Hindawi
International Journal of Agronomy
Volume 2020, Article ID 8887318, 20 pages
https://doi.org/10.1155/2020/8887318

Research Article

Assessing Soil Nutrients Variability and Adequacy for the Cultivation of Maize, Cassava, and Sorghum in Selected Agroecological Zones of Cameroon

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Received 26 June 2020; Revised 10 December 2020; Accepted 14 December 2020; Published 28 December 2020

Academic Editor: Othmane Merah

Access to information on soil nutrients status and variability is essential in understanding the potential of soils and their responsiveness to management interventions in agriculture. The current study evaluated soil nutrients status in selected agroecological zones (AEZs) of Cameroon and identified variations and their adequacy for maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. (Moench)), and cassava (*Manihot esculenta* Crantz) production. A total of 163 soil samples were collected from surface (0–15 cm) layer for the determination of pH, organic matter (OM), estimated nitrogen release (ENR), sulphur (S), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), boron (B), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), aluminium (Al), phosphorus (P), total exchangeable capacity (TEC), and base saturations. The results showed different degrees of variability in soil nutrients ranging from low to very high in all the AEZs. The soils in all the AEZs were consistently deficient in available phosphorus, sulphur, boron, and zinc in varying proportion and might be inadequate to supply cultivated maize, sorghum, and cassava with the nutrients needed to achieve optimal growth. The soils were also prone to Mg-induced K deficiency, which could limit the growth of maize, sorghum, or cassava. These results therefore suggest that management of inherent soil properties should be based on-site specific situations.

1. Introduction

Environmental degradation is a worldwide problem caused by inappropriate cropping system and land-use and soil management practices and has attracted attention in sustainable agricultural production systems [1–3]. Soil quality degradation is among the top development challenges that demand urgent remedial actions [3, 4]. In Cameroon, the rapid rise in population has led to increase pressure on available arable land. This has resulted in land degradation and subsequent soil fertility decline because of increasingly intense land use without sufficient organic and mineral inputs [5]. Under intensive farming systems, crops grown with inadequate supply of nutrients cause soil fertility deterioration and the emergence of multinutrient deficiencies in many places [6, 7]. Soil fertility status is thus the mainstay on which all input-based high agricultural production systems can be built [8].

Feeding the ever-growing population where low soil fertility is a primary constraint to food production is a serious challenge [9, 10]. Thus, to reduce soil fertility-related constraints, there is need for the encouragement of soil fertility management practices which include promotion of organic manure and compost, green manuring, and balanced use of chemical fertilizers [11–13]. However, soil fertility management cannot be fostered without an appropriate and rapid assessment of soil nutrients status so that decision makers and farmers can be aware of the soil fertility constraints and then make informed decisions to improve crop yields and better manage soil nutrients [14]. Other countries such as India in 2012, Kenya and Nepal in 2014 [12], and recently Cameroon have adopted the use of soil-testing mobile vans for farmers to have their soil tested for nutrient deficiencies and fertilizer requirements. Regardless of their present drawbacks, chemical methods of agricultural soil testing are the most frequently used diagnostic tools of soil nutrient status and the need of fertilization derived from it [15].

Information on soil nutrients status is still very scarce and also much localized [16–21]. Therefore, the agroecological zone (AEZ) approach is needed for assessing and understanding the soil nutrients status at a much larger scale in order to provide farmers with information and recommendations that will improve agricultural productivity. There is an immense dependence of agriculture productivity on soil physicochemical properties. These properties vary widely with soil types, which in turn control water and nutrient uptake by plants [22, 23]. Cameroon is divided into five agroecological zones (AEZs) and is distinguishable by dominant physical, climatic, and vegetative features. The climate varies with terrain, from tropical along the coast to semiarid and hot in the North [24]. Altitude plays a significant role in changing the climatic characteristics, soil properties, and land-use patterns. This further drives the soil microbial functions and nutrient interaction with plants [25]. Since altitudinal gradient directly affects the soil characteristics which in turn affect soil-water-plant relationship, measurements of the spatial variability in soil properties are also crucial [23]. Information on the spatial distribution of soil properties within a field to larger landscapes, regions, and/or AEZs is a prerequisite for best management decisions such as selection of appropriate fertilizer dose, methods, and frequency of its application [26].

So far, in Cameroon, fertilizer trails were conducted on few research stations and no effort was made to extrapolate the results to a wider range of environments. This could be one of the reasons of the yield variation in food crops in the different agroecological zones [27] as soil chemical properties are found to be variable and change rapidly. The crop yield gaps could therefore be related to inadequate replenishment and improper management of soil nutrients [24]. In this regard, the objectives of this study were to evaluate nutrients status of soils in selected agroecological zones and identify variations and their adequacy for maize, sorghum, and cassava production. Relationships between soil chemical properties were also studied.

2. Materials and Methods

2.1. Description of Study Area. Cameroon lies in sub-Saharan Africa, located on the Gulf of Guinea, between latitudes 1.7°N–13.8°N and longitudes 8.4°E–16.8°E. It has five major agroecological zones (AEZs) (Figure 1) [24]. The study areas were located in four AEZs and are as follows.

Sudano-Sahelian (AEZ 1) with maize, millet-sorghum, groundnut, rice, cowpea, soybean, onion, sesame, fruits, and cotton as the main crops produced is made up of low altitude plain, many of which are flooded during the rainy season, which lasts for about 4 months (June–September) and a few gentle dune slopes [28]. The dry season is very pronounced and runs for about eight months extending from October to May. The mean annual rainfall and the mean annual air temperature in the area are 800 mm and 29°C, respectively [29]. Vegetation cover is dry savannah strongly degraded and converted into agricultural lands with few native species. The major soil groups in this area are as follows: *Lixisols*, *Luvisols*, *Vertisols*, *Regosols*, *Fluvisols*, *Gleysols*, *Leptosols*, *Planosols*, *Plinthosols*, and *Arenosols*.

High Guinea Savannah (AEZ 2) with maize, yam, cassava, sweet potatoes, rice, and bean as the main cultivated crops consists of a high plateau (average altitude is 1100 m) and mean annual temperature of 23°C. The dry season lasts for 4 to 6 months, and the main soil groups present are *Nitisols*, *Ferralsols*, *Acrisols*, *Luvisols*, *Leptosols*, and *Cambisols*.

Western Highlands (AEZ 3) with maize, beans, potatoes, rice, sweet potatoes, vegetables, and coffee as the major crops produced features many high plateaus (1000–1800 m) and very high altitude mountains. Annual rainfall generally exceeds 2000 mm, and the mean annual temperature is 21°C. The main soil groups present here are *Ferralsols*, *Nitisols*, *Gleysols*, *Andosols*, *Cambisols,* and *Leptosols*.

Bimodal Humid Forest (AEZ 5) with plantain, cassava, banana, maize, cocoyam, sweet potatoes, cocoa, oil palm, rubber, coffee, maize, and fruits are the main crops produced. This region is made up of a vast low altitude plain (mean altitude is 650 m). It is characterized by green forest vegetation and by abundant precipitations. There are basically 2 rainy and 2 dry seasons and a mean annual temperature of 25°C. The various soil groups in this area are *Ferralsols*, *Nitisols*, *Acrisols*, *Gleysols*, *Fluvisols*, and *Andosols* [28].

2.2. Soil Sampling, Processing, and Physicochemical Analysis. In all the selected sites, 163 composite soil samples were collected with an auger from top soils (0–15 cm) of agriculturally farmed fields and fallow lands in 27 localities span in 4 AEZs in Cameroon, namely, (1) Sudano-Sahelian, (2) High Guinea Savannah, (3) Western Highlands, and (4) Humid Forest with bimodal rainfall pattern (Figure 1 and Table 1). Each composite sample was formed by bulking 15 subsamples. The previous land uses at the different sites are shown in Figure 1 and Table 1. Out of the 163 composite soil samples collected from the study sites, 62 were from localities in the Far North (AEZ 1), 46 in the North (AEZ 1), 18 in the Centre (AEZ 5), 32 in Adamawa (AEZ 2), and 5 in the West region (AEZ 3) (Table 1). These sites were chosen because food production here is still largely in the hands of smallholder farmers/groups whose cultivation practices continue to be characterized by the use of basic tools, low fertilizer inputs, limited control of plant pests and diseases, and low yield. The soil samples were air-dried and sieved through 2 mm screen to remove stones and plant debris and then sent to the Brookside Laboratories INC, New Bremen, USA, for analysis. Soil pH was determined in the ratio of 1 : 1

soil-water suspensions using a digital pH meter [30]. OM (%) was determined by loss on ignition method at 360°C [31] and ENR (lbs acre^{-1}) which is a computed estimate of nitrogen that may be released annually through organic matter decomposition calculated based on the loss on ignition method. S (ppm), Ca (mg kg^{-1}), Mg (mg kg^{-1}), K (mg kg^{-1}), Na (mg kg^{-1}), B (mg kg^{-1}), Fe (mg kg^{-1}), Mn (mg kg^{-1}), Cu (mg kg^{-1}), Zn (mg kg^{-1}), Al (mg kg^{-1}), and P (mg kg^{-1}) were determined after extraction with Mehlich-3 solution [32]. Mehlich-3 multinutrient soil extraction method was adopted in this study because it is cost-effective, less time-consuming, extracts multiple nutrients, and is being used by many regional organizations [33]. TEC (meq/100 g) was obtained by summation of the cations [34]. The base (Ca, Mg, K, and Na) saturations (%) were calculated as the percentage of soils total exchange capacity occupied by the base cation for any given sample. Available phosphorus (P) was also determined by the Bray II method [35].

2.3. Data Analysis. The data were subjected to statistical analysis using Microsoft Excel 2016 and SPSS statistical package 25.0. Soil nutrients level in the samples was analyzed using descriptive statistics (means, standard deviations, minimum and maximum values, skewness, and kurtosis) and their variability assessed using coefficient of variation (CV). Less than 20% CV is regarded as low variability, between 20 and 50% CV is regarded as moderate variability, and between 50 and 100% CV is regarded as high variability. Any CV above 100% is regarded as very high variability [36]. The mean, standard deviation, skewness, kurtosis, and CV were not computed for soil nutrients with one or more measurements below the limit of quantification (for example, (S and P) < 1; B < 0.2, and Zn < 0.4 mg kg^{-1}). The hypothesis of data normality was verified by the Shapiro–Wilk test. To compare the variability in soil parameters among the regions, nonparametric analyses were applied, using the Kruskal–Wallis and Mann–Whitney *U* tests to determine the significance of differences since majority of the soil properties did not have normal distributions; Box and Whisker plots were drawn, and here the measurements of the physicochemical properties below the limit of quantification were set at zero. Based on critical values of soil nutrients established for the soil nutrient extraction methods used in this study, the soil nutrients were rated very low, low, medium, high, or very high. The adequacy of these soil nutrients for the cultivation of maize (in all the sites), sorghum (in the sites examined in the Far North and North regions), and cassava (in the study sites of Adamawa and Centre regions) was assessed by comparing the soil nutrients to the critical value or range recommended for optimal maize, sorghum, and cassava growth and yield. Correlations among the soil properties were checked by Spearman's correlation coefficient. Also measurements of soil properties less than the limits of quantification were eliminated in the calculations.

3. Results and Discussion

3.1. Summary Statistics of Soil Properties. The summary of the descriptive statistical data of the chemical properties of soil samples in selected AEZs of Cameroon grouped according to regions is presented in Tables 2–6. The results showed the complexity of soil nutrients variability within the regions. Most of the chemical properties showed positive skewness in all the regions except for the West region with an important number of negative skewness (Table 6). The kurtosis was also highly variable, with some values greater than 1 or less than −1 (Tables 2–6). The highest value of Kurtosis coefficient was for Na base saturation data in the Far North (Table 2). By the Shapiro–Wilk statistical measurement at $P < 0.05$, it was found that most of the data in the Far North, North and Adamawa regions had nonnormal distribution (Tables 2, 3, and 5). However, most of the data for Centre and West regions had normal distribution (Tables 4 and 6).

The CV was less variable for soil pH in all the regions (Tables 2–6). This variability was similar to those reported by other authors [37, 38]. Soil pH is one of the soil physicochemical properties that influence the availability of plant nutrients. Although the variability reported for pH was low for all the regions, small changes in pH value have significant effects on nutrient availability. CV was also low for soil Ca base saturation in the Far North region. The concentration of Na in soil samples in the Centre region and S, Ca, Mg, K, Na, and Al in the West region also had low CV.

The moderate to very high CVs for most of the soil properties revealed considerable variability which could be attributed to inherent soil forming factors and management practices of various crops that alter the inherent spatial structure of soil properties [26, 39]. It is therefore suggested that site-specific nutrients management to improve soil productivity in the sampling locations be applied.

3.2. Soil Chemical Properties

3.2.1. Soil pH. Soil pH-H_2O for samples in the Far North region ranged from 5.10 to 8.90 (Table 2) with the majority of soils in the acidic to neutral pH range. About 16.13%, 14.52%, 22.58%, 35.48%, 4.84%, 3.23%, and 3.23% of the soil samples from this area were categorized as strongly acidic (pH 5.1–5.5), moderately acidic (5.6–6.0), slightly acidic (6.1–6.5), neutral (6.6–7.3), slightly alkaline (7.4–7.8), moderately alkaline (7.9–8.4), and strongly alkaline (8.5–9.0), respectively, as per the ratings of the United State Department of Agriculture Natural Resources conservation classification of soil pH [40]. For soil samples in the North region, pH was found to range from acidic to neutral (pH 4.7–7.5) (Table 3). About 8.70%, 32.61%, 32.61%, 10.87%, 13.04%, and 2.17% of the soil samples were rated as very strongly acidic (4.5–5.0), strongly acidic, moderately acidic, slightly acidic, and neutral and slightly alkaline, respectively. For soil samples in the Centre, Adamawa, and West regions, all the pH values were acidic and ranged from 3.9 to 6.0 for Centre, 4.2 to 6.0 for Adamawa, and 4.8 to 6.2 for the West region (Tables 4–6). About 27.78% of soil samples in the Centre region and 37.5% in the Adamawa were extremely acidic (pH 3.5–4.4). 33.33% of soil samples in the Centre, 37.5% in the Adamawa, and 20% in the West were very

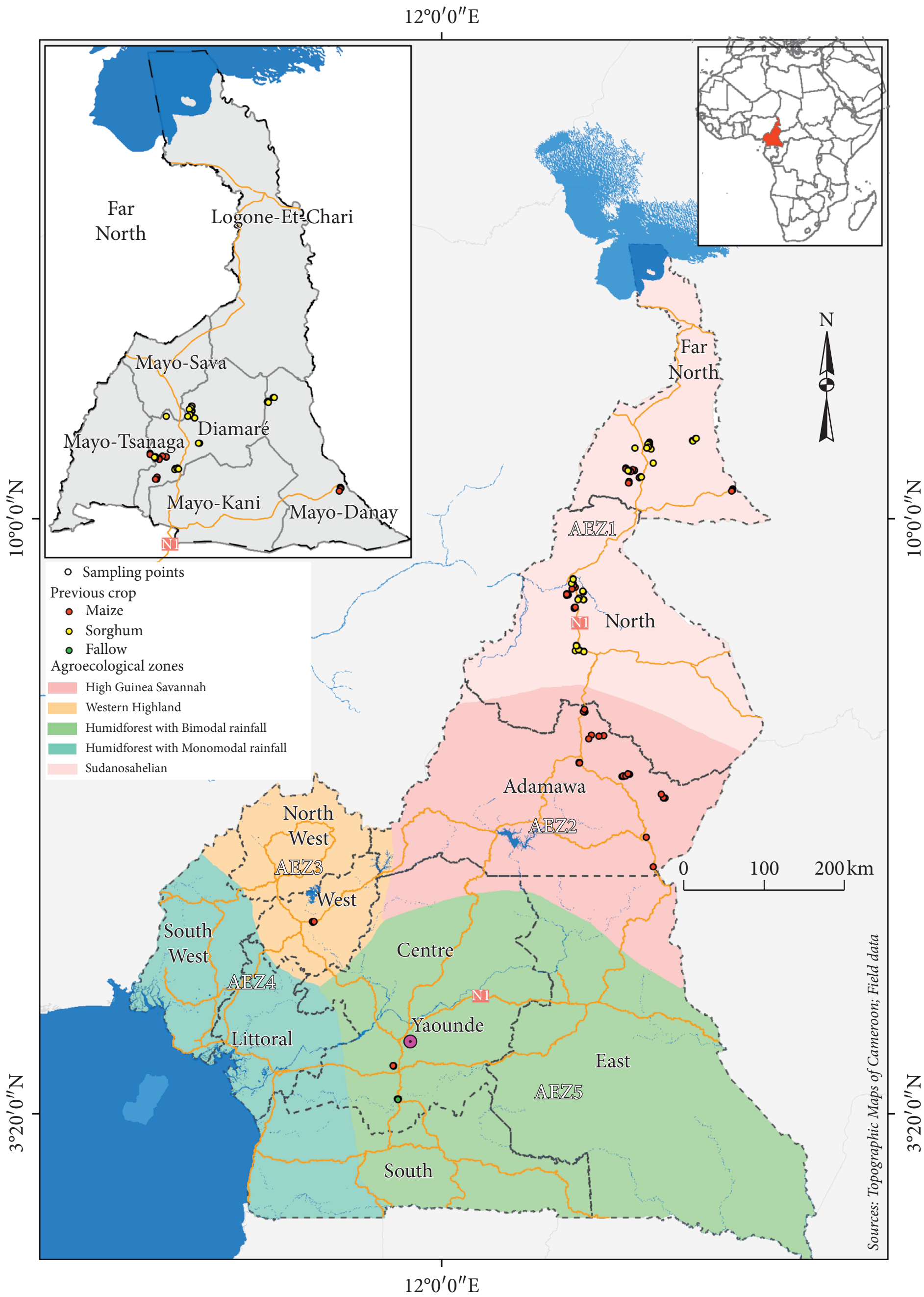

Figure 1: Location of the sampling points and locations in the different agroecological zones of Cameroon. AEZ, agroecological zone.

strongly acidic. 22.22% of soil in the Centre, 9.38% in Adamawa, and 20% in West region were strongly acidic, whereas 16.67% in Centre, 15.63% in Adamawa, and 40% in West were moderately acidic soils. Also 20% of the soil samples in West region were slightly acid. The optimum pH range for most agricultural crops is between 5.5 and 7.5. Thus, 79.03% of soils samples in Far North, 67.39% in North, 22.22% in Centre, 18.75% in Adamawa, and 60% in West region were favourable for most crops. However, pH of acidic soil can be increased by using finely ground agricultural lime (limestone or chalk), wood ash, industrial calcium oxide (burnt lime), magnesium oxide, basic slag (calcium silicate), and oyster shells. On the contrary, the pH of alkaline soils can be decreased by using acidifying fertilizers (ammonium sulphate, ammonium nitrate, and urea) or organic materials (peat or sphagnum peat moss) [41].

Solubility and toxicity of aluminium in soils is very dependent on soil pH. Mehlich-3 method, however, does not determine the likelihood of aluminium toxicity but measures the dilute acid soluble Al that is Al likely to fix applied soluble P. High Mehlich-Al (>1500 mg/kg) [42, 43] can be taken to indicate high phosphate fixation and consequently good sulphate retention. Conversely, a low Mehlich-Al (<900 mg/kg) indicates a lower anion retention and the potential for greater leaching losses of sulphate. 100% of soil samples in the Far North, North, and West regions had

Table 1: Sampling sites used for the study.

No.	Locality	No. of samples	Division	Region	Previous crop	Agroecological zone
1	Gazawa	10	Diamaré	Far North	Maize	Sudano-Sahelian (AEZ 1)
2	Mokong	3	Mayo Tsanaga	Far North	Maize	
3	Gawel	3	Diamaré	Far North	Maize	
4	Guiring	3	Diamaré	Far North	Sorghum	
5	Guirvidig	10	Diamaré	Far North	Sorghum	
6	Soukoungo	5	Diamaré	Far North	Sorghum	
7	Salak	10	Diamaré	Far North	Sorghum	
8	Papata	5	Diamaré	Far North	Sorghum	
9	Dogba	8	Diamaré	Far North	Sorghum	
10	Yagoua	5	Mayo Danay	Far North	Maize	
11	Sangueré Paul	5	Benoué	North	Maize	
12	Bibol	10	Benoué	North	Maize	
13	Djalingo	4	Benoué	North	Maize	
14	Gouna	9	Benoué	North	Sorghum	
15	Karewa	3	Benoué	North	Sorghum	
16	Kismatari	5	Benoué	North	Sorghum	
17	Bamé	5	Benoué	North	Sorghum	
18	Ngong	5	Benoué	North	Maize	
19	Nkolbisson	3	Mfoundi	Centre	Maize	Bimodal Humid Forest (AEZ 5)
20	Mbalmayo 1	15	Mefou Afamba	Centre	Fallow	
21	Wassande	9	Vina	Adamawa	Maize	High Guinea Savannah (AEZ 2)
22	Bellel	5	Mbere	Adamawa	Maize	
23	Mbe	5	Vina	Adamawa	Maize	
24	Meiganga	3	Mbere	Adamawa	Maize	
25	Ngangasao	5	Vina	Adamawa	Maize	
26	Wakwa	5	Vina	Adamawa	Maize	
27	Mangoum	5	Noun	West	Maize	Western Highlands (AEZ 3)

Table 2: Summary statistics of soil chemical properties within Far North region ($n = 62$).

Soil properties	Max	Min	Mean	SD	CV (%)	Kurtosis	Skewness	Shapiro–Wilk (P value)
TEC (100 meq/100 g)	35.4	3.80	16.09	7.79	48.41	−0.04	0.78	0.002
pH	8.9	5.10	6.50	0.84	12.95	0.49	0.63	0.049
Organic matter (%)	1.96	0.26	0.95	0.40	41.70	0.30	0.83	0.005
Estimated N release (lbs acre^{-1})	59	10	35.26	11.59	32.87	−0.63	0.11	0.38
S (ppm)	11	1	5.71	1.89	33.17	0.94	0.28	0.011
P (mg kg^{-1})	120	<1	—	—	—	—	—	—
Ca (mg kg^{-1})	4251	291	1990.71	1039.62	52.22	−0.56	0.54	0.013
Mg (mg kg^{-1})	1003	72	355.03	221.59	62.41	0.83	1.13	0.000
K(mg kg^{-1})	600	66	159.34	83.66	52.50	11.73	2.73	0.000
Na (mg kg^{-1})	695	12	74.19	118.19	159.30	19.93	4.28	0.000
Al (mg kg^{-1})	825	193	470.24	149.20	31.73	−0.23	0.46	0.116
Ca saturation (%)	80.20	35.25	60.78	11.09	18.24	−0.32	−0.74	0.001
Mg saturation (%)	26.84	10.43	17.56	3.65	20.79	−0.09	0.34	0.678
K saturation (%)	9.19	0.92	2.92	1.68	57.47	4.07	1.96	0.000
Na saturation (%)	25.74	0.50	2.02	3.54	174.78	35.07	5.60	0.000
H (%)	42	0.00	11.68	12.25	104.86	−0.04	1.05	0.000
B (mg kg^{-1})	0.73	<0.2	—	—	—	—	—	—
Fe (mg kg^{-1})	177	54	102.34	30.97	30.26	0.265	0.74	0.002
Mn (mg kg^{-1})	191	29	84.69	38.89	45.91	−0.319	0.60	0.009
Cu (mg kg^{-1})	2.83	0.41	1.25	0.58	46.19	−0.068	0.72	0.007
Zn (mg kg^{-1})	3.46	<0.4	—	—	—	—	—	—

Min: minimum; Max: maximum; SD: standard deviation; CV: coefficient of variation; values with "<" indicate the limit of quantification.

Mehlich-Al <900 mg/kg, while 77.78% and 21.88% of soils in the Centre and Adamawa regions had Mehlich-Al <900 mg/kg (actual soil pH values and chemical properties of the sampling sites are given in Tables 1S–5S of the Supplementary Material).

3.2.2. Organic Matter and Estimated Nitrogen Release. The OM contents were in the range of 0.26–1.96%, 0.38–1.85%, 1.99–8.16%, 0.6–16.29%, and 0.36–0.91% on the surface soil samples in the Far North, North, Centre, Adamawa, and West regions, respectively (Tables 2–6).

Table 3: Summary statistics of soil chemical properties within North region ($n = 46$).

Soil properties	Max	Min	Mean	SD	CV	Kurtosis	Skewness	Shapiro–Wilk (P value)
TEC (100 meq/100 g)	35.08	2.08	7.49	6.01	80.25	9.86	2.85	0.000
pH	7.5	4.7	5.80	0.66	11.39	0.16	0.83	0.015
Organic matter (%)	1.85	0.38	0.78	0.32	41.59	1.19	1.07	0.001
Estimated N release (lbs acre^{-1})	57	15	29.96	10.67	36.03	1.19	0.48	0.005
S (ppm)	7	<1.00	—	—	—	—	—	—
P (mg kg^{-1})	111	2.00	12.11	18.55	153.16	21.15	4.50	0.000
Ca (mg kg^{-1})	4232	213	814.46	751.03	90.67	9.70	2.85	0.000
Mg (mg kg^{-1})	1140	25	136.02	190.29	139.90	18.07	3.99	0.000
K(mg kg^{-1})	183	30	72.78	30.25	41.57	2.82	1.46	0.000
Na (mg kg^{-1})	166	8	25.63	27.63	107.80	14.98	3.51	0.000
Al (mg kg^{-1})	698	202	379.07	116.34	30.34	0.17	0.76	0.048
Ca saturation (%)	74.59	28.77	52.39	11.68	22.30	−0.87	−0.08	0.476
Mg saturation (%)	27.08	7.52	12.94	4.46	34.46	1.65	1.35	0.000
K saturation (%)	5.71	1.23	3.03	1.13	37.24	−0.35	0.46	0.233
Na saturation (%)	5.94	0.63	1.54	0.92	59.79	10.92	2.72	0.000
H (%)	51	0.00	24.11	14.33	58.61	−0.89	−0.13	0.141
B (mg kg^{-1})	0.80	<0.2	—	—	—	—	—	—
Fe (mg kg^{-1})	297	41	104.13	59.94	56.76	2.06	1.47	0.000
Mn (mg kg^{-1})	252	16	103.26	50.88	49.27	0.98	0.99	0.013
Cu (mg kg^{-1})	3.01	0.24	1.02	0.75	73.10	0.68	1.29	0.000
Zn (mg kg^{-1})	5.36	<0.4	—	—	—	—	—	—

Min: minimum; Max: maximum; SD: standard deviation; CV: coefficient of variation; values with "<" indicate the limit of quantification.

Table 4: Summary statistics of soil chemical properties within Centre region ($n = 18$).

Soil properties	Max	Min	Mean	SD	CV	Kurtosis	Skewness	Shapiro–Wilk (P value)
TEC (100 meq/100 g)	12.77	4.72	9.00	2.23	24.71	−0.76	−0.15	0.863
pH	6.0	3.9	4.85	0.58	12.03	−0.46	0.49	0.453
Organic matter (%)	8.16	1.99	3.48	2.05	58.80	1.61	1.68	0.000
Estimated N release (lbs acre^{-1})	116	60	78.17	18.93	24.22	−0.026	1.07	0.003
S (ppm)	23	4.00	10.11	5.78	57.16	0.11	1.09	0.009
P (mg kg^{-1})	8	<1.00	—	—	—	—	—	—
Ca (mg kg^{-1})	1204	280	601.67	276.92	46.03	−0.29	0.91	0.033
Mg (mg kg^{-1})	219	58	109.83	47.03	42.82	0.59	1.13	0.24
K (mg kg^{-1})	122	15	59.06	28.82	48.80	−0.29	0.56	0.668
Na (mg kg^{-1})	16	9	13.17	2.46	18.65	−1.13	−0.30	0.05
Al (mg kg^{-1})	1223	457	756.22	200.07	26.46	0.44	0.81	0.464
Ca saturation (%)	59.37	17.48	33.32	12.01	36.05	−0.08	0.79	0.205
Mg saturation (%)	18.69	4.88	10.36	4.02	38.79	−0.29	0.93	0.018
K saturation (%)	3.64	0.59	1.76	0.94	53.59	−0.46	0.74	0.112
Na saturation (%)	1.47	0.35	0.69	0.28	40.48	2.40	1.42	0.032
H (%)	66.00	15.00	46.17	14.45	31.29	−0.46	−0.07	0.087
B (mg kg^{-1})	0.33	<0.2	—	—	—	—	—	—
Fe (mg kg^{-1})	197	35.00	109.94	36.89	33.55	1.14	0.29	0.876
Mn (mg kg^{-1})	234	1.00	115.83	72.73	62.79	−0.75	−0.13	0.285
Cu (mg kg^{-1})	2.37	1.06	1.73	0.35	20.27	−0.22	−0.03	0.947
Zn (mg kg^{-1})	2.63	<0.4	—	—	—	—	—	—

Min: minimum; Max: maximum; SD: standard deviation; CV: coefficient of variation; values with "<" indicate the limit of quantification.

These values fall under very low (1.61% and 4.35%) and low (82.26% and 89.13%) to moderate (16.13% and 6.52%) range for the Far North and North regions, respectively; low (33.33%), moderate (44.44%), high (5.56%), and very high (16.67%) for the Centre region; very low (12.50%), low (12.50%), moderate (3.13%), and very high (71.88%) for Adamawa, and very low (100%) for West region (Table 7). ENR ranged from 10 to 59, 15 to 57, 60 to 116, 24 to 128, and 14 to 36 lbs acre^{-1} in samples in the Far North, North, Centre, Adamawa, and West regions, respectively (Tables 2–6). These values are calculated estimates of nitrogen that may be released annually through organic matter decomposition, and the rating is similar to that of organic matter [44]. With the exception of most of the examined soils in Adamawa and the Centre regions, the low OM levels in the soil samples explain why ENR was low in these soils. This is attributed to the fact that OM is the main source of nitrogen for crops grown without fertilizer application [45].

Table 5: Summary statistics of soil chemical properties within Centre region ($n = 32$).

Soil nutrient	Max	Min	Mean	SD	CV	Kurtosis	Skewness	Shapiro–Wilk (P value)
TEC (100 meq/100 g)	26.54	3.53	8.41	5.00	59.43	4.40	1.83	0.000
pH	6.00	4.20	4.79	0.55	11.47	−0.15	1.05	0.000
Organic matter (%)	16.29	0.60	7.49	5.27	70.44	−1.06	0.49	0.001
Estimated N release (lbs acre^{-1})	128	24	96.69	32.60	33.72	−0.24	−1.01	0.000
S (ppm)	29	<1.00	—	—	—	—	—	—
P (mg kg^{-1})	24	<1	—	—	—	—	—	—
Ca (mg kg^{-1})	3129	135	554.94	531.31	95.74	18.45	3.93	0.000
Mg (mg kg^{-1})	480	16.00	94.22	92.25	97.91	9.83	2.89	0.000
K (mg kg^{-1})	543	23.00	86.59	93.68	108.18	19.03	4.09	0.000
Na (mg kg^{-1})	20.00	8.00	13.13	3.43	26.16	−0.69	0.22	0.144
Al (mg kg^{-1})	1486	399	1066.28	312.93	29.35	016	−1.09	0.000
Ca saturation (%)	60.85	17.13	32.04	12.16	37.94	0.51	1.27	0.000
Mg saturation (%)	16.82	2.13	8.96	3.94	43.98	−0.81	0.23	0.420
K saturation (%)	7.77	0.82	2.84	1.79	63.08	0.70	1.13	0.003
Na saturation (%)	1.50	0.33	0.81	0.31	38.69	−0.74	0.40	0.953
H (%)	61.00	15.00	47.53	13.97	29.38	0.35	−1.26	0.000
B (mg kg^{-1})	0.71	<0.2	—	—	—	—	—	—
Fe (mg kg^{-1})	234	35.00	70.66	36.88	52.19	12.11	3.00	0.000
Mn (mg kg^{-1})	140	2.00	36.34	38.84	106.88	1.41	1.57	0.000
Cu (mg kg^{-1})	2.07	0.37	1.26	0.47	37.69	−0.88	−0.09	0.514
Zn (mg kg^{-1})	1.31	<0.4	—	—	—	—	—	—

Min: minimum; Max: maximum; SD: standard deviation; CV: coefficient of variation; values with "<" indicate the limit of quantification.

Table 6: Summary statistics of soil chemical properties within West region ($n = 5$).

Soil properties	Max	Min	Mean	SD	CV	Kurtosis	Skewness	Shapiro–Wilk (P value)
TEC (100 meq/100 g)	5.12	2.46	3.54	1.20	34.04	−2.46	0.66	0.191
pH	6.20	4.80	5.80	0.58	10.41	−1.60	−0.61	0.585
Organic matter (%)	0.91	0.36	0.53	0.23	42.93	2.68	1.69	0.074
Estimated N release (lbs acre^{-1})	36.00	14.00	20.80	9.01	43.32	2.72	1.70	0.074
S (ppm)	7.00	5.00	6.20	0.84	13.49	−0.61	−0.51	0.314
P (mg kg^{-1})	12.00	7.00	8.8	1.92	21.86	2.61	1.52	0.223
Ca (mg kg^{-1})	352	277	315.80	27.81	8.81	0.42	−0.17	0.953
Mg (mg kg^{-1})	56.00	48.00	50.80	3.56	7.02	−1.12	0.94	0.159
K (mg kg^{-1})	51.00	35.00	44.20	6.87	15.54	−1.52	−0.24	0.419
Na (mg kg^{-1})	20.00	14.00	17.20	2.28	13.26	0.18	−0.41	0.814
Al (mg kg^{-1})	370	260	321.40	49.85	15.51	−2.73	−0.47	0.278
Ca saturation (%)	62.03	30.47	48.08	13.03	27.10	−1.66	−0.54	0.784
Mg saturation (%)	16.26	8.63	12.84	3.24	25.24	−2.13	−0.48	0.663
K saturation (%)	4.27	2.55	3.37	0.69	20.33	−1.28	0.16	0.999
Na saturation (%)	2.83	1.53	2.25	0.54	23.83	−1.53	−0.36	0.925
H (%)	49.00	12.00	27.20	16.07	59.07	−1.96	0.65	0.467
B (mg kg^{-1})	0.43	<0.2	—	—	—	—	—	—
Fe (mg kg^{-1})	293	47.00	98.60	108.70	110.25	4.99	2.23	0.000
Mn (mg kg^{-1})	127	29.00	85.00	41.92	49.33	−2.05	−0.60	0.418
Cu (mg kg^{-1})	1.42	0.44	0.76	0.39	50.91	3.07	1.71	0.139
Zn (mg kg^{-1})	0.74	0.42	0.58	0.14	23.92	−2.44	0.18	0.554

Min: minimum; Max: maximum; SD: standard deviation; CV: coefficient of variation; values with "<" indicate the limit of quantification.

3.2.3. Phosphorus. Available P (Mehlich-3 extractable) varied between 1.0 and 120 mg kg^{-1}, 2.0 and 111 mg kg^{-1}, <1.0 and 8.0 mg kg^{-1}, <1.0 and 24 mg kg^{-1}, and 7.0 and 12 mg kg^{-1} in soil samples in the Far North, North, Centre, Adamawa, and West regions, respectively (Tables 2–6). It was found to be very low, low, medium, high, and very high in 53.23%, 19.35%, 14.51%, 4.84%, and 8.06% of the samples in Far North; very low, low, medium, and very high in 84.78, 8.70, 2.17, and 4.35% of samples in North; and very low, low, and medium in 93.75, 3.13, and 3.13% of samples in Adamawa, respectively. Available phosphorus was 100% low for samples in Centre and West regions (Table 7). Generally, available P was deficient in all the soils studied. The small percentages of moderately available P in samples in Adamawa and the high and very high available P content in samples in the Far North and North regions might be due to fertilizer residues in the fields as a result of high P application [46]. This is consistent with other reports stating that soil

Table 7: Critical values of nutrients and soil properties.

Soil chemical properties	Critical level					
	Very low	Low	Medium	High	Very high	Reference
Organic matter (%)	0–0.3	0.4–1.2	1.3–2.2	2.3–3.2	3.3+	[44]
Estimated N release (lbs acre^{-1})	0–26	27–37	38–47	48–57	58+	[44]
Total exchangeable cation (meq/100 g)	0–4	5–11	12–24	25–40	41+	[49]
P (mm kg^{-1})	0–12	13–22	23–35	36–68	69+	[50]
Ca (mm kg^{-1})	0–307	308–503	504–700	701–895	896+	[50]
Mg (mm kg^{-1})	0–22	23–41	42–71	72–147	148+	[50]
K (mm kg^{-1})	0–20	21–40	41–72	73–138	139+	[50]
S (mm kg^{-1})	0–10	11–20	21–30	31–40	41+	[59]
B (mm kg^{-1})	–	<0.70	0.71–1.00	>1.00	—	[60]
Fe (mm kg^{-1})	–	<60	60–420	>420	—	[60]
Mn (mm kg^{-1})	–	<30	30.1–200	>200	—	[60]
Cu (mm kg^{-1})	–	<1.6	1.6–4.5	>4.5	—	[60]
Zn (mm kg^{-1})	–	<2.2	2.21–5.0	>5.0	—	[60]

available P variability is related to land-use type and soil management practices [3, 47]. The results also pointed out the need to consider application of liming materials to bring soil pH up to ideal levels (pH 6–7) as P is generally available to crops at this pH range [47]. Low soil pH severely limits P availability to plants, which may cause deficiency symptoms even where high soil test P levels exist [48].

3.2.4. Total Exchangeable Capacity and Exchangeable Bases. Total exchangeable capacity (TEC) varies between 3.80 and 35.4, 2.08 and 35.08, 4.72 and 12.77, 3.53 and 26.54, and 2.46 and 5.12 meq/100 g for soil samples in the Far North, North, Centre, Adamawa, and the West regions, respectively (Tables 2–6). According to Landon [49], the soil samples from the Far North (1.61, 38.71, 46.77, and 12.90%), North (32.61, 56.52, 8.70, and 2.17%), and Adamawa (28.13, 56.25, 12.5, and 3.13%) were categorized as very low, low, medium, and high in TEC, respectively (Table 7). TEC of soil samples in the Centre region was categorized as very low (5.56%), low (83.33%), and medium (11.11%), whereas TEC level was very low (80%) and low (20%) for samples in the West region.

The range of exchangeable K values recorded in soil samples in the Far North, North, Centre, Adamawa, and West regions was 66–600, 30–183, 15–122, 23–543, and 35–51 mg kg^{-1}, respectively (Tables 2–6). Based on rating suggested by Heckman, in 1998 (Table 7), about 3.23%, 46.77%, and 50% of sampled soils in Far North were qualified under medium, high, and very high, respectively, in exchangeable K. In the North region, exchangeable K in the soils was in the range of low (4.35%), medium (56.52%), high (34.78%), and very high (4.35%), and in the Centre region, it was in the range of very low (5.56%), low (27.78%), medium (33.33%), and high (33.33%). Additionally, 9.38%, 56.25%, 25%, and 9.38% of the samples in the Adamawa region were qualified as having low, medium, high, and very high exchangeable K level, respectively, while 20% and 80% of samples in the West region were qualified medium and high in exchangeable K level [50].

The range of values for exchangeable Ca was between 4251 and 291, 4232 and 213, 1204 and 280, 3129 and 135, and 352 and 277 mgkg^{-1} for soil samples in the Far North, North, Centre, Adamawa, and West regions, respectively (Tables 2–6). About (1.61%, 1.61%, 3.23%, 9.68%, and 83.87%), (13.04%, 30.43%, 17.39%, 8.70%, and 30.43%), (5.56%, 50%, 16.67%, 5.56%, and 22.22%), and (13.38%, 25%, 21.88%, 9.38%, and 9.38%) of samples in the Far North, North, Centre, and Adamawa regions were found to be very low, low, medium, high, and very high in exchangeable Ca, respectively, whereas 20% and 80% of samples in the West region were very low and low in exchangeable Ca, respectively (Table 7). Availability of Ca varies enormously from soil to soil and is highly dependent on a number of other factors. Ca deficiency was found to occur only in soils of low pH values less than 5.5. Landon [49] also reported deficiencies of Ca in soils at pH ≤ 5.5.

Exchangeable Mg also varied widely from soil to soil in the study areas. The range of values was between 72 and 1003, 25 and 1140, 58 and 219, 16 and 480, and 48 and 56 mg kg^{-1} for samples in the Far North, North, Centre, Adamawa, and West regions, respectively (Tables 2–6). Exchangeable Mg showed high (17.74%) and very high (82.26%) levels for samples in the Far North and low (8.70%), medium (34.78%), high (34.78%), and very high (21.74%) for samples in the North region (Table 7). Additionally, about 27.78%, 55.56%, and 16.67% of samples in the Centre region were medium, high, and very high, respectively; about 3.13%, 18.75%, 31.25%, 34.38%, and 12.50% of soils samples in the Adamawa region were very low, low, medium, high, and very high, respectively, while 100% of soil samples in the West region was medium. There is usually an inverse and adverse relationship between a very high concentration of one cation in the soil and the availability and uptake of other cations by plant [33, 51]; that is, if Ca and/or Mg dominates the exchange complex over K, it may reduce K availability and potentially result in K deficiency [33, 52, 53]. This implies that K availability does not only solely depend on the K content of soils but also depends on the relative amounts of other cations (Ca and Mg). Thus, knowledge on the relative proportion of cations (Ca, Mg, and K) than single cation evaluation (e.g., K) has been suggested in exploring

Table 8: Spearman rank order correlations of measured chemical properties for soil samples in the Far North region.

	TEC	pH	OM	ENR	S	P	Ca	Mg	K	Na	B	Fe	Mn	Cu	Zn	Al
TEC	1															
pH	0.213	1														
OM	0.849**	0.234	1													
ENR	0.848**	0.234	1.000**	1												
S	0.074	0.033	0.063	0.066	1											
P	−0.172	0.025	−0.089	−0.092	0.087	1										
Ca	0.950**	0.431**	0.864**	0.864**	0.035	−0.105	1									
Mg	0.943**	0.364**	0.869**	0.868**	0.029	−0.209	0.939**	1								
K	0.472**	0.248	0.562**	0.559**	0.102	0.164	0.520**	0.574**	1							
Na	0.731**	0.357**	0.534**	0.535**	0.185	−0.345**	0.706**	0.763**	0.267*	1						
B	−0.140	−0.048	0.129	−0.132	0.026	0.174	−0.108	−0.183	−0.141	−0.027	1					
Fe	0.369**	−0.188	0.457**	0.457**	0.061	0.501**	0.347**	0.329**	0.306*	0.094	0.160	1				
Mn	0.319**	0.629**	0.389**	0.389**	0.180	0.043	0.437**	0.347**	0.185	0.245	0.208	0.106	1			
Cu	0.906**	0.289*	0.821**	0.820**	0.067	0.039	0.912**	0.890**	0.496**	0.700**	−0.070	0.498**	0.266*	1		
Zn	−0.348*	0.309*	−0.150	−0.147	−0.224	0.625**	−0.169	−0.278	0.075	−0.431**	−0.009	0.204	0.157	−0.164	1	
Al	0.695**	−0.138	0.561**	0.559**	0.115	−0.395**	0.577**	0.624**	0.337**	0.563**	−0.062	0.186	−0.035	0.527**	−0.573**	1

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed); total number of soil samples $n = 62$; P ($n = 61$); B ($n = 47$); Zn ($n = 47$); OM (%); TEC (meq/100 g); ENR (lbs acre^{-1}); S (ppm); P (mg kg^{-1}); Ca (mg kg^{-1}); Mg (mg kg^{-1}); K (mg kg^{-1}); Na (mg kg^{-1}); B (mg kg^{-1}); Fe (mg kg^{-1}); Mn (mg kg^{-1}); Cu (mg kg^{-1}); Zn (mg kg^{-1}); Al (mg kg^{-1}).

Table 9: Spearman rank order correlations of measured chemical properties for soil samples in the North region.

	TEC	pH	OM	ENR	S	P	Ca	Mg	K	Na	B	Fe	Mn	Cu	Zn	Al
TEC	1															
pH	0.253	1														
OM	0.769**	0.244	1													
ENR	0.773**	0.246	0.999**	1												
S	−0.239	−0.052	0.024	0.023	1											
P	−0.161	0.064	−0.364*	−0.368*	−0.311*	1										
Ca	0.918**	0.561**	0.722**	0.725**	−0.239	−0.096	1									
Mg	0.886**	0.547**	0.711**	0.712**	−0.194	−0.110	0.945**	1								
K	0.660**	0.307*	0.642**	0.641**	−0.129	−0.070	0.647**	0.676**	1							
Na	0.574**	0.433**	0.585**	0.588**	0.116	−0.072	0.612**	0.650**	0.503**	1						
B	0.008	0.082	0.152	0.155	−0.100	−0.032	0.003	0.003	−0.017	0.063	1					
Fe	0.600**	0.217	0.617**	0.619**	−0.054	−0.189	0.563**	0.531**	0.526**	0.643**	0.050	1				
Mn	0.012	0.427**	−0.047	−0.044	0.044	0.106	0.157	0.188	0.124	−0.171	0.129	−0.271	1			
Cu	0.621**	0.394**	0.603**	0.597**	0.039	−0.061	0.653**	0.673**	0.469**	0.815**	0.041	0.772**	−0.154	1		
Zn	−0.133	0.148	−0.110	−0.126	0.021	0.344	−0.047	−0.021	−0.040	−0.046	0.010	−0.026	0.033	0.145	1	
Al	0.491**	−0.043	0.630**	0.631**	0.160	−0.330**	0.405**	0.461**	0.309*	0.524**	−0.017	0.362*	−0.220	0.550**	−0.170	1

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed); total number of soil samples $n = 46$; S ($n = 43$); B ($n = 29$); Zn ($n = 31$); OM (%); TEC (meq/100 g); ENR (lbs acre^{-1}); S (ppm); P (mg kg^{-1}); Ca (mg kg^{-1}); Mg (mg kg^{-1}); K (mg kg^{-1}); Na (mg kg^{-1}); B (mg kg^{-1}); Fe (mg kg^{-1}); Mn (mg kg^{-1}); Cu (mg kg^{-1}); Zn (mg kg^{-1}); Al (mg kg^{-1}).

Table 10: Spearman rank order correlations of measured chemical properties for soil samples in the Centre region.

	TEC	pH	OM	ENR	S	P	Ca	Mg	K	Na	B	Fe	Mn	Cu	Zn	Al
TEC	1															
pH	−0.047	1														
OM	0.420	0.301	1													
ENR	0.411	0.314	0.998**	1												
S	0.039	−0.831**	−0.430	−0.438	1											
P	−0.119	−0.545*	−0.373	−0.387	0.806**	1										
Ca	0.622**	0.713**	0.455	0.456	−0.590**	−0.425	1									
Mg	0.455	0.702**	0.389	0.377	−0.580*	−0.480	0.876**	1								
K	0.108	−0.265	−0.057	−0.045	0.427	0.448	−0.188	−0.174	1							
Na	−0.313	0.226	0.170	0.157	−0.197	0.080	−0.114	0.092	0.053	1						
B	0.571	0.432	0.107	0.126	−0.500	−0.433	0.643	0.429	−0.107	−0.055	1					
Fe	−0.003	−0.501*	−0.438	−0.432	0.605**	0.427	−0.387	−0.591**	0.163	−0.438	0.000	1				
Mn	−0.070	−0.156	−0.486*	−0.469*	0.311	0.247	−0.150	−0.389	−0.062	−0.435	0.000	0.661**	1			
Cu	0.203	−0.608**	−0.547*	−0.546*	0.826**	0.650**	−0.275	−0.392	0.263	−0.337	−0.107	0.636**	0.452	1		
Zn	0.463	0.352	0.272	0.274	−0.157	−0.185	0.492	0.293	0.063	−0.365	0.739	0.203	0.396	0.038	1	*
Al	0.038	−0.163	0.418	0.408	0.118	0.171	−0.098	0.086	0.223	0.457	−0.286	−0.300	−0.720**	−0.097	−0.640*	1

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed); total number of soil samples $n = 18$; P ($n = 17$); B ($n = 7$); Zn ($n = 15$); OM (%); TEC (meq/100 g); ENR (lbs acre^{-1}); S (ppm); P (mg kg^{-1}); Ca (mg kg^{-1}); Mg (mg kg^{-1}); K (mg kg^{-1}); Na (mg kg^{-1}); B (mg kg^{-1}); Fe (mg kg^{-1}); Mn (mg kg^{-1}); Cu (mg kg^{-1}); Zn (mg kg^{-1}); Al (mg kg^{-1}).

TABLE 11: Spearman rank order correlations of measured chemical properties for soil samples in the Adamawa region.

	TEC	pH	OM	ENR	S	P	Ca	Mg	K	Na	B	Fe	Mn	Cu	Zn	Al
TEC	1															
pH	−0.098	1														
OM	0.212	−0.579**	1													
ENR	0.227	−0.594**	0.996**	1												
S	0.052	−0.686**	0.520**	0.528**	1											
P	0.415*	0.208	−0.161	−0.163	−0.022	1										
Ca	0.791**	0.354*	−0.188	−0.181	−0.208	0.554**	1									
Mg	0.644**	0.445*	−0.239	−0.217	−0.377*	0.225	0.671**	1								
K	0.202	0.145	0.013	0.029	−0.012	0.125	0.087	0.390*	1							
Na	0.633**	−0.389*	0.479**	0.503**	0.520**	0.287	0.281	0.161	0.105	1						
B	−0.194	0.500	0.201	0.245	−0.299	−0.064	0.140	−0.122	−0.073	−0.059	1					
Fe	0.017	0.596**	−0.403*	−0.398*	−0.370	0.500**	0.376*	0.244	−0.013	−0.027	0.180	1				
Mn	−0.029	0.664**	−0.814**	−0.813**	−0.633**	0.223	0.390*	0.446*	0.043	−0.418*	−0.049	0.422*	1			
Cu	0.266	−0.045	0.560**	0.570**	0.131	0.133	0.267	0.074	−0.054	0.284	0.511	0.125	−0.239	1		
Zn	0.486	0.203	0.314	0.314	−0.200	0.429	0.429	0.429	0.314	0.754	0.500	0.771	−0.543	0.086	1	
Al	0.455**	−0.542**	0.468**	0.470**	0.511**	0.005	0.093	0.050	0.154	0.580**	−0.249	−0.439*	−0.432*	−0.058	0.029	1

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed); total number of soil samples $n = 32$; S ($n = 28$); P ($n = 30$); B ($n = 10$); Zn ($n = 6$); OM (%); TEC (meq/100 g); ENR (lbs $acre^{-1}$); S (ppm); P (mg kg^{-1}); Ca (mg kg^{-1}); Mg (mg kg^{-1}); K(mg kg^{-1}); Na(mg kg^{-1}); B (mg kg^{-1}); Fe (mg kg^{-1}); Mn (mg kg^{-1}); Cu (mg kg^{-1}); Zn (mg kg^{-1}); Al (mg kg^{-1}).

Table 12: Spearman rank order correlations of measured chemical properties for soil samples in the West region.

	TEC	pH	OM	ENR	S	P	Ca	Mg	K	Na	B	Fe	Mn	Cu	Zn	Al
TEC	1															
pH	−0.900*	1														
OM	0.700	−0.600	1													
ENR	0.564	−0.410	0.975**	1												
S	0.580	−0.738	0.369	0.189	1											
P	0.051	−0.205	−0.616	−0.763	0.406	1										
Ca	0.500	−0.200	0.600	0.667	−0.369	−0.616	1									
Mg	0.872	−0.872	0.872	0.763	0.460	−0.289	0.564	1								
K	0.872	−0.975**	0.718	0.553	0.649	0.000	0.308	0.947*	1							
Na	0.718	−0.821	0.872	0.763	0.541	−0.342	0.359	0.947*	0.921*	1						
B	—	—	—	—	—	—	—	—	—	—	—					
Fe	−0.100	0.200	0.100	0.205	−0.791	−0.564	0.700	0.154	−0.051	0.051	—	1				
Mn	0.800	0.900*	−0.800	−0.667	−0.527	0.205	−0.400	−0.975**	−0.975**	−0.975**	—	−0.100	1			
Cu	0.800	−0.600	0.700	0.667	0.000	−0.359	0.900*	0.821	0.667	0.616	—	0.500	−0.700	1		
Zn	0.300	−0.100	0.800	0.872	0.211	−0.718	0.400	0.410	0.205	0.462	—	−0.100	−0.300	0.300	1	
Al	0.600	−0.700	0.900*	0.821	0.527	−0.462	0.300	0.872	0.821	0.975**	—	0.000	−0.900*	0.500	0.600	1

**Correlation is significant at the 0.01 level (2-tailed); *correlation is significant at the 0.05 level (2-tailed); total number of soil samples $n = 5$ (NB: most of B concentrations were below detection limit); OM (%); TEC (meq/100 g); ENR (lbs acre^{-1}); S (ppm); P (mg kg^{-1}); Ca (mg kg^{-1}); Mg (mg kg^{-1}); K (mg kg^{-1}); Na (mg kg^{-1}); B (mg kg^{-1}); Fe (mg kg^{-1}); Mn (mg kg^{-1}); Cu (mg kg^{-1}); Zn (mg kg^{-1}); Al (mg kg^{-1}).

nutrient antagonism and ensuring sufficient supply of each nutrient. Yet, this potential-induced limitation has been overlooked mostly by depending only on soil exchangeable K values to ascertain soil K status [33, 52, 54]. Since Mehlich-3 extraction solution was used in this study, a K–Mg threshold value of 0.7 described by Loide [55] and temporarily adopted by Laekemariam et al. [33] to demonstrate the potential Mg-induced K deficiency was used. The results showed that, with the exception of 6.25% of samples in the Adamawa region (K-Mg > 0.8), the soils in all the experimental sites were prone to Mg-induced K deficiency (Supplementary material: Tables 1S–5S). Intensive cropping, complete removal of crop residue, wide spread use of fertilizers materials which contain little or no Mg and K, or nonuse of mineral Mg and K fertilizer in soils of the study areas might have been the cause of this imbalance.

Osemwota et al. [56] showed that, under field conditions, exchangeable Ca–Mg ratios showed no significant effect on Mg availability, uptake, and maize grain yield in the Ca–Mg ratio between 1 and 8. Others have argued that if soil calcium and magnesium levels and soil pH are acceptable, variation in the Ca–Mg ratio between 2 and 8 has no influence on crop yield [57]. The Ca–Mg ratio revealed that all soil samples from the different AEZs were within this range.

3.2.5. Sulphur. Mehlich-3 extractable S in the study sites ranged from 1.0 to 11, <1.0 to 7.0, 4.0 to 23, <1.0 to 29, and 5.0 to 7.0 mg kg^{-1} for soils in the Far North, North, Centre, Adamawa, and West regions, respectively (Tables 2–6). The available S contents of samples in the Far North (98.39%), North (100%), Centre (66.67%), Adamawa (78.13%), and West (100%) regions were found to be very low. 1.61%, 22.22%, and 15.63% were found to be low for samples in the Far North, Centre, and Adamawa regions, whereas 11.11% and 6.25% of samples were medium for soils in the Centre and Adamawa regions, respectively [58]. S deficiency has not been reported and is overlooked in the study areas as is not part of the routine soil analysis in Cameroon.

3.2.6. Micronutrients. The Mehlich-3 extractable B ranged from less than 0.20 to 0.73, 0.80, 0.33, 0.71, and 0.43 mg kg^{-1} in the surface soils in the Far North, North, Centre, Adamawa, and West regions, respectively (Tables 2–6). The majority of the soil samples in the Far North (98.39%), North (95.65%), Centre (100%), Adamawa (96.88%), and West (100%) regions were under low B category (Table 7), whereas the remaining soil sample proportions: 1.61%, 4.35%, and 3.13% were qualified under moderate B level, respectively, for Far North, North, and Adamawa regions. Also, Mehlich-3 extractable Zn ranged from less than 0.40 to 3.46, 5.36, 2.63, and 1.31 mg kg^{-1} in the surface soils in Far North, North, Centre, and Adamawa regions, respectively, and from 0.42 to 0.74 mg kg^{-1} in soil samples in the West region (Tables 2–6). The majority of the soil samples in the Far North (91.49%), North (93.48%), Centre (94.44%), Adamawa (100%), and West (100%) regions were also low in Zn (Table 7). Just like S and B, Zn deficiencies have not been reported and are overlooked in the study areas and not part of the routine soil analysis. Mehlich-3 extractable Fe ranged from 54 to 177, 41 to 297, 35 to 197, 35 to 234, and 47 to 293 mg kg^{-1} for soil samples in the Far North, North, Centre, Adamawa, and West regions, respectively (Tables 2–6). Contrary to low level of Mehlich-3 extractable B and Zn in majority of the sampled soils, Fe was moderate for most of the soils in the Far North (96.77%), North (73.91%), and Centre (94.44%), while the other proportions were low. Nonetheless, 53.13% and 80% of the soils examined in the Adamawa and West regions were low in Fe, respectively, while the remaining percent is moderate (Table 7). Mehlich-

3 extractable Cu ranging from 0.41 to 2.83, 0.24 to 3.01, 1.06 to 2.37, 0.37 to 2.07, and 0.44 to 1.42 mg kg^{-1} (Tables 2–6) was low in 74.19%, 78.26%, 38.89%, 75%, and 100% in soil samples in the Far North, North, Centre, Adamawa, and West regions, respectively, while 25.81%, 21.74%, 61.11%, and 25% of soils from the Far North, North, Centre, and Adamawa were moderate (Table 7). Although Cu level was low in most of the sites (<2 mg kg^{-1}) (Supplementary material: Tables 1S–5S), this value is however recommended for cereal crops [59]. Accordingly, Mehlich-3 extractable Mn was found in the range of 29 to 191, 16 to 252, 1 to 234, 2 to 140, and 29 to 127 mg kg^{-1} in soils from the Far North, North, Centre, Adamawa, and West regions, respectively (Tables 2–6). 96.77%, 91.30%, 61.11%, 46.88%, and 80% of these values fall under medium range, while 3.23%, 4.35%, 16.67%, 53.13%, and 20% were low for the examined sites in the Far North, North, Centre, Adamawa, and West regions, respectively. Bitondo et al. [60] found out that, in an intensively Cultivated Typic Dystrandepts in Mount Bambouto in the West region of Cameroon, 53% and 8% of the soils examined were deficient in Cu and Zn, respectively, while Fe and Mn were inadequate supplies.

3.3. Soil Nutrient Adequacy for Maize, Sorghum, and Cassava Production. Maize is cultivated in all the agroecological zones of Cameroon and is regularly consumed by 12 million Cameroonians [61]. Cassava thrives across a wide range of agroecological zones (zones 2 and 5 in this study) with an annual production of 2.3 million tons [62], while sorghum is mostly cultivated in the Sudano-Sahelian zone (Far North and North regions) with an annual production of 100 thousand tons. In 2015, the government of Cameroon and her partners launched the Agriculture Investment and Market Development Project (aka PIDMA) aimed at boosting production of maize, cassava, and sorghum for local agroindustries. However, productions of these crops have remained low due to poor soil fertility and high fertilizer cost among other factors [63].

Despite the rating of plant nutrients in soil, various crops differ in their nutrient requirements. Each crop has its own specific macro- and micronutrients requirements for optimum growth and yield. In addition, the nutrient requirements and final nutrient contents of a particular crop can also vary depending on the cultivar. Nutrient requirements for a specific type of crop would be useful as a soil interpretation guide for fertilizer and amendment suggestions according to the growing area [64].

Critical level of a soil nutrient including other important soil chemical properties like pH is defined as the soil test value below which an increase in crop yield can be obtained with addition of the nutrient in question [65]. The nutrient is therefore considered adequate and will probably not limit crop growth. The Mehlich-3 soil test method has been considerably studied with different crops and calibrated with other soil test methods so that there is substantial information in literature [66].

Based on a literature review reported by Wendt [65], relating to the Mehlich-3 extractant, the following critical level of nutrients (Ca, 42 mg kg^{-1}; Mg, 64 mg kg^{-1}; Mg/Ca, > 0.067; K, 59 mg kg^{-1}; P, 17 mg kg^{-1}; Zn, 0.9 mg kg^{-1}; and Cu, 0.4 mg kg^{-1}) were adapted to interpret soil test values for maize production. These values were obtained by dividing the values reported by Wendt [65] with their mean soil density (1.18 g cm^{-3}) to convert from mg dm^{-3} to mg kg^{-1}. The pH range of 5.2–8.5 has been found to be adequate for maize production [67]. In this regard, about 96.77%, 86.96%, 22.22%, 21.88%, and 80% of soils in the Far North, North, Centre, Adamawa, and West regions were in the desirable range, respectively. However, the optimum pH range for maize is 5.8–7.8. The majority of soils in the Centre and Adamawa regions needs lime materials to raise soil pH to the adequate range for maize cultivation. The observed pH values in these two regions might be associated with removal of bases through crop harvest and leaching of base cations [53]. All of the fields sampled in the Far North had adequate soil Ca, Mg, Mg/Ca ratio, K, and Cu, while only 38.71% and 27.42% had sufficient P and Zn levels, respectively. All of the crop fields in the North region had sufficient Ca level and Mg/Ca ratio. 63.04%, 60.87%, and 89.13% had sufficient Mg, K, and Cu levels, respectively, while the majority of the soils were deficient in P (89.13%) and Zn (80.43%) for maize production. Moving to the Centre region, none of the field was deficient in Ca, Mg/Ca ratio, and Cu, and only 5.56% of the fields had insufficient Mg level for maize production. Contrary to the above nutrients, all of the sampled fields were severely deficient in P (100%), while 55.56% of the soils had K and Zn contents below the critical level for maize. The crop fields in the Adamawa regions had adequate Ca (100%), Mg/Ca ratio (100%), and Cu (96.88%). Almost half the sampled fields were deficient in Mg (43.75%) and K (40.62%), while almost all the fields were low in Zn (90.62%) and severely low in P (96.87%). All the crop fields in the West region had sufficient Ca, Mg/Ca ratio, and Cu but deficient in Mg, K, P, and Zn for the production of maize.

Howeler [68–70] reported approximate soil chemical characteristics according to the nutritional requirements for cassava. Ammonium acetate was used as extractant for soil exchangeable K, Ca, and Mg extraction. However, Wendt [65] showed that, on average, the Mehlich-3 method extracted almost identical amount of exchangeable Ca and Mg and slightly more K as the ammonium acetate method. These values were therefore adapted to interpret soil nutrients in this study. Mylavarapu et al. [71] evaluated Mehlich-1 and Mehlich-3 extraction procedures for plant nutrients in acid and near neutral soil pH range of Florida soils and showed that micronutrients had approximately equivalent extractability. The critical values of Howeler [70] for micronutrients were also adapted in this study, while the critical level of S was that reported for S critical level for cassava in Ethiopia [53]. P was analyzed by the Bray II method. Thus, the following range/level was rated as suitable for cassava production: P, > 4 mg kg^{-1}; K, 59–98 mg kg^{-1}; Ca, 200–1000 mg kg^{-1}; Mg, 48–120 mg kg^{-1}; S, 20 mg kg^{-1}; Zn, 1.0–5.0 mg kg^{-1}; Cu, 0.3–1.0 mg kg^{-1}; Fe, 10–100 mg kg^{-1}; and Mn, 10–100 mg kg^{-1}. Cassava tolerates wider soil pH range (4.5–8.2) with optimum pH ranging from 5.2 to 7.0 [66]. Majority of the pH values of soil samples from the

Centre (72.22%) and Adamawa (62.50%) regions (AEZs 2 and 5) within the adequate range (4.5–8.2) for cassava production. However, only 22.22 and 21.88% of the examined soil samples in the Centre and Adamawa regions were in the best pH range (5.2 to 7.0) for growing cassava, respectively. All the fields in the Centre region had adequate Ca, Mg, Cu, and Fe, while 83.33% had Mn above the suitable range for cassava. However, P (100%), K (55.56%), S (88.89%), and Zn (66.67%) were below the critical level for cassava production. In the Adamawa region, Cu and Fe were adequate in all of the soil samples. Ca, Mg, and Mn were sufficient in most of the study area, as 93.75%, 68.75%, and 75.00% of the soils had Ca, Mg, and Mn above their critical values or sufficient ranges, respectively, for cassava. Also, K sufficiency in the soils was just above average (56.25%), while majority of the soils were deficient in P (90.62%), S (93.75%), and Zn (93.75%) for cassava production. Laekemariam [53] found out that smallholder cassava farms in Southern Ethiopia were deficient amongst other soil nutrients in P, S, and Zn.

Kahsay et al. [72] and Amed and Jeb [73] reported the soil chemical properties suitability criteria for grain sorghum production where exchangeable cations (K, Ca, and Mg) were extracted by the ammonium acetate method such that 59–156 $mg\,kg^{-1}$ was used as suitable range for K; 800–2000 $mg\,kg^{-1}$ for Ca, and 60–600 $mg\,kg^{-1}$ for Mg. Soil critical available P determined by Mehlich-3 was 20 $mg\,kg^{-1}$ [74]. The critical limit for Zn, Cu, and Fe in sorghum soils is >0.3 or 0.8 mg DTPA–Zn kg^{-1} (for soils with pH <7 and pH >7, respectively), >0.2 mg DTPA–Cu kg^{-1}, and >4.00 mg DTPA–Fe kg^{-1}, respectively [75]. According to relationship between Mehlich-3 (M3) extractable nutrients and standard diethylenetriaminepentaacetic acid (DTPA) soil tests of University of Missouri (M3-Zn = 1.5 DTPA-Zn + 0.7, M3-Cu = 0.88 DTPA-Cu + 0.45, and M3-Fe = 2.3 DTPA-Fe + 97.2), the Mehlich-3 critical values >1.15 or 1.90 mg Zn kg^{-1} (for soils with pH <7 and pH >7, respectively); 0.63 mg Cu kg^{-1} and >107.60 mg Fe kg^{-1} were therefore calculated [76]. Just like maize, the adequate pH range for sorghum is 5.2–8.5 [67]. 93.55% and 82.61% of the examined soil samples in the Far North and North regions were in the adequate pH range and had 83.87% and 67.39% within the optimum range (5.5–8.2) for sorghum production, respectively. All soil samples in the Far North region had K and Mg above the critical value, and most of the soils Ca (90.32%) and Cu (91.94%) were also above the critical value for sorghum production. Nonetheless, 67.74%, 79.03%, and 64.52% of soil samples were deficient in P, Zn, and Fe, respectively, for sorghum production. For the North region, majority of the soils were sufficient in K (60.87%), Mg (69.57%), and Cu (63.04%) while deficient in P (93.48%), Ca (65.22%), Zn (89.13%), and Fe (60.87%) (all percentages were calculated from Tables 1S–5S of the supplementary material).

Generally, the soils in all the AEZs were consistently low in P, S, B, and Zn for maize, sorghum, and cassava production systems. In addition, P and Zn are mutually antagonistic in certain circumstances and can cause yield reductions in many crops due to either P or Zn deficiency. In most cases, the P-induced Zn deficiency is due to application of P fertilizer at high dose to the soils that are low or marginal in available Zn [77].

3.4. Comparison of Some Soil Chemical Properties. Kruskal–Wallis and Mann–Whitney *U* tests were conducted to compare the variation and median of soil properties between regions in the selected agroecological zones. Kruskal–Wallis test revealed that most of the analyzed soil parameters significantly differed between the study areas ($P < 0.005$). Mann–Whitney *U* test showed significant variation ($P < 0.005$) in most of the soil properties across the regions (Figure 2). The variation in soil properties across the regions might be due to differences in altitude, precipitation, properties of the dominant soils, and land use [28]. The exchangeable bases (Ca, Mg, K, and Na), pH, and TEC were significantly higher for the Far North region as compared to the other regions. This could be due to the presence of high 2 : 1 smectite clay content of the studied *Vertisols* in this region [28, 29]. The median values of H and Al were significantly higher for soils in Adamawa and the Centre regions as compared to Far North, North, and West regions (Figure 2). The pH is a measure of H^+ concentration in soils; the more acidic the soil, the lesser the bases (Ca, Mg, K, and Na) [8]. It has been suggested that the proportions of the basic cations of the effective cation exchange capacity are more relevant to plant performance than the actual levels in soil [52, 78].

3.5. Correlation Relationships. The results of Spearman's correlation analyses carried out to determine relationships between soil chemical properties in the sampling areas are shown in Tables 8–12. Most of the soil chemical properties of samples in the Far North, North, and Adamawa regions were significantly correlated with each other (Tables 8, 9, and 11) as compared to samples in Centre and West regions (Tables 10 and 12). For example, TEC, Ca, Mg, ENR, OM, and Cu had very strong positive significant correlations ($0.80 \leq r \leq 1.0$) in soil samples in the Far North region (Table 8) and strong ($6.0 \leq r \leq 7.9$) to very strong significant positive correlation for samples in the North region (Table 9). These correlations show the role that OM plays in retention of these base cations and in CEC for soils in these regions. Soil OM did not correlate with TEC for soils in Centre, Adamawa, and West regions. OM is often considered as the most important soil property due to its essential effect on other soil properties, especially CEC, sum of base cations, and nutrient content [79]. A strong positive correlation was also observed between TEC and (Ca and Mg) for samples in the Adamawa region (Table 11). Other noticeable correlation is the moderate negative correlations between pH and Al for soils in the Adamawa region which might be as a result of the extreme to very strong acid pH range of soils in these areas. Hamilton et al. [80] found negative correlation between soil pH and Al saturation on tropical acidic soils in Brazil. Apart from the dependence of Al on pH, other authors have obtained negative correlation between pH and Mn [81, 82]. Contrary to the findings above,

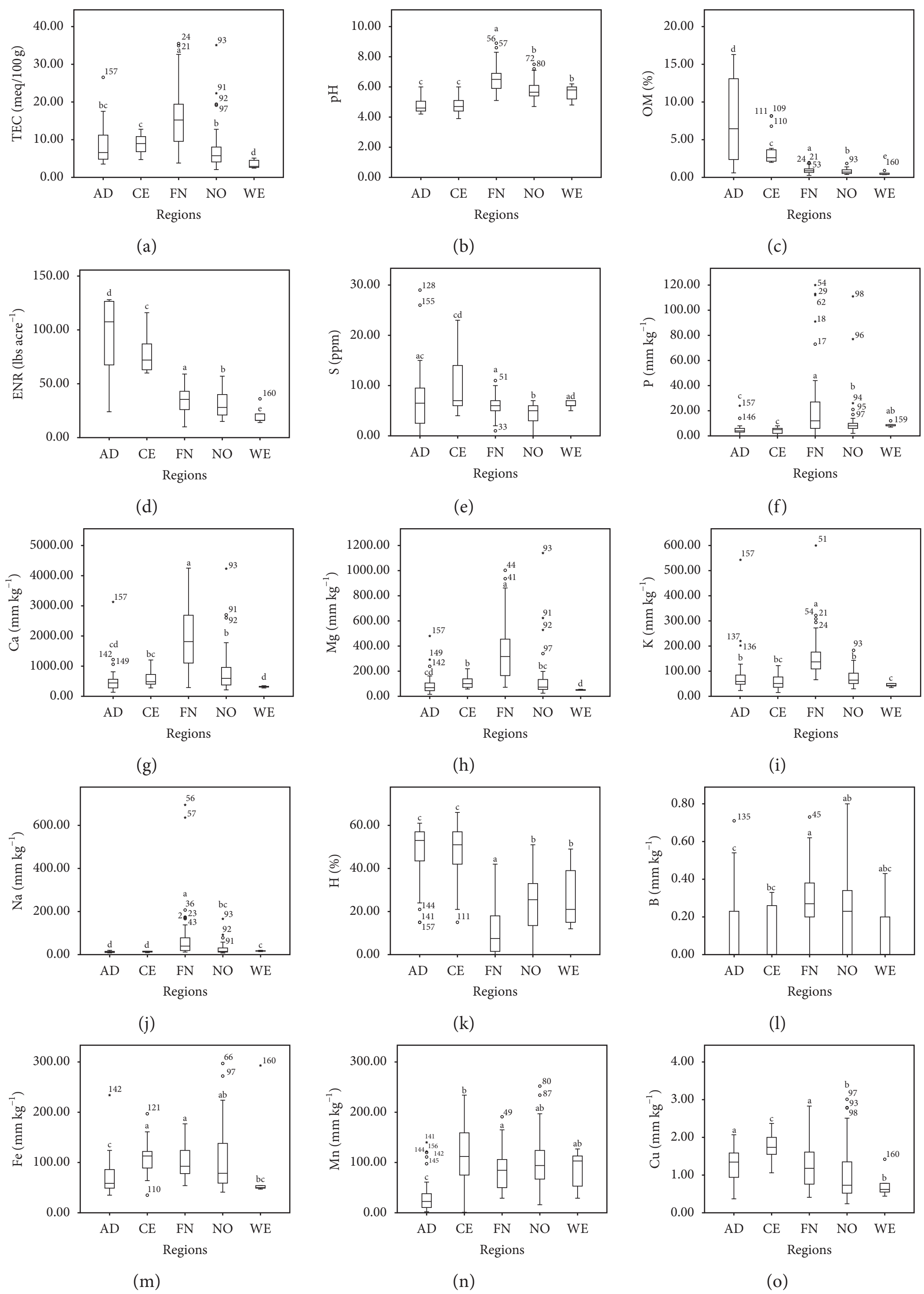

Figure 2: Continued.

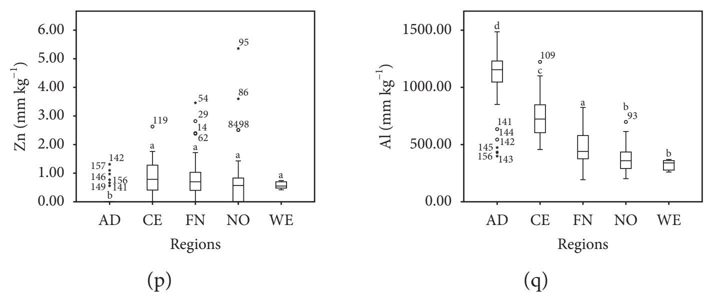

Figure 2: Box plots comparing soil chemical properties in 5 regions. Kruskal–Wallis and Mann–Whitney *U* tests were applied. Groups with no significant difference are marked by the same letter. AD, Adamawa region; CE, Centre region; FN, Far North region; NO, North region; WE, West region. (a) TEC (meq/100 g); (b) pH; (c) OM (%); (d) ENR (lbs acre^{-1}); (e) S (mm kg^{-1}); (f) P (mm kg^{-1}); (g) Ca (mm kg^{-1}); (h) Mg (mm kg^{-1}); (i) K (mm kg^{-1}); (j) Na (mm kg^{-1}); (k) H (%); (l) B (mm kg^{-1}); (m) Fe (mm kg^{-1}); (n) Mn (mm kg^{-1}); (o) Cu (mm kg^{-1}); (p) Zn (mm kg^{-1}); (q) Al (mm kg^{-1}).

a significant positive correlation between pH and Mn was obtained for soils in Far North, North, Adamawa, and West regions (Tables 8, 9, 11, and 12).

3.6. Soil Fertility Management Implications of the Soil Properties. Low soil available P, S, B, and Zn were identified as major limiting factors in all the study areas. In addition, most of the soils were prone to Mg-induced K deficiency, and soil pH values in some areas were strongly acidic. Therefore, soil management interventions such as incorporation of organic residues like farmyard manure and plant residues and lime (in acid soils) are recommended for maize in all the AEZs, cassava in the Centre and Adamawa regions, and sorghum in the North and Far North regions. For sustainable crop production, there is also need for guided inorganic fertilizers with S, B, and Zn as an integral part of recommended blended or compound (NPK) fertilizers.

4. Conclusion

This study revealed considerable soil nutrients variability within regions and across different AEZs of Cameroon. The soils in all the regions were consistently deficient in multiple soil nutrients (P, S, B, and Zn) and might be inadequate to supply cultivated maize, sorghum, and cassava with the nutrients needed to achieve optimal growth. Most of the soil samples were acidic with the Centre and Adamawa regions having extremely to very strongly acidic soils. These results suggested that management of soil nutrients and pH should be based on cropping system, and other land-use and site-specific information for appropriate resource management and restoration of soil properties over these heterogeneous landscapes. Thus, it is recommended that analysis of sulphur and micronutrients is included in local routine soil analysis and that the results of the soil tests are calibrated against crop responses from applications of plant nutrients so as to establish fertilizer recommendations for the different farming systems which will favour buildup of soil organic matter. The study however has been limited by a small number of soil samples from different regions, and therefore, a large number of samples are required for future work.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The authors received no specific funding for this work.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was carried out with financial support from PIDMA. The authors are grateful to Marcien Kuété and Kamdem Gabriel for the topographic map of Cameroon carrying the field data. The authors are also thankful to the Brookside Laboratories INC, New Bremen, USA, for carrying out the soil chemical analyses.

Supplementary Materials

Table 1S: soil properties and GPS points of soil samples in the Far North region. Table 2S: soil properties and GPS points of soil samples in the North region. Table 3S: soil properties and GPS points of soil samples in the Centre region. Table 4S: soil properties and GPS points of soil samples in the Adamawa region. Table 5S: soil properties and GPS points of soil samples in the West region. (*Supplementary Materials*)

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