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Spatial-temporal variability in under-canopy soil fertility and nutritional contents of cashew trees in Makonde Plateau of southeastern Tanzania

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A B S T R A C T

This study was conducted out to evaluate the soil fertility in under the cashew tree canopy and nutritional contents of cashew trees on the Makonde Plateau in southeast Tanzania. Seven villages were included, all of which were geographically close to one another yet had the same agro-ecology. The cashew plant samples were taken above the same longitudinal segment as the soil samples, which were taken in under canopies of cashew trees. Nitrogen, Phosphorus, Potassium, Magnesium, Calcium, and micro nutrients (Iron, Zinc, Sodium, and Copper) were all examined in the samples. However, soils were analysed for Organic Carbon, Organic Matter, and pH with soil samples taken at two different depths of 0–30 cm and 30–50 cm, these tests were conducted during the wet and dry seasons. The results confirmed that Calcium, Magnesium, Sodium, and Iron varied significantly with soil depth, as well as with soil depth, seasons, and their interactions, for Organic Carbon and Organic Matter. During the wet season, Nitrogen, Phosphorus, and Zinc concentrations in cashew trees were all statistically higher. Nitrogen and Phosphorus were significantly strong and positively ($r = 0.95$) correlated in cashew plants with respect to all other nutrients, suggesting synergistic effects. These results imply that macro nutrients including Nitrogen, Phosphorus, Potassium, Magnesium, and Calcium, and micronutrients such as Iron, Zinc, Sodium and Copper limit cashew production in the research area. It is necessary to determine site-specific recommendations and dosages for these nutrients.

1. Introduction

The cashew tree (*Anacardium occidentale*) is a tropical evergreen tree that produces cashew nuts, one of the most well-known and in-demand nuts in the world. Some nations, including India, Vietnam, Indonesia, the Philippines, Tanzania, Nigeria, Ghana, Mozambique, Benin, Mali, Burkina Faso, and others, make significant economies out of the cashew crop. The top 10 countries with respect to cashew production worldwide in 2021 cashew harvesting year includes; Ivory Coast (837,850.12), India (738,000.00), Vietnam (399,307.75), Philippines (255,931.01), Tanzania (210,786.00), Indonesia (170,462.00), Burkina Faso (137,722.07), Mozambique (135,160.94), Nigeria (118,623.66), and Benin (111,103.00) [1]. Cashews are primarily grown in Tanzania's southeastern region and along the country's eastern coastline strip. Southeastern Tanzania, Makonde Plateau in particular is known for its cashew farming, as well as

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other significant food crops like pigeon peas (Cajanus cajan (L) Millsp.), cassava (Manihot esculenta), sesame (Sesamum indicum L.), and bambara nuts (Vigna subterranea (L.) Verdc) [2,3].

A plant's nutritional state has an impact on both its growth and the yields that are anticipated [4]. One of the prerequisites for making decisions on the best techniques for protocol preparation for fertilization or soil amendment is having a basic understanding of the nutritional state of agricultural plants (crops) and soils [5]. Micronutrients such as Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu), Sodium (Na), Chlorine (Cl), and Molybdenum (Mo) as well as macronutrients such as Nitrogen (N), Phosphorous (P), Potassium (K), Magnesium (Mg), Calcium (Ca), and Sulphur (S) are taken into account when determining the nutritional status of plants and soil [5,6]. Richness in crop plant nutrients is directly correlated with growth and yield due to photosynthesis [1,7–9]. When fertilizers are applied to the soil, plants' nutritional status is enriched and their overall health is increased, which in turn promotes better crop development and yields [9]. The kind (species) of crop, its growth stage in the life cycle, the season during which the crop is growing and the level of nutrient availability in the soil where the crop is grown are the main factors that determine the amount of the plant's nutrient requirements [9].

Nutrients like Phosphorus, Potassium, Magnesium, Calcium, Boron, Copper, and Zinc are crucial during the flowering and fruiting phases of crop plants, including cashews, for a variety of functions, including plant cell division, cell elongation, cell strengthening for resistance to pathogenic reactions [10–12]. Nutrients are important for organ (young tissues i.e. buds, flowers, nuts) development, are components of enzymes, components of Adenosine triphosphate (ATP) the energy unit of a plant necessary during photosynthesis, they are potential for movement of water in plants, enzyme activations, and they achieve immunity of plants against pests, weather variability and pathogens [10–12]. However, for many objectives, such as soil moisturizing and pH dynamism, including availability and accessibility of these nutrients to plants, weather and climatic behaviour, particularly rainfall and temperature, are significantly dependent [11,12]. Sustained and normal distributed rainfall improves soil Organic Matter, mineral presence in soils and regulates soil pH [10]. Prolonged temperature may lead to increased evaporations ultimately drought occurrence and threatening soil microbe functions [10]. Wet and dry seasons are caused by changes in the weather, particularly temperature and rainfall. Moreover, during the dry season in Tanzania, cashews are in their reproductive stage, from which they generate blossoms and nuts. The nutritional needs of cashew trees rise during this time of year [11,12].

In order to practice agriculture in the Makonde Plateau, farmers typically remove land, leaving it naked and vulnerable to surface runoff. Mulching is rarely used to conserve moisture in soils. In the cashew fields, collecting and burning plant waste is a widespread activity. Although the region is suitable for cashew production, there are few reports of the use of synthetic fertilizers there, primarily due to lack of awareness of their significance and high market costs [3,13,14]. Therefore, one of the limits on cashew production in the area is still the replacement of deficient or mined nutrients [15]. The nutrient status of a crop fluctuates with crop phenology, which is mostly governed by the life cycle, but also by the effects of the weather (temperature and rainfall) [10,11]. As a result of drought and the cashew plant's inability to absorb nutrients from the soil, the seasonal decrease in rainfall of less than 500 mm might cause stress [11]. Long-term dryness, on the other hand, inhibits soil microbial activity and reduces the amount of nutrients available to plants, including cashew crops, endangering the crop's capacity to both reproduce and grow vegetatively [10,11].

In the Makunde Plateau of southeastern Tanzania, knowledge on the temporal nutrient dynamics in soils and in cashew during the two contrasting seasons (dry and wet) is limited [16]. In the main cashew-growing soils of Tanzania's southeastern agro-ecological zone, the soils' pedological characterization has been documented [14]. The pedological characterization, however, did not take into account temporal variability within the soils and/or capture soil-cashew nutrient connections throughout the two dissimilar seasons. The primary goal of this study was to establish fertilizer use strategies for cashew to increase production in Tanzania's southeastern region, specifically by two objectives: (a) to assess the soil fertility levels under the canopy at various depths between 0 and 30 cm and between 30 and 50 cm during the rainy and dry seasons in the Makonde Plateau of southeastern, Tanzania. The main assumption was that the observed parameters in soils could change depending on the depth of the soil sample and/or the time of year the sample was taken. (b) To evaluate the nutritional content of cashew leaves during the wet and dry seasons on the Makonde Plateau in southern Tanzania. The main theory here is that there can be seasonal variations in the characteristics assessed in cashew leaves. The results of this study should close the knowledge gap regarding soil amendment for improved cashew production in Tanzania's Makonde Plateau and other cashew-growing regions with comparable characteristics. They should also provide an interesting insight into decision-making in developing appropriate cashew plant and soil management practices through fertilizer application.

2. Materials and methods

2.1. Description of study area

In Mtwara region, this study was carried out in December 2021 and July 2022. Southeast Tanzania (10°31′12″ S, 40°17′60″ E) is where the region is located, and it is typically characterized by a unimodal form of rainfall that begins in November or December and lasts through April and May [17]. The typical range of yearly total precipitation is normally 800–1245 mm, and the average annual temperature is 24 °C [17]. The predominant soil type in this region is sand to sandy loam [10], which is distinguished by its high friability and depth of more than 2 m together with dense flora embedded in it. According to the World Reference Base (WRB), the soils in the research areas are classified as Kandosols (Reference Soil Group) with their qualifiers (leptic, vetic, and acric), and ferralsols in select portions of the study area in accordance to similar soil classification by [18]. Few livestock keeping methods are practiced in the area, and consequently, the application of livestock manure to improve crop performance is rare. Seven villages from three districts, including Tandahimba, Newala, and Mtwara Rural, were included in the study (Fig. 1). The villages were Mtopwa, Mcholi, Namiyonga, and Mahumbika in Newala, Nanguruwe and Mbawala Juu in Mtwara Rural, and Nanyanga in the Tandahimba region. The potential of a village to produce cashew nuts for at least 26 tonnes per season in comparison to other villages in the Mtwara region was a criterion for study sites (villages) selection. But the Makonde Plateau was chosen due to its historical supremacy in cashew production trend as compared to other regions in the southeastern zone of Tanzania.

2.2. Study design and sampling of soil and cashew leaves

A reconnaissance assessment of the Makonde Plateau was carried out to identify the features of the visible land variability and to design a strategy for soil and plant sample collection. Three districts on the plateau—Newala (Mcholi, Mtopwa, Namiyonga, and Maumbika), Tandahimba (Nanyanga), and Mtwara Rural (Nanguruwe and Mbawala Juu)—and the villages that they correspond to—were chosen for the study. Given that the Makonde Plateau is located in the same agro-ecological zone, it is anticipated that there won't be much variation in the parameters to be examined for soils and cashew plants between districts and/or between villages. Because of this, the diversity in districts and/or villages was not taken into account in the current study. However, the soil samples were taken at two different depths of 0–30 cm and 30–50 cm, and samples of the cashew plant were also taken in two different seasons (dry and wet).

Consequently, for the parameters that are assessed in soils, two factors—namely, sampling depths and seasons—were taken into account, whereas for the parameters that is assessed in cashew plants, just one factor—namely, seasons—was considered. As part of the standard method, soil and plant samples were collected by moving zigzag throughout the cashew field [19]. In order to eliminate bias that could be brought on by the effects of light, a cashew tree's minimum of 16 leaves were collected, of which four leaves were selected in each of the four cardinal directions (West, East, North, and South). Three cashew orchards' average cashew leaves were used to represent a replicated village for a given season. The soils collected in order to target the rooting depths of cashew trees that were at least 5 years old, with 75 % of their feeder roots located in the topsoil or subsoil around cashew tree's under canopy soils [20, 21]. Sampling during the wet and dry seasons was crucial to evaluating the role of soils in feeding cashew plants throughout the year period [22]. Composite and disturbed soil samples were collected from soil depth of 0–30 and 30–50 cm each weighing 500 g and averaged from three cashew fields to represent a village.

2.3. Laboratory analysis of soil and plant samples

Procedures for soil and plant sample analysis are as per description below;

Fig. 1. Map with selected study villages to represent Makonde Plateau in southeastern Tanzania.

Description of the laboratory procedures for the analysis of samples.

Samples for analysis	Nutrients analysed from samples	Methods of nutrients analysis in lab	Reference
Soils at depth of 0–30 and 30–50 cm	TN, P, K, Fe, Mg, Cu, Zn, Na, EC, OC, C:N and pH	-TN by Micro-Kjeldahl digestion-distillation -Extractable P by Bray and Kurtz - 1 -Potassium (K) extracted using flame photometer method -Micronutrients after microwave digestion quantified by atomic adsorption spectrophotometer	[23–25]
Plant tissues	TN, P, K, Fe, Mg, Cu, Zn, Mn,	-The grinded powder was digested by the HNO_3–H_2O_2 procedure and the digests were analysed for the listed nutrient contents using procedure by [25]	[25]

2.4. Weather information of the area during the study

For the purpose of this research, weather parameters were recorded for both the dry and wet seasons. Maximum rainfall in the seasons of 2021 and 2022 was 639.9 mm, with a mean monthly rainfall of 126.5 mm (Fig. 2). In 2021, rain fell from January through May; in contrast, it fell from December through May in 2022. Rainfall was, however, distributed inequitably during both seasons. The monthly high and low temperatures were, respectively, 30.6 °C and 22.6 °C (Fig. 2). The months of June through November of 2021 featured dry spells. The weather data was collected on purpose since changes in weather parameters are linked to nutrient availability to plant root zones [26,27].

2.5. Statistical data analysis

Following the soil sample depths (0–30 cm and 30–50 cm) and seasons of sampling (wet and dry), a split-plot experiment obeying randomized complete block design, the analysis of variance (ANOVA) was carried out to evaluate the variability of the measured parameters in soils. The replicating villages were handled as a random effect, whilst the sampling seasons were treated as the main-plot and the sampling depths as the sub-plot in the treatment arrangement. Standard errors of differences of means (S.E.D.) at a 5 % threshold were used to compare the significant treatment means using Tukey's post-hoc multiple comparison. Equation (1) depicts the factors-effect model in detail.

$$Y = \mu + \alpha i + \beta j + (\alpha\beta)ij + \varepsilon ij \quad (1)$$

where *Yij* is the observed assessed parameter in the *ijth* factors; μ is the overall (grand) mean of the assessed parameter; α_i and β_j are the main effects of the factors seasons of sampling and soil sampling depths, respectively; $(\alpha\beta)_{ij}$ is the two-way (first order) interactions between the factors seasons of sampling and soil sampling depths; εij is the random error associated with the observation of the assessed parameter in the *ijth* factors.

To examine the variation in the measured parameters in cashew plants, the data was subjected to a one-way analysis of variance (ANOVA), in which the seasons were treated as the primary fixed effect (one factor) and the replicate villages as a random factor. Pairwise comparison of the means was accomplished using the least significant differences (LSD) and the Tukey's post-hoc multiple comparisons used to measure the significant treatment means by the 5 % significant threshold. The factor effect model is illustrated in Equation (2).

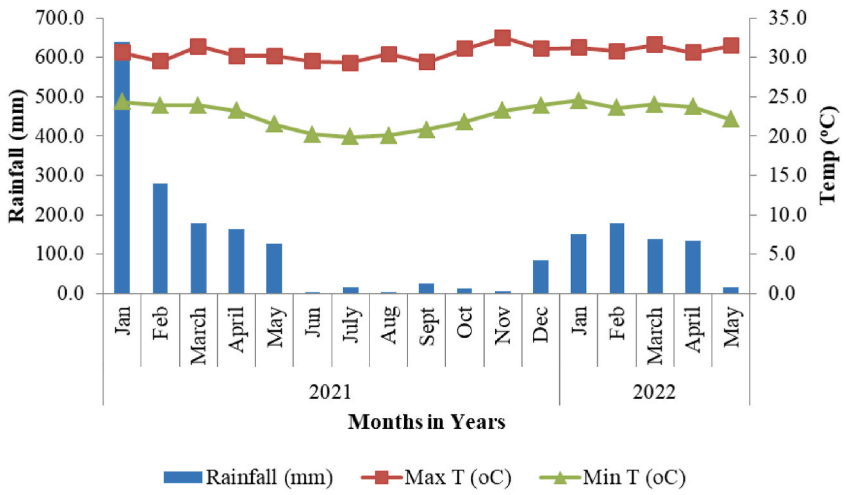

Fig. 2. Rainfall and temperature trends in months between 2021 and 2022 seasons.

Table 1
ANOVA of some soil parameters measured in two soil depths of 0–30 and 30–50 and two seasons of wet and dry in the Makonde Plateau of southeastern Tanzania.

Source of variation	d.f	Measured variables in soils and statistical parameters (F.pr.)												
		pH	O·C	O.M	N	C/N	EC	Ca	K	Mg	Na	Cu	Fe	Zn
Seasons	1	0.457	0.011	0.013	0.416	0.452	0.426	0.216	0.653	0.224	0.233	0.068	0.551	0.184
Residual	6													
Soil depths	1	0.206	<0.001	<0.001	0.134	0.307	0.011	0.001	0.264	<.001	0.003	0.773	0.013	0.189
Seasons × Soil depths	1	0.229	0.035	0.034	0.81	0.458	0.522	0.712	0.454	0.221	0.192	0.494	0.402	0.859
Residual	12													
Total	27													

Key: d.f. = degrees of freedom; F pr. = test-F probability; pH = power of hydrogen; P = Phosphorus; OC = Organic Carbon; O.M. = Organic Matter; N = Nitrogen; C/N = Carbon to Nitrogen ratio, EC = electrical conductivity; Ca = Calcium; Mg = Magnesium; K = Potassium; Na = Sodium, Cu = Copper; Fe = Iron; Zn = Zinc.

Table 2
Means of the selected soil parameters measured in two soil depths of 0–30 and 30–50 and two seasons of wet and dry in the Makonde Plateau of southeastern Tanzania.

Factors considered	[a]Measured parameters in soils and their respective quantities												
Seasons	pH	EC	N	OC	OM	K	Ca	Mg	Na	P	Fe	Cu	Zn
		μS cm^{-1}	%			cmol$_{(+)}$ kg^{-1}				mg kg^{-1}			
Wet	6.05^{a}	0.04^{a}	0.03^{a}	0.23^{b}	0.40^{b}	0.11^{a}	1.27^{a}	5.75^{a}	0.05^{a}	10.41^{a}	50.7^{a}	3.04^{a}	0.45^{a}
Dry	5.91^{a}	0.03^{a}	0.04^{a}	0.18^{a}	0.31^{a}	0.14^{a}	0.96^{a}	5.17^{a}	0.06^{a}	9.9^{a}	43.5^{a}	2.93^{a}	0.33^{a}
S.E.D.	0.181	0.012	0.009	0.014	0.023	0.052	0.221	0.431	0.012	0.357	11.451	0.521	0.081
L.S.D.	0.282	0.025	0.024	0.033	0.057	0.131	0.553	1.055	0.014	0.872	28.031	1.225	0.201
P - value	0.457	0.426	0.416	0.012	0.011	0.653	0.216	0.224	0.233	0.202	0.551	0.068	0.184
Soil depths (cm)													
0–30 cm	6.05^{a}	0.021^{a}	0.04^{a}	0.252^{c}	0.43^{c}	0.09^{a}	1.27^{b}	4.54^{b}	0.07^{b}	10.35^{a}	57.4^{b}	2.57^{a}	0.44^{a}
30–50 cm	5.91^{a}	0.047^{b}	0.03^{a}	0.158^{a}	0.27^{a}	0.16^{a}	0.96^{a}	6.38^{c}	0.04^{a}	9.97^{a}	36.8^{a}	2.4^{a}	0.35^{a}
S.E.D.	0.102	0.009	0.006	0.019	0.033	0.052	0.071	0.293	0.012	0.521	7.072	0.558	0.072
L.S.D.	0.281	0.019	0.014	0.042	0.072	0.121	0.163	0.638	0.011	1.135	15.411	1.216	0.152
P - value	0.206	0.011	0.134	<0.001	<0.001	0.264	0.001	<0.001	0.003	0.484	0.013	0.773	0.189
Seasons × Soil depths													
Wet (0–30 cm)	6.06^{a}	0.023^{a}	0.03^{a}	0.3^{b}	0.52^{b}	0.101^{a}	1.44^{a}	4.64^{a}	0.066^{a}	10.32^{a}	64.1^{a}	3.32^{a}	0.50^{a}
Wet (30–50 cm)	6.05^{a}	0.054^{a}	0.03^{a}	0.16^{a}	0.28^{a}	0.123^{a}	1.10^{a}	6.86^{a}	0.037^{a}	10.5^{a}	37.3^{a}	2.76^{a}	0.41^{a}
Dry (0–30 cm)	6.04^{a}	0.02^{a}	0.04^{a}	0.20^{a}	0.35^{b}	0.084^{a}	1.10^{a}	4.44^{a}	0.066^{a}	10.37^{a}	50.7^{a}	1.81^{a}	0.39^{a}
Dry (30–50 cm)	5.77^{a}	0.04^{a}	0.03^{a}	0.16^{a}	0.27^{a}	0.189^{a}	0.82^{a}	5.89^{a}	0.052^{a}	9.44^{a}	36.3^{a}	2.04^{a}	0.28^{a}
S.E.D.	0.212	0.013	0.010	0.024	0.040	0.074	0.241	0.521	0.008	0.631	13.462	0.754	0.112
L.S.D.	0.401	0.028	0.025	0.049	0.085	0.157	0.551	1.141	0.018	1.326	29.741	1.582	0.234
P - value	0.230	0.524	0.812	0.035	0.034	0.454	0.711	0.223	0.192	0.309	0.402	0.494	0.859

[a] Means in a column with *P* –value <0.05 and different latters differ significantly; otherwise, they are statistically similar.

$$Y = \mu + \alpha i + \varepsilon ij \quad (2)$$

where *Yi* is the assessed parameter in the *i*th factor; μ is the overall (grand) mean; α_i is the main effect of the factor seasons; εi is the random error associated with the observation of assessed parameter in the *i*th factor.

3. Results

3.1. Temporal variability in soil parameters

Electrical conductivity, exchangeable Calcium, Magnesium, and Sodium were the three variables that showed the most significant ($P < 0.05$) effects (Table 1). Seasons, soil sampling depths, and their interactions all significantly affected the Organic Carbon and Organic Matter (Table 1). In addition, only Iron differed substantially ($P = 0.013$) with soil depths, with a larger quantity of Iron (57.4 mg kg-1) recorded at a soil depth of 0–30 cm relative to the amount of iron (36.8 mg kg-1) at a depth of 30–50 cm (Table 1).

Seasons, soil depth, and their interactions all showed statistical variations in Organic Carbon and Organic Matter levels. Organic Carbon levels were higher ($p < 0.05$) in the rainy season (0.23 %) than in the dry season (0.18 %), and at soil depths of 0–30 cm (0.252 %) than at depths of 30–50 cm (0.158 %). Given that it is a derivative of the measured organic carbon, the amounts of Organic Matter exhibited a similar trend. However, compared to a depth of 0–30 cm, the exchangeable Magnesium concentration was substantially greater (6.38 cmol(+) kg-1) at the soil sampling depth of 30–50 cm (Table 2). The measured exchangeable Sodium showed a similar trend, but a higher amount (0.07 cmol(+) kg-1) was found at the soil sampling depth of 0–30 cm, with no discernible seasonal effects or interactions between the seasons (Table 2).

3.2. Effect of seasons on the variability of nutrients in cashew plants

Seasonal effects were significant for nitrogen ($p < 0.001$), Phosphorus ($p = 0.035$), but not for Potassium ($p = 0.052$). With regard to the micronutrients under study, only Zinc showed a significant ($p = 0.029$) seasonal effect; Copper, Iron, and Manganese did not. Other nutrients such as Potassium, Copper, Iron, and Manganese were also higher during the same wet season, though their quantities were not significantly ($P > 0.05$) different from those recorded during the dry season (Table 3). The concentrations of Nitrogen, Phosphorus, and Zinc in cashew plants were significantly ($P < 0.05$) higher during the wet season.

3.3. Plant digests' nutritional correlations

More strongly favorable correlations between Nitrogen and Phosphorus were found than between any other nutrients (Table 4). However, the results demonstrated a slightly good correlation between macro and micronutrients from plant digests and the slight relationship between Nitrogen and Potassium. Except for the weakly negative correlations between P and Zn, P and Cu, and K and Cu, Cu, Mn, and Zn, there were weakly positive correlations between the macronutrients. Except for Cu (which was inversely correlated by 0.267), all other nutrients had positive weak relationships with Fe. Table 4 also showed a small but significant association between Potassium (K) and Zinc (Zn) ($p < 0.05$).

4. Discussion

Nutritional deficiencies in soils from study areas (Makonde plateau) are typically caused by consistently mined nutrients as a result of the annual harvest of cashew nuts and apples without replacement through crop fertilization [28]. Nutritional values seemed to increase with rain effects in soils, as the wetter the season, the higher the values recorded i.e. soil's pH (6.05), electrical conductivity (0.04 Scm-1), Organic Carbon (0.23 %) and Organic Matter (0.31 %), Exchangeable Calcium (0.96 cmol(+) kg-1) and Magnesium (5.75 cmol(+) kg-1), available Phosphorus (10.41 mgkg-1), and extractable micronutrients like Iron (50.7 mgkg-1), Copper (3.04 mgkg-1), and Zinc (0.45 mgkg-1). When it rains during the rainy season, chemical characteristics including pH and soil nutrients alter dynamically [27,29]. Due to moist soils that influence soil microbe populations based on the favourability of their habitats (moist soils and pH levels less than 6.5), which in turn mediates the decomposition rates and derived carbon to the topsoil ecosystems, Organic

Table 3
Means of the selected nutrients measured in cashew plants during wet and dry seasons in the Makonde Plateau of southeastern Tanzania.

Variables	[a]Measured nutrients and their respective quantities						
	N	P	K	Cu	Fe	Mn	Zn
	%			ppm			
Wet season	1.30[b]	0.03[b]	0.21[a]	0.81[a]	26.50[a]	1.93[a]	0.16[b]
Dry season	0.62[a]	0.01[a]	0.19[a]	0.67[a]	18.40[a]	1.41[a]	0.06[a]
S.E.D.	0.113	0.001	0.011	0.341	3.502	0.551	0.041
L.S.D.	0.264	0.010	0.020	0.823	8.561	1.355	0.093
P - value	<0.001	0.035	0.052	0.685	0.059	0.388	0.029

[a] Means in a column with *P* –value <0.05 and different latters differ significantly; otherwise, they are statistically similar.

Table 4
Correlations of Plant digests' nutritional statuses.

	TN (%)	P (%)	K (%)	Fe (ppm)	Cu (ppm)	Mn (ppm)	Zn (ppm)
TN (%)	1						
P (%)	0.946[d]	1					
K (%)	0.523[c]	0.15[a]	1				
Fe (ppm)	0.12[a]	0.06[a]	0.12[a]	1			
Cu (ppm)	−0.148[a]	0.036[a]	0.098[a]	−0.267[b]	1		
Mn (ppm)	−0.246[b]	−0.122[a]	−0.177[a]	0.142[a]	0.021[a]	1	
Zn (ppm)	−0.069[a]	0.038[a]	−0.297[b]	0.114[a]	0.215[b]	0.021[a]	1

*Means in a column with different latters differ significantly; otherwise, they are statistically similar.
TN – Total Nitrogen, P – Phosphorus, K – Potassium, Fe – Iron, Cu – Copper, Mn – Manganese and Zn – Zinc

Matter (OM) and Organic Carbon (OC) are most likely higher at wet than dry seasons [29,30]. The exchangeable cations are regulated by the microbial activities within the soil, and the cations are likewise responsible for the diversity and functioning of the microbes [31,32]. In contrast, during the dry season, total Nitrogen, exchangeable Potassium, and Sodium levels were high. This is brought on by decreased nutrient leaching (Potassium and Nitrogen) and increased atmospheric emission of NO, NO_2 and N_2O during dry seasons [33,34].

In assessing the effects of soil sampling depths on the measured soil parameters, the soil depth of 0–30 cm recorded high level of soil pH (up to 6.06), total Nitrogen (0.04 %), Organic Carbon (0.252 %) and Organic Matter (0.43 %), exchangeable Calcium (1.27 $cmol_{(+)}$ kg^{-1}) and Sodium (0.07 $mgkg^{-1}$), available Phosphorus (10.35 $mgkg^{-1}$), and the micronutrients Iron (57.4 $mgkg^{-1}$), Copper (2.57 $mgkg^{-1}$), and Zinc (0.44 $mgkg^{-1}$). On the other hand, high electrical conductivity was likely caused by higher moisture levels at soil depths of 30–50 cm compared to beneath soil surfaces (0–30 cm) [34]. High exchangeable Magnesium and Potassium were also found at the soil sampling depth of 30–50 cm; this is because nutrients, particularly Potassium, are susceptible to leaching [34]. The assessed soils were observed acidic (pH 5.5–6.0) through seasons, soil sampling depths and their interactions, which could be attributed to the sandy loam texture. This pH might have promoted the very low levels of exchangeable Sodium (<0.10 $cmol_{(+)}$ kg^{-1}), hence absence of the effects rooting from salinity. Similarly, medium acid conditions display constraints related to solubility of micronutrients such as Copper and Zinc, nonetheless increasing the solubility of Iron [35]. Solubility of Fe affects fixation of Phosphorus making it unavailable for crop uptake thereby might affect yields [36,37].

The variations in the micronutrient concentrations detected in these soils indicate the influence of soil pH, which is a key factor in the solubility of micronutrients and the likelihood of availability and/or facilitation of macronutrients like phosphorus in soils. Under the threshold of 13 mg P kg-1 soil, the low quantities of accessible Phosphorus found in these soils were noted [36,38]. Given the hydration potential of Potassium, other significant primary minerals (such as Nitrogen and Potassium) are limiting whereas Phosphorus is a constraint to crop yield in these soils [36]. Additionally, Calcium appears to be a secondary macronutrient with a significant excess (>0.22 $cmol_{(+)}$ kg-1 soil) at the soil sampling depth of 0–30 cm, but its expression is significantly masked by the deficiencies of other secondary macronutrients, especially Magnesium, which is a secondary macronutrient with a significant excess at the soil sampling depth of 30–50 cm. Additionally, Organic Matter was very low (1.0 %), indicating that there aren't many organic substrates available to act as a habitat for good microbes and a storehouse for plant nutrients [38,39].

According to the findings, Nitrogen and Potassium showed low to extremely low levels (deficiency) in comparison to the recommended ranges of nutrients by Refs. [38,40]. Under conditions of high soil temperature and low soil moisture (rainfall), Nitrogen and Potassium can volatilize [37,41]. The research areas' low rainfall (less than 700 mm) and rising temperatures (over 32 °C for two years straight) may have contributed to the Nitrogen and Potassium shortages. Because cashew trees are not fertilized in the study sites, this is likely a limiting factor for nutrient replenishment. Similar hypotheses on the role of nutrients in refilling deficient crops for higher yields were addressed by Refs. [42–44]. Additionally, the Makonde Plateau's low rainfall during the 2021–2022 seasons (Fig. 2) may be a sign of an impending drought. Given that there has been little rain lately, the soil's moisture level may have decreased; the droughts may be endangering the nutritional balance of cashew trees [37]. A lack of moisture can affect how well soil nutrients are absorbed by plant roots and crop satisfaction [37].

Seasonal differences have a considerable impact on both Nitrogen and Phosphorus. This may be linked to their synergistic actions since they support physiological processes in the cytoplasm of plants [45]. Nitrogen is essential for facilitating the uptake of other nutrients by the feeder roots of plants. This suggests that the more Nitrogen there is in the soil and plant, the more other nutrients are absorbed by the plant, boosting its physical-chemical processes. Optimized Nitrogen supply might greatly ensure the uptake of Phosphorus and so many other nutrients such as Potassium, Magnesium, Iron, Manganese and Zinc from soils [46]. The balanced use of nutrients for increased agricultural plant yield performance, however, is crucial for sustainable nutrient utilization [47]. Therefore, when replenishing nutrients, it is important to take into account the balancing, synergistic, and antagonistic effects of both micro and micro nutrients.

Findings from this study suggest that high nutrients concentration in cashew plants is attributed to the dormant vegetative phase which later become active during the reproductive phase (flowering and nut setting) whereby cashew plants utilize reserved nutrients for plant physiological functions triggering the need for nutritional additives [46,48,49]. However, all nutrients were below the critical ranges in plants (cashew trees), an observation which is also in line with the levels of the same nutrients recorded in soils where the same cashew plants were growing implying the need for fertilizer application to replenish the deficient. The notion that the measured nutrients in cashew leaves could differ between the two seasons is confirmed by the seasons' significant impact on the concentrations of Nitrogen, Phosphorus, and Zinc. The nutritional status of plant tissues differs between the wet and dry seasons because soil nutrients are more easily obtainable in moist soils [45]. Phosphorus (P) can be found in permanent form in dry soil capillaries as compared to damp soil clods when there is sufficient Organic Matter [50]. Nitrogen and Potassium are quickly leached from sandy soils and places where water is retained. Furthermore, diffusion and water flow have a significant impact on the movement of nutrients from the soil to the root zone, where they are taken up by plant cells [37,45,48,51]. However, stresses due to drought (shortage of rainfall) on crops and plants, such as cashew, can cause nutrient deficiencies as it limits the movement of nutrients and water [19,52–54]. Similar circumstances described by Ref. [53] on Olea europaea, in which the drought decreased crop growth and output (yield) [40,41,49,54]. This advocates the need of soils amendment in cashew orchards through tillage (ridging and or soil clods opening), especially during the rainy or wet season for smooth plant physiological activities such as vascular water movement, nutrients translocation and root percolation.

5. Conclusions and recommendations

From the findings, there hasn't been much effort put into fertilizing the soils and cashew trees on the Makonde Plateau, judging by the lack of nutrients in the soils and cashew plants in relation to the seasons and soil depth. Additionally, the soils are generally productive, although better management practices are needed to increase cashew production. Foliar sprays can be used to deliver deficient macro- and micronutrients to cashew plants. Basal cashew fertilization is suggested during wet seasons and foliar fertilization during dry. In likely soils, acid-forming fertilizers like SA (sulphate of ammonium) should be avoided or used sparingly since they can increase soil acidity. Acidity may prevent excessive nutrient leaching below the rooting zone and the availability of Phosphorus and Molybdenum to cashew tree roots. The routine of adding organic substrates and compost throughout the rainy season will enhance the soil particle aggregation and therefore improve soil structure. As a result, the soils' ability to hold water, provide nutrients, and increase cation exchange will all be advanced. Further research to assess the Sulphur content status of soils and cashew plants is suggested, as this study did not take this into account because the study area would not be sufficient to fully represent Tanzania's cashew-growing regions. Since, the primary fungicide employed in the nation to combat powdery mildew has a sulphur concentration of 95 %. However, based on current soil conditions and nutritional qualities of cashew plants, training is advised for farmers. Moreover, it is necessary to determine site-specific recommendations and dosages based on fertilizer nutritional contents.

Data availability

Data that support the findings of this study are provided/available at the results section.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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