These variables highlight nutrient availability dynamics and their implications for soil management. The second component, named soil texture component, comprised of variables defining texture with the highest: clay (-0.943), sand (0.919) and silt (0.889). This component illustrates soil texture's role in nutrient retention. Coefficient of variation and means complemented the result of the PCA results. Except for EA (18.83%) and Mg²⁺ (16.57%), which showed a moderate variability, all other variables exhibited relative homogeneity across the field. The results suggest that increases in EA, soil pH, K⁺, AP, and CEC positively influence soil fertility, while declines in OM and BS may lead to nutrient depletion. This underscores the need to manage soil acidity and nutrient levels to enhance cashew productivity while sustaining soil health. Additionally, the negative loading of clay implies that the prevalent sandy texture in the study area promotes nutrient leaching, necessitating soil amendments to improve nutrient absorption and moisture retention. These insights are vital for smallholder farmers seeking to optimize crop yields amid increasing agricultural intensification.

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1. Introduction

Cashew (*Anacardium occidentale*), a tropical nut tree crop, has gained significant economic importance in Nigeria. Although cultivated for over 400 years with minimal attention to its commercial potential, (Aliyu, 2012), large-scale cultivation and research efforts intensified from the 1970s onward. From available records cashew nut production in shell increased from 7,000 tonnes per 15,000ha in 1961 to 45,000 tonnes harvested from 75,000ha in 1991, sharply rose to 417,000 tonnes per 238,000ha in 1999, peaked at 800,000 tonnes per 360,000 ha in 2009, drastically reduced to 99,010 tonnes produced over 126,490ha in 2014, fluctuates around 100,000 tonnes per 140,000 ha onwards, until 2023 with only 88,475 tonnes yield from 172004ha, and 80943.66 tonnes per 170224ha in 2024 (FAO, 2025). Thus, there has been intensive production of cashew in this region, because it has become a vital source of income, food, and industrial raw materials. It also contributes substantially to the Nigerian economy by providing employment for over one million people and generating significant foreign exchange earnings (Eze et al., 2023) of over \$400 million (Balogun, 2026).

Sudan Savanna is located in-between the Sahel and Guinea savanna biomes. It therefore, shares climatic, vegetational, and to some extent, soil characteristics closely similar to those of the southern Sahel savanna as well as northern Guinea savanna. Thus, it is characterized predominantly by Arenosols (sandy, low in nutrient and moisture retention) and Plinthosols (constitute hardpans, impedes root growth and infiltration) types of soils (FAO et al., 2012). Although the texture of the Arenosols supports the cropping of cashew in the area (Jayawardana, 2023; Rankel, 2024), the soils have poor nutrient and moisture retention capacities. Thus, Arenosols require careful management practices. This is because, where there is severe land cultivation over a long period of time with no special measures in place, it may result in the depletion of available nutrients (Musa & Adamu, 2019) by crop uptake and leaching during wet season or due to irrigation practices. Despite this, cashew crops are grown in scattered individual trees and pockets of orchards under the Sudan savanna of Nigeria like some parts in Kebbi, Zamfara, Sokoto, Katsina, Kano, Jigawa (Edu et al., 2023) and Bauchi states. Moreover, in these places, the crop is grown mostly in small scale orchards by local farmers who lack adequate sustainable management practices, especially in the event of decreasing crop yield. This may prevent the local farmers from making informed decision towards improving the soil quality of the cashew orchards in order to turn around the poor trend in the yield. Thus, there is

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need for this category of farmers to be acquainted with the nutrient dynamics of their farmlands in order to manage variability in soil nutrients to support sustainable production of cashew apples and nuts through sustainable management practices.

Nutrient dynamics can be affected by various factors including age of cashew crops (Oloyede et al., 2018), land use practices, crop management (Musa & Adamu, 2019; Obumselu et al., 2024), seasonal variations (Turner et al., 2013; Koçak, 2022) and inherent soil properties (Richardson et al., 2021). Previous studies have indicated that nutrient depletion due to continuous cropping without adequate nutrient replenishment could lead to reduced soil fertility, thereby impacting cashew yield and overall farm productivity (Aikpokpodion et al., 2009; Shehu et al., 2015; Oloyede et al., 2018; Musa & Adamu, 2019; Ibiremo et al., 2023). Although older cashew trees have large canopies and abundant leaf litter available for decomposition, they exhibit higher nutrient status (Oloyede et al., 2018).

Soil properties such as pH, texture, and organic matter content, are essential in nutrient availability (Salehi et al., 2019). For instance, soils with higher organic matter content have better nutrient retention and availability for plant uptake, because it provides organic colloids that adsorb nutrients onto their charged surfaces. Low pH soils (<6) make nutrients like iron, manganese, and aluminium more soluble, which may lead to toxicity; however, phosphorus becomes less available because of fixation with iron and aluminium oxides (Grandel, 2020). On the other hand, pH 6-8 triggers the availability of more phosphorus, calcium and magnesium for plant uptake, while high pH results in lower solubility of micronutrients like iron and zinc. This lower solubility causes deficiencies in plants (Barrow & Hartemink, 2023). Fine-textured soils (constituting high clay) can adsorb nutrients more effectively because of large, charged surface area, thus, making them more nutrient-rich (Weil & Brady, 2017). On the other hand, coarse-textured soils (more of sand) tend to have lower nutrient retention capabilities (Gatiboni, 2022) and often require more frequent fertilization and/or addition of organic residue to retain nutrient

elements and compounds. Hence, management practices such as crop rotation and the use of cover crops could maintain soil fertility by increasing organic matter content and facilitating nutrient cycling; integrated nutrient management also, which combines organic amendments with chemical fertilizers, could also improve soil fertility and enhance cashew productivity (Awoonor et al., 2022).

Therefore, the study observed that there was no attempt to evaluate the major components determining the nutrient dynamics in cashew fields in Sudan Savanna, Northeastern Nigeria. The closest was that of Musa & Adamu (2019). However, they focused on spatial variability of soil physico-chemical properties under cashew in comparison with mango field. Few other studies were rather conducted in Guinea Savanna biome in relation to cashew crops in Nigeria (Aikpokpodion et al., 2009; Adeboye et al., 2011; Olatunji, & Ewetola, 2015; Oloyede et al., 2018; Dada, 2021; Dodoo et al., 2023). Hence, understanding the major components of soil nutrient dynamics is essential for optimizing cashew yield and maintaining soil health. Thus, the necessity for localized research that investigates the nutrient dynamics to understand the main components in cashew field. This is imperative, as it is associated with much limited attention to nutrient management (Mangalassery et al., 2019). It is against this backdrop that this study aims to assess the determinants of soil nutrient dynamics under cashew cultivation in the Sudan savanna zone of Nigeria.

Study Area

The study area, Shira, is located in the Sudan savanna region of Shira local government area, Bauchi State, Nigeria. It spans roughly an area of 64 km² (Abdulkadir, 1978). It is located between latitudes 11°26'18" and 11°29'58" N, and longitudes 10°01'27" and 10°04'26" E. The landscape features an elevation range from 407 to 624 m above sea level, with the highest point found atop one of the inselbergs in the south-eastern part of the region (Musa & Adamu, 2019).

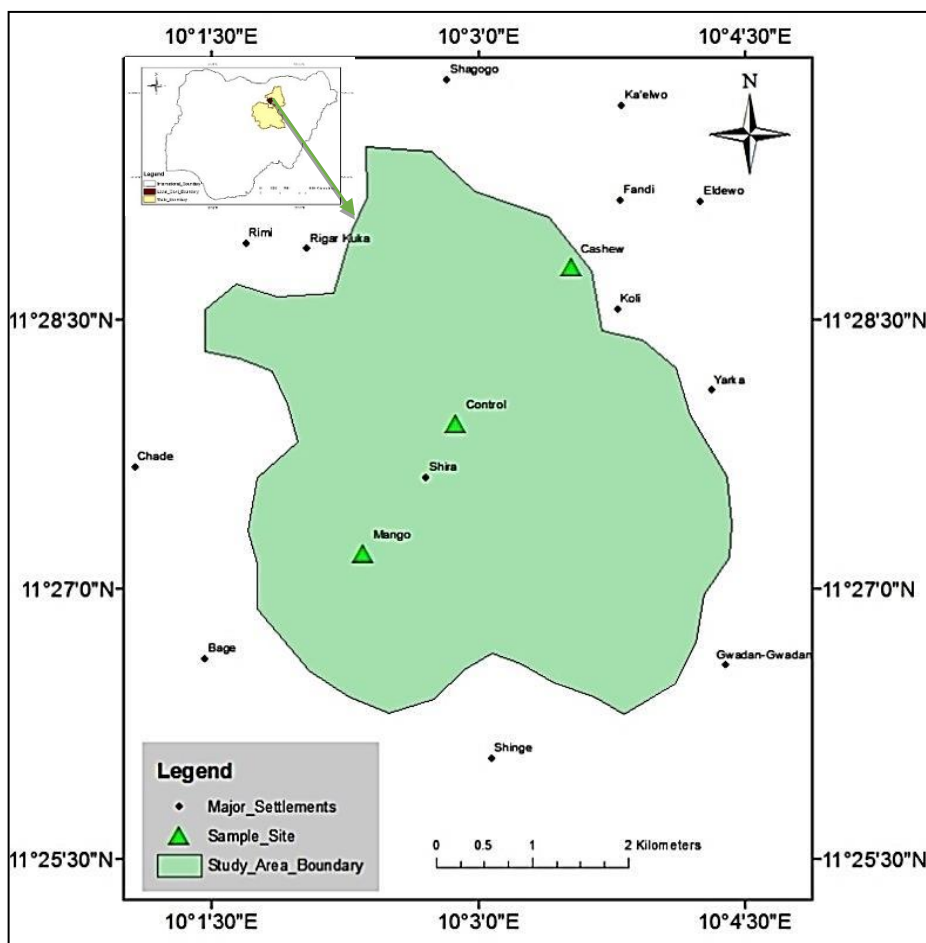


Figure 1: Shira, the Study Area

Source: Ministry of Lands and Survey, Bauchi State/ Google Image (2025)

The area is characterized by rounded hills and granitic boulders, a rugged terrain that promotes excellent drainage. Water flows through a series of small streams towards the southwest, and eventually to the adjacent farmlands and discharging into a tributary of River Zigau, which then empties its water into River Jama'are (Musa & Adamu, 2019). This implies that available nutrients in the soils, as well as some of those released from weathering of the granites can be laterally leached out and translocated due the surface runoff leading to impoverishment of the soils.

The climate of the study area is categorized as tropical continental (As) based on Köppen's classification, featuring distinct wet and dry seasons (Arnfield, 2025). The average annual rainfall is approximately 810 mm, with August being the wettest month, receiving around 284 mm of precipitation. The month of July also contributes significantly, with over 200 mm of rainfall. Rainfall typically ends in the first two weeks of October, ushering in a dry season lasting from November to March/April.

The vegetation of the study area plays a crucial role in soil development and agricultural practices. The region is covered by Sudan savanna vegetation, characterized by short grasses, shrubs, and deciduous trees. Key species include indigenous species such as tamarind (*Tamarindus indica*), *Acacia albida*, baobab (*Adansonia digitata*); and exotic species like neem (*Azadirachta indica*), *Moringa oleifera*, guava (*Psidium guajava*), mango (*Mangifera indica*), and cashew (*Anacardium occidentale*) among others (Musa & Adamu, 2019).

The geology and soil characteristics are vital to this study because they directly influence soil development and agricultural productivity. Shira's geology forms part of the basement complex of the Hausa Plains in Northern Nigeria and consists primarily of deep weathered Precambrian granitic rocks that have produced boulders and colluvium. Additionally, deposits of fine sand from the Lantewa sand dunes are present (Thiemeyer, 2000). The soils are classified as ferruginous soils, with reddish-brown colours. This classification aligns with the Arenosols and Plinthosols identified by FAO/UNESCO (1988) and Jones et al. (2013). Specifically, hypoluvic Arenosols and petric Plinthosols predominate. However, the selected area consists of hypoluvic Arenosols which are characterized by sandy loam texture (Musa & Adamu, 2019).

Shira supports the cultivation of crops such as cereals like millet, sorghum, and rice, including others such groundnuts, cowpeas, beni seeds, watermelons, tomatoes, soya bean, and peppers. Tree crops such as cashew, mango, and guava (though now only found in traces) are also grown in the area. Most farming activities rely on rainfed agriculture, although irrigation is utilized during the dry season to grow crops like rice, sugarcane, and vegetables. This study area was selected to serve as a reference guide to areas with similar soil characteristics, climatic conditions and mode of management practices of cashew cultivation whose farmers lack modern techniques to manage their

farmlands. Such farmers also run a small-scale production, and where necessary, pay little attention to fertilizers options in order to supplement the increasingly lost nutrients of the Arenosols.

Materials and Methods

Sampling Procedure

A cultivated cashew field was purposively selected (being the largest in the study area) for the collection of soil samples. A plot measuring 40 x 80m was marked out, subdivided into eight quadrats measuring 20 x 20m (400 m²) each. Each quadrat was further subdivided into four 10 x 10 m grids for the collection of representative soil samples systematically. Five soil samples were taken at a depth of 0-30 cm (similar to Widiatmaka et al., 2014; Dada, 2021) from each quadrat, 1 at the centre of each grid, and 1 at the adjoining point of the four grids. The five samples from each quadrat were then thoroughly mixed into one composite sample of which a sub-sample was scooped out. This was easily done in the field by hand, because the soil was loose and friable. Thus, a total of 40 representative soil samples were used to form 8 composite samples. See Figure 2 showing the design of the soil sampling. These composite samples were placed in labelled polyethylene bags. The soil samples were air-dried, ground, sieved through a 2 mm mesh under a room temperature condition, and then taken to the laboratory for routine test.

Laboratory Analysis

The laboratory analysis was centred on key soil properties that influence nutrient dynamics and crop productivity, including particle size distribution, soil pH, exchangeable cations (Ca²⁺, Mg²⁺, Na⁺, K⁺), available phosphorus, cation exchange capacity (CEC), base saturation, organic matter (OM), and total nitrogen (TN). Particle size distribution was determined using hydrometer method, OM using Walkley-Black titration method which is commonly adopted in research (Liebens, 2007), and TN using Kjeldahl method (Jones, 2001). More so, Soil pH was determined potentiometrically in a 0.01m CaCl₂ solution at a 1:2 soil-to-solution ratio (Jones, 2001), and EA was quantified by potassium chloride (KCl) extraction and titration method (Hoskins, 1997; Robarge, 2008). Moreover, Ca²⁺, Na⁺, and K⁺ were analyzed using flame photometry (Maniyunda et al., 2013), while Mg²⁺, was determined by absorption spectrophotometer method (Moges et al., 2013). Available phosphorus was determined using Bray no. 1 method (Jones, 2001). In addition, CEC was calculated by summing the exchangeable cations and exchange acidity; while base saturation was computed by dividing the total exchangeable bases by CEC and then multiplying by 100 (Jones, 2001; Havlin et al., 2005).

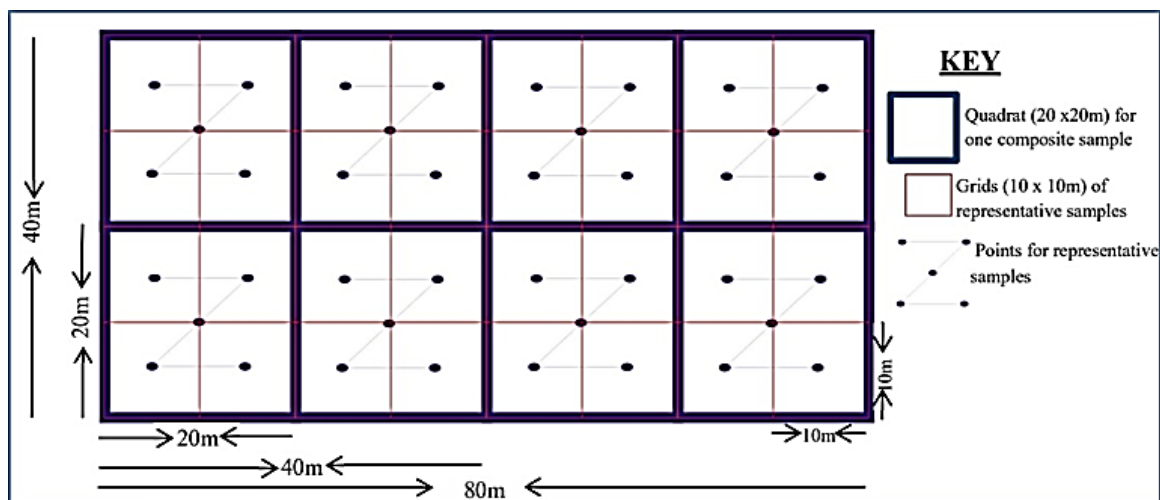


Figure 1. Soil Sample Collection Design

Table 1. Methods of Laboratory Analyses of Soil Properties

Soil Properties	Method of Analysis	Reference
Particle Size Distribution	Hydrometer method	Liebens (2007)
Organic Matter	Walkley-Black titration	Liebens (2007)
Total Nitrogen	Kjeldahl method	Jones (2001)
Soil pH	Potentiometrically in a 0.01m CaCl ₂ solution at a 1:2 soil-to-solution ratio	Jones (2001)
Exchangeable Acidity	Potassium chloride (KCl) extraction and titration	Hoskins (1997); Robarge (2008)
Exchangeable Calcium	Flame photometry	Maniyunda et al. (2013)
Exchangeable Magnesium	Absorption spectrophotometer	Moges et al. (2013)
Exchangeable Potassium	Flame photometry	Maniyunda et al. (2013)
Exchangeable Sodium	Flame photometry	Maniyunda et al. (2013)
Available Phosphorus	Bray No. 1 method	Jones (2001)
Cation Exchange Capacity	Summation of exchangeable cations and exchange acidity	Jones (2001); Havlin et al. (2005)
Base Saturation	Division of total exchangeable bases by CEC, then multiplied by 100	Jones (2001); Havlin et al. (2005)

Table 2: Principal Component Analysis of the Soil Physico-chemical Properties under Cashew Crops

Soil Properties	Components			Descriptive Statistics		
	Nutrient Supply	Soil Texture	Sand	Mean	Std. Dev.	CV
% Sand	.171	.919*	.048	70.26	0.23	0.32
% Silt	.382	.889*	-.052	17.87	0.31	1.74
% Clay	-.306	-.943*	.010	11.87	0.52	4.34
Organic Matter (OM)	-.890*	-.340	-.019	2.39	0.10	4.17
Total Nitrogen (TN)	.609	-.197	.575	0.20	0.01	3.92
Soil pH	.923*	.299	.078	6.52	0.09	1.42
Exchangeable Acidity (EA)	.953*	.262	-.073	0.57	0.11	18.83
Exchangeable Calcium (Ca ²⁺)	.617	.669	-.012	1.39	0.02	1.67
Exchangeable Magnesium (Mg ²⁺)	-.155	-.099	.767*	0.23	0.04	16.57
Exchangeable Potassium (K ⁺)	.943*	.256	-.045	0.20	0.01	4.51
Exchangeable Sodium (Na ⁺)	-.074	-.144	-.744*	0.79	0.02	2.75
Cation Exchange Capacity (CEC)	.923*	.307	.037	3.17	0.13	3.99
Available Phosphorus (AP)	.750*	.344	.309	10.16	0.18	1.75
Base Saturation (BS)	-.944*	-.247	.102	82.18	2.70	3.29
Component Defining Variables	E.A	% Sand	Mg²⁺			
Total Eigen Values	6.796	3.653	1.598			
% Variance Explained	48.543	26.094	11.416			
% Cumulative Explained	48.543	74.637	86.053			

Key: * = significant loadings ≥ 0.7 used in interpreting the components, Std. Dev. = Standard Deviation, CV = Coefficient of Variation

Data Analysis

Soil physico-chemical property data were analysed using principal component analysis (PCA) to identify the main components of soil nutrient dynamics under cashew cultivation in the study area.

The PCA was employed as an exploratory tool to aid the researchers to identify the effective number of dimensions referred to as components within a data set and to eliminate variables that provide little information (Udofia, 2011). Variables with loadings $\geq \pm 0.7$ from the rotated component matrix were considered significant (threshold) and used in the interpretation of the PCA as employed by Ifabiyi et al. (2010) and Iwara et al. (2011). However, to determine meaningful number of components for explanation of the PCA results, some criteria must be satisfied including eigenvalue-one, scree test, proportion of variance accounted for, and the interpretability criteria. Thus, the main components simplify the number of soil properties that can be considered more in addressing the dynamics in the soil nutrients under the cashew cultivation in the study area. IBM SPSS v.29 was used for the test of the PCA.

Additionally, to compliment the PCA results, coefficient of variation (C.V.) and mean were employed. Where a high C.V. occurs, it indicates greater

variability or heterogeneity, while a low C.V. suggests homogeneity. This variability is categorized based on C.V. fiducial limits, where 0–15% denotes low variability, 16–35% signifies moderate variability, and over 35% indicates high variability (Wilding, 1985).

Results and Discussions

The results of the PCA and descriptive statistics for the cultivated field of cashew are presented in Table 2. The result of the principal component analysis with varimax rotation and eigenvalues greater than unity reveals that redundant variables in the soil physico-chemical properties were knocked down and reduced to three main components that can best explain the variability in the soils. Therefore, considering all these criteria, component 3 was not considered in the explanation, because they did not conform with the interpretability criteria of the PCA. It is suggested that a component cannot provide a satisfactory solution if it has less than 3 defining variables (Principal Component Analysis, n.d). Thus, component 3 has only two highly loaded parameters (exchangeable sodium and exchangeable magnesium).

Result of Principal Component Analysis of Soil Physico-chemical Properties in Cashew Field

The first two components satisfied all the required criteria and accounted for a cumulative of 74.6% of the total variance explained, thus, satisfying the required minimum cumulative variance recommendation of 60% by Keho (2012) or 70% by Lehman et al. (2013). Hence, the first two components are retained and used in the explanation of the result of the PCA (Table 2) for soil physico-chemical properties in the cashew field. Figure 3 presents the scree plot, and Figure 4 is the component plot in rotated space showing the three components for the soil properties under cashew.

Component 1 (Nutrient Supply Component)

Component 1 accounted for about 48.5% of the total variance explained. It has the highest loading on EA (0.953). Other variables with high positive loadings include pH, K^+ , AP and CEC; while those with high negative loadings are OM and BS. This component was named 'nutrient supply component.' It implies that CEC increases with EA, pH, K^+ , and AP; while BS and OM decrease. The increase in CEC may be attributable to increase in levels of EA and K^+ . The result also suggests that higher levels of EA (often due to H^+) can increase CEC because these acidic cations also occupy exchange sites. More so, Fe^{3+} and Al^{3+} form the basis of EA, and AP in the form of phosphate (PO_4^{3-}), a negatively charged compound, cannot be directly adsorbed onto the surfaces of organic colloid, but can be attracted to Fe^{3+} and Al^{3+} ions which can serve as an interface between OM and phosphorus (Havlin et al., 2005). Therefore, phosphorus might have been available to cashew trees through Fe^{3+} and Al^{3+} . In addition, an increase in the levels of K^+ contributes to the increase in CEC, because it is a key cation that also occupies exchange sites in the soil.

The increase in soil pH suggests an increase in exchangeable bases especially, Ca^{2+} and K^+ which could have been due to an increase in CEC. This increase in pH could be responsible for the increase in AP, because lower pH reduces its availability and other nutrients such as molybdenum, affecting N-fixation and causes crop toxicity due to elements such as aluminium or manganese that become more soluble at a lower pH (Grandel, 2020). The mean pH level (6.52) (Table 2) in this cashew field, even though below neutral, is still somewhat within the required range of 4.5 – 6.5 as suggested by Phan (2022). If the pH increases continuously, there could be nutrient balances, thus,

making them available, because there would be few H^+ ions taking up available negative charges (McCaughey et al., 2017). However, where the pH increases resulting in high alkalinity, the crops could be prevented from absorbing the essential nutrients even when adequate, because alkaline soils contain high calcium carbonate content (Grandel, 2020; Barrow & Hartemink, 2023). On the other hand, high alkalinity may allow for increased uptake of zinc or copper, thus, leading to their toxicity in the crops (Barrow & Hartemink, 2023).

The fall in base saturation (BS) value indicates a lower proportion of basic cations, relative to acidic cations (H^+ and Al^{3+}). This is most especially on Mg^{2+} which had a very low negative loading and moderate coefficient of variability (16.57%) (Table 2) within the field. This may suggest that as K^+ and AP increase, there might be competition among cations that could reduce the overall base saturation. This condition might accentuate leaching of the bases, especially Mg^{2+} and Na^+ both of which entail weak negative relationship.

Moreover, where there is a decrease in OM, it can negatively affect CEC, as organic matter contributes to nutrient retention through the addition of organic colloids, and soil structure. However, if the increase in EA, K^+ , and AP is significant, it might offset the negative impact of reduced OM on CEC. Nevertheless, the result of coefficient of variation for all these highly loaded soil chemical properties in the cashew field indicated low variability (<15%) within, except for the mean value of Mg^{2+} as highlighted above - exhibiting moderate variability.

This component therefore, exhibits the attributes of supplying nutrients in the soils of the cashew field. Hence, this component reflects the variability in the soil nutrients under the cashew field. Consequently, the component highlights the soil properties that need special attention to enhance fertility in the fields where cashew crops are grown in the study area. Therefore, efforts to improve the overall soil nutrients in those fields should focus on organic treatment methods which might improve the level of CEC and consequently enhance nutrient retention. This should be augmented with effective management practices and careful monitoring systems.

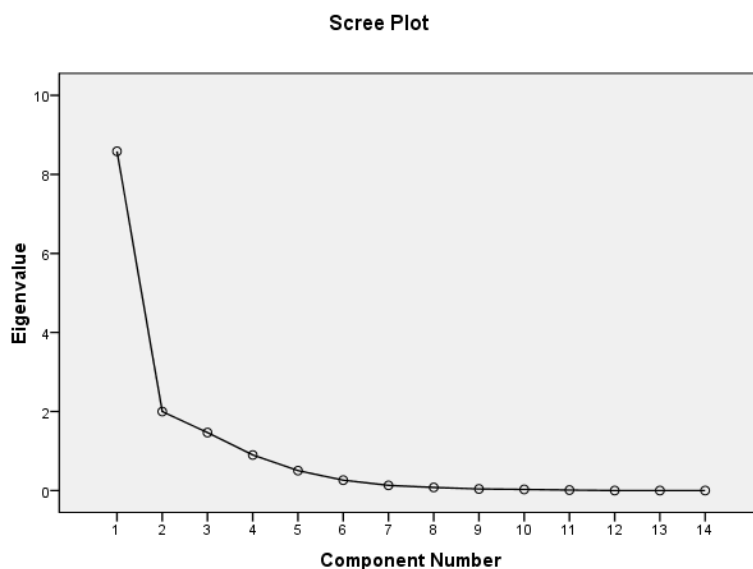


Figure 3: A Scree Plot Showing the Components for the Soil Physico-chemical Properties in Cashew Field

Component Plot in Rotated Space

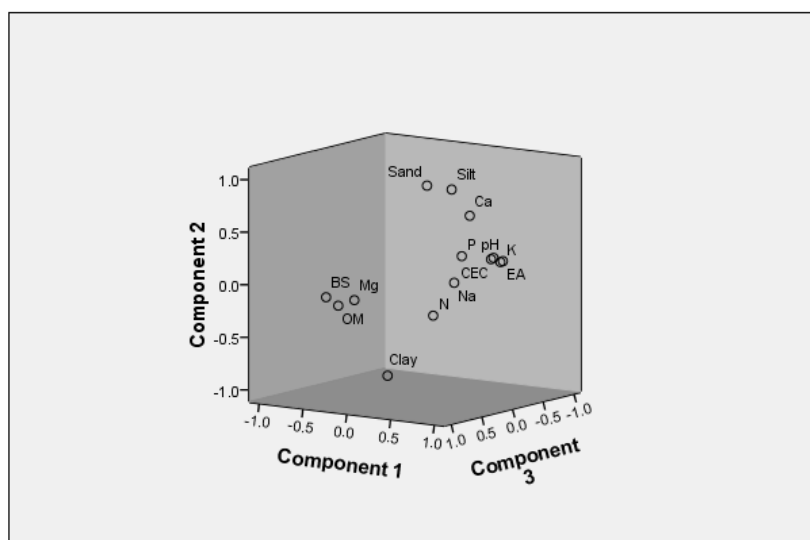


Figure 4: Component Plot in Rotated Space Showing the Soil Physico-chemical Properties in Cashew Field

Component 2 (Soil Texture Component)

This component accounted for about 26% of the total variance explained. The highest loading was revealed to be on percent clay (-0.943). This was followed by highly positively loaded percent sand (0.919) and silt (0.889). Thus, this component was named ‘soil texture component’. The texture of the cashew field is equally sandy loam, as can be seen from the relative mean proportions of the soil separates (Table 2). The result therefore, implies that an increase in percent sand and silt could lead to decrease in clay content which has negative loading. This results in a decrease in soil colloids that offer micelles on which nutrient elements and compounds are adsorbed on to (Foth, 2006). This condition may accentuate the leaching of exchangeable nutrient elements to the lower horizons. However, there is usually very small (fine) proportion of silt that forms part of mineral colloids. It is most likely that the mineral colloids in the cashew field are of silicate produced from the weathering of the predominant deeply weathered granitic rocks in study area.

In addition, the coefficient of variation result for all the variables under this component, reveal low variability. An increase in silt content, particularly, the finer particles, would enhance the soil texture, leading to improved nutrient adsorption and water retention in the cashew field. However, with the pronounced decrease in clay content, the texture is likely becoming poor in its capacity to retain nutrients and moisture. Hence, similar to component 1 (nutrient supply component), in order to prevent excessive leaching and sudden moisture loss, the soil structure can be enhanced by using organic amendments and zero-tillage practices, especially in the pocket areas around the cashew tree crops.

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Conclusion

The application of Principal Component Analysis (PCA) in this study revealed two most important components as the major determinants of nutrient dynamics in the soils under cashew cultivation: a *nutrient supply component* and *soil texture component*, which together accounted for 74.6% of the variance in soil nutrient dynamics. The nutrient supply component highlighted critical relationships between EA, soil pH, K⁺, AP, and CEC. These results suggest that increases in these nutrients positively influence soil fertility, while declines in OM and BS could lead to nutrient unavailability. This underscores the need to manage soil acidity and nutrient levels to enhance cashew productivity while maintaining soil health. The soil texture component underscored the influence of soil texture, characterized by the proportions of sand, silt, and clay which significantly affects nutrient and moisture retention. The negative loading of clay in particular, suggests that the sandy texture prevalent in the study area may lead to increased leaching of nutrients, highlighting the need for soil amendments to improve moisture retention and nutrient adsorption.

To optimize cashew yields while maintaining soil health, the study advocates for nutrient management approaches that consider the unique soil characteristics of Arenosols. Emphasis should be placed on sustainable practices, such organic fertilizers and soil conservation techniques, to address the challenges posed by the sandy soil texture and nutrient dynamics identified in this research.

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