Water Practice & Technology

IWA PUBLISHING

Water Practice & Technology Vol 19 No 3, 761 doi: 10.2166/wpt.2024.035

Seasonal quality and statistical assessment of physicochemical properties and base saturation of Hadejia-Nguru wetland soils, Northwest/Eastern Nigeria

Sa'adatu Eri Mohammed[a], Deborah Olubunmi Aderibigbe[b], Muhammad Dayyab Saeed[c], Simphiwe Maurice Nelana[d], Ahmadu Musa[a] and Olushola Sunday Ayanda[e,*]

[a] Department of Chemistry, Federal University Dutse, PMB 7156, Dutse, Jigawa State, Nigeria
[b] School of Basic Sciences, Nigeria Maritime University, Okerenkoko, Delta State, Nigeria
[c] Department of Pure and Industrial Chemistry, Bayero University, Kano, Nigeria
[d] Department of Chemistry, Vaal University of Technology, Vanderbijlpark 1900, South Africa
[e] Department of Chemistry, Federal University Oye-Ekiti, P.M.B 373, Oye-Ekiti, Ekiti State, Nigeria
*Corresponding author. E-mail: olushola.ayanda@fuoye.edu.ng

ABSTRACT

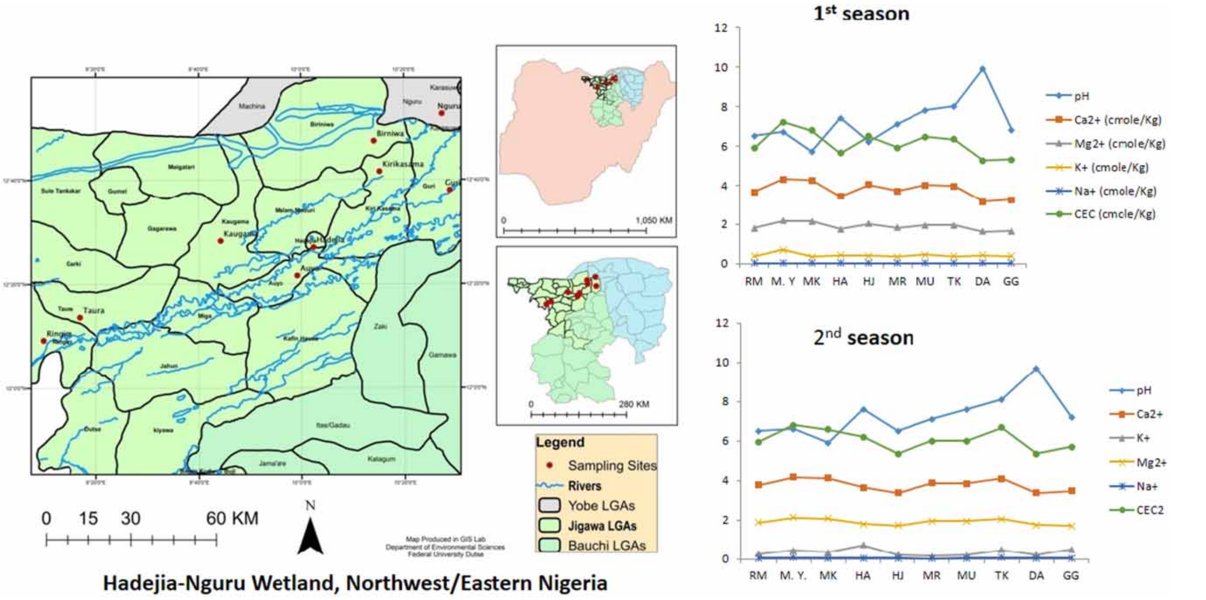
The evaluation of Hadejia-Nguru wetland soils was carried out for two consecutive dry seasons. Standard analytical techniques were adopted to analyze the samples and statistical models were used to assess the spatial and temporal distribution of the parameters selected. The average pH values of the soil samples were mostly alkaline, and all the measured values were also within the approved standards. Experimental results revealed a significantly positive correlation between Ca and Mg for both seasons as indicated by the *p*-values and a high coefficient of determination (R^2) for both metals with cation exchange capacity (CEC) values as the predictors. The regression analysis showed that the changes in CEC and pH levels in the soil were dependent on changes in Ca and Mg content of the soil. The data obtained showed that the increase in pH is directly proportional to the CEC and base saturation of the soils. A higher percentage of Ca than other cations (Mg, K and Na) was observed from the base saturation of the soils. The pH, base saturation, and CEC levels in the soils are suitable for most crops grown in the area, which has the potential to support a wide range of crops with further exploration.

Key words: base saturation, physicochemical properties, spatial and temporal distribution, statistical analysis, wetland soils

HIGHLIGHTS

- The physicochemical characteristics of Hadejia-Nguru wetlands soils were investigated.
- Statistical models were used to assess the spatial and temporal distribution of the parameters.
- Metals play a crucial role in determining the soil quality.
- Investigations indicated that the study area is suitable for the farming of vegetables and cereal crops.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Wetland soils are formed when an area is periodically or continuously flooded, leading to the saturation of the soil. The waterlogged soil creates anaerobic (lacking oxygen) conditions that limit the decomposition of organic matter. The buildup of this organic matter contributes to the formation of the soil in wetland areas. Wetlands are of ecological and geological importance because of the global effect on greenhouse gases and climate change (Akpan *et al.* 2017; Sui *et al.* 2021). Agricultural use of wetlands has significantly increased in many developing countries (Silvius *et al.* 2000) particularly Nigeria and other African countries. This may have been necessitated by increasing population, economic and financial motivation, food insecurity reasons and climate change effects such as flood, irregular rain pattern (Atta-Darkwa *et al.* 2020). The majority of environmental degradation is caused by human activities such as rapid urbanization, industrialization, population explosion, agricultural waste, and anthropogenic activity in and around ponds (Gilbert *et al.* 2019; Osinuga & Oyegoke 2019). Wetlands, which provide habitat for aquatic life and are becoming increasingly important in irrigated agriculture, are a result of these activities. To evaluate the ability of this type of soil to retain water for aquatic flora and fauna, and to provide various nutrients for biological production, important soil constituents such as pH, exchangeable bases, and cation exchange capacity (CEC) are analyzed. Examining specific aspects of water, soils, and biota as well as aspects of hydrology, biogeochemical cycling, habitat, and food webs can help identify wetlands from uplands and other ecosystems (Sui *et al.* 2021). Soil comprises of various minerals, organic matter, and fragmented rocks that have undergone environmental transformations. These natural components also serve as a vital sink for numerous pollutants and toxins. However, the introduction of pollutants and contaminants can cause significant changes in the physicochemical properties of wetland soils and these are important indicators of soil fertility and nutrient availability. The physicochemical properties of wetland soils play a crucial role in regulating the ecological functions of wetlands, whereas, base saturation is an important indicator of soil fertility and nutrient availability.

In recent years, there has been growing interest in studying the seasonal quality regarding the physicochemical properties and base saturation of wetland soils, but it was keenly noted that most of these studies were carried out between wet and dry seasons which has made this study unique since it was carried out between two dry seasons. This is because wetlands store soil moisture for long periods, thus providing residual moisture for crop growth during the dry season, when no rain-fed crops can be grown in upland fields (Scoones 1991; Alibu *et al.* 2019). Barbosa *et al.* (2019) studied the spatial variability of the physicochemical properties of soils from seasonally flooded forest fragments on a tropical plain. The study revealed that anoxic conditions during flooding promote chemical reactions characteristic of anaerobic environments, modifying the pH and soil organic matter (SOM) in addition to the gleying of soils subjected to flooding, which are then covered by sediments after the dry season. The authors concluded that, Ipucas (wetlands) soils are susceptible to anthropic changes and are dependent on seasonal flood pulses and that pH and CEC varied at different depths of the wetland soil. Similarly, in a study by Hu *et al.* (2021), the soil physicochemical properties and distribution characteristics of heavy metals under various planting patterns in the mangrove restoration wetland in Jinjiang, Fujian Province were investigated. The study revealed that the SOM, total nitrogen (TN), and total phosphorus (TP) in the low-density area were higher than those in the high-density area. Moreover, the trend in average concentrations of heavy metals was as follows: Zn > V > Pb > Cr > Cu > Ni > As > Co > Cd. Overall, the authors opined that the results obtained could help in choosing feasible restoration methods for wetland restoration. Hailegnaw *et al.* (2019) evaluated the mutual relationships of biochar and soil pH, CEC, and exchangeable base cations in a model laboratory experiment. They revealed that the application of biochar significantly increased pH but both increased and decreased CEC at a percentage depending on the levels of exchangeable calcium in the soil as observed in soils with lower and higher Ca^{2+}, respectively. The authors concluded that the original values of pH, CEC and exchangeable Ca^{2+} played great roles for determining the levels of these physicochemical parameters in the soil. Another study by Cui *et al.* (2022) observed seasonal variations in the physicochemical properties and base saturation of wetland soils in the Yellow River Delta, China. The study found that the SOM, TN, and TP were significantly higher in the wet season than in the dry season. The base saturation also increased during the wet season. The study concluded that the wet season is the critical period for nutrient accumulation and retention in wetland soils.

In contrast, Li *et al.* (2020) as part of their research investigated the effects and relative influence of soil physical (clay and silt) and chemical (pH and iron) properties on soil organic carbon content and nutrient availability (i.e. nitrogen, phosphorus, and potassium). They found that more than climate, soil physicochemical properties primarily predicted the continent-scale soil organic carbon storage and nutrient availability. They concluded that the importance of physicochemical properties was evident across soil depths and ecosystem types (i.e. tropical, temperate, arid, and cropland). Wu *et al.* (2019) conducted a study on the differences in soil properties between the dry season and rainy season in the Mun River Basin. Findings of their study revealed that the overall soil condition of the basin was poor, and the soil quality in the rainy season was more uniform than in the dry season. The soil quality in forests and dry fields was higher than in other land use types, while the soil conditions in most paddy fields were not ideal. In general, the results were helpful for soil improvement and for increasing the grain production in the Mun River Basin. Yirgu *et al.* (2020) conducted an agro-ecological assessment of the physicochemical properties of soils in Kulfo Watershed, South Western Ethiopia, and found that the watershed was dominated by low TN, very low available phosphorus, high potassium, and low CEC. They concluded that wetland soils play a critical role in regulating the ecological functions of wetlands, and their physicochemical properties, including base saturation, pH, SOM, and nutrient availability are important indicators of soil fertility and health.

Several studies have shown that wetland soils exhibit seasonal variations in their physicochemical properties and base saturation, with the wet season generally being the optimal period for nutrient accumulation and retention. Moreover, anthropogenic activities, such as conversion of natural forest or savannah to farmland, can degrade the soil and reduce its fertility over time. Therefore, proper measures, such as soil and water conservation, use of organic manure, and supplementation of phosphorus and exchangeable potassium, are necessary for rehabilitating soil productivity and sustaining wetland ecosystems. A study by Tolimir *et al.* (2020) found that the conversion of natural forest or savannah to farmland reduces the silt contents, moisture content, SOM, organic carbon, TN, available phosphorus, pH, CEC and exchangeable bases, but increases bulk density, electrical conductivity, exchangeable acidity and sand content significantly. They concluded that the conversion of forestland into farmland without proper measures degrades the soil with time. Umeri *et al.* (2017) evaluated the physical and chemical properties of some selected soils in mangrove swamp zones of Delta State, Nigeria. The authors discovered that the soils generally had low pH, and potassium in the soils, but adequate CEC, Mg, Ca, Zn, Cu, and Mn. They concluded that the soils will support arable crop production and also recommended that phosphorus and exchangeable potassium be artificially supplemented to enhance the nutrients in the soil.

The review of literature have indicated the implications for wetland management and restoration and have also highlighted the importance of understanding the seasonal quality and statistical assessment of physicochemical properties and base saturation of wetland soils, and the need for sustainable management practices to maintain soil fertility and support ecosystem services. Therefore, the physicochemical quality of soil from 10 wetlands is carried out in this study, owing to the increasing importance of the selected wetlands to the economy of the communities around them. These communities feed and commercialize their produce throughout Nigeria and such activities should be strengthened when research data on the quality of the wetlands used as a major source of irrigation for agricultural practices are studied for recognition internationally. It is commonly recognized that wetlands supply residual moisture needed for crop development in the dry season, hence, the time selected for the study was made within two consecutive dry seasons.

2. MATERIALS AND METHODS

2.1. Study area

The Hadejia-Nguru wetlands are an expansive and unique wetland complex located in North Eastern, Nigeria. The wetlands are situated between 12.6877° N and 10.5767° E, the wetlands span 3,500 km^2 and are comprised of a network of permanent lakes, seasonally flooded pools, and rivers – notably the Hadejia-Jama'are, which drain into Lake Chad (Figure 1). Covering just 2.6% of Nigeria's land area of 923,768 km^2, these wetlands are an important part of the Sahel savannah and offer a wealth of opportunity for research and conservation efforts.

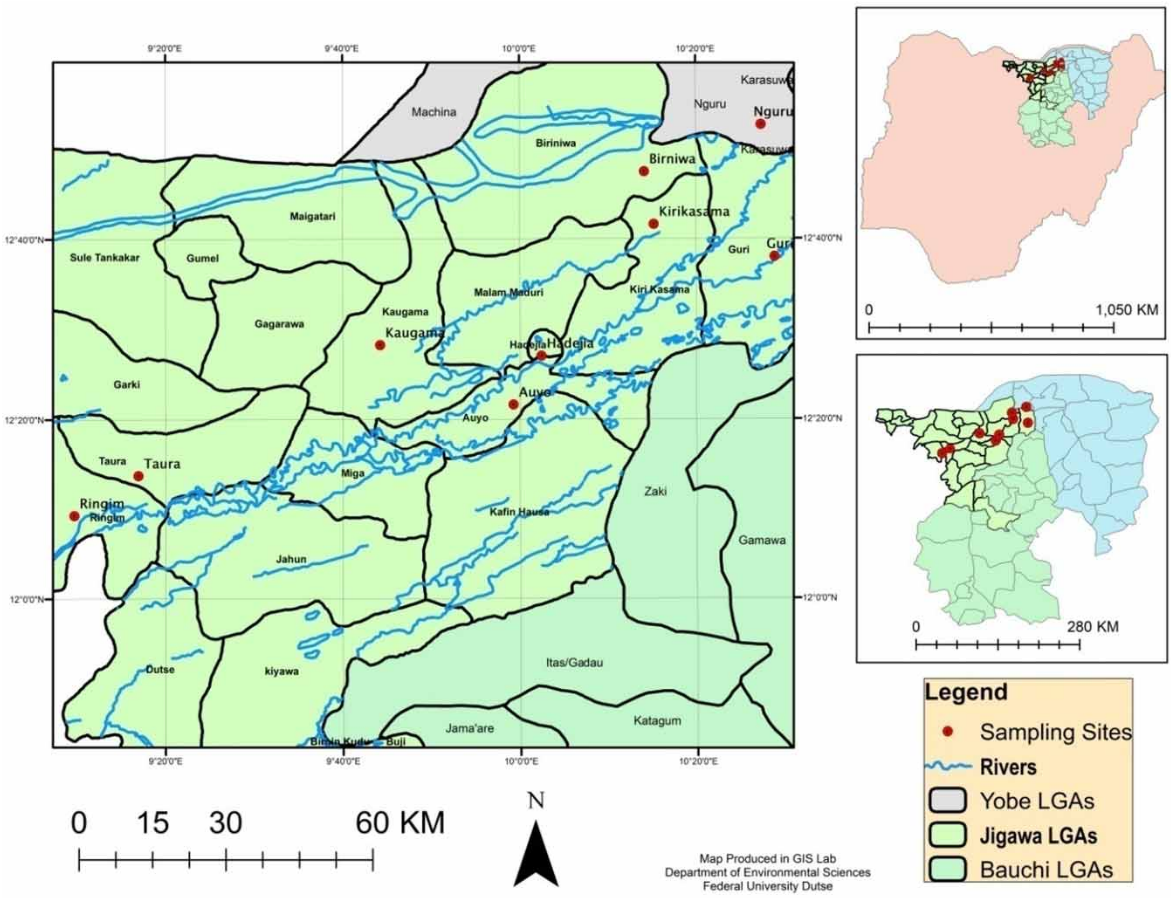


Figure 1 | Map showing the local government areas, rivers, and sampling sites.

2.2. Soil sampling and treatment

The soil samples were collected in May of each year (dry season) for two consecutive years from 10 sampling locations labeled RM, MY, MK, HA, HJ, MK, MU, DA, and GG. The sampling sites are wetlands situated progressively along the same axis in the Northwest/Eastern Nigeria. Two of the sampling sites were located within Ringim Local Government Area (sites RM and MY).

Around 1.0 kg of soil sample was collected from four sections of a sampling location with an auger sampler at a depth of 0–15 cm. A total of 30 samples were collected from 10 sampling sites for analysis. The soils were air dried under laboratory conditions to reach a constant weight by spreading into thin layers, ground, sieved to remove larger aggregates using a 0.5-mm polyethylene sieve, properly labeled, and stored in clean, airtight polyethylene containers (Nounamo *et al.* 2002; Tan 2010).

2.3. Physicochemical analysis of soil

2.3.1. Determination of soil pH

Air-dried soil sample (50 g, < 0.5 mm) was weighed into a 100-mL glass beaker. Double distilled water (50 mL) was added using a graduated cylinder. The mixture was thoroughly mixed with a glass rod and allowed to stand for 30 min while stirring at intervals of 10 min. The pH was determined after 1 h by inserting the electrode in the suspension (3 cm deep). Reading was taken to one decimal place after 30 s to allow for stability. The combined electrode was removed from the suspension, rinsed thoroughly with distilled water, and carefully dried with a paper towel (Estefan *et al.* 2013).

2.3.2. Determination of exchangeable cations/CEC

Dried soil sample (25.0 g) was weighed and added to a 500-mL Erlenmeyer flask followed by the addition of 125 mL of ammonium acetate (NH_4OAc) and the mixture was thoroughly shaken and allowed to stand for 16 h. The mixture was filtered and the soil was gently washed four times with 25-mL portions of NH_4OAc. The leachate was filtered into a volumetric flask (250 mL) and diluted to the mark with double distilled water in preparation for analysis of exchangeable Ca, Mg, and Na ions by flame atomic absorption spectrometry, and exchangeable K ion by flame emission spectrometry (Ross & Ketterings 1995).

2.3.3. Statistical analysis

Hypothesis:

H_0 = There is no difference in the group mean values of the heavy metals

Ha = There is difference in the group mean values of the heavy metals

All experimental data were recorded in triplicates. Descriptive statistics carried out on the data include mean, standard deviation, and coefficient of variation to determine the variability and degree of dispersion in the data. The normality of the data was also confirmed by the Shapiro-Wilk test at $p > 0.05$. Charts were used to pictorially depict the relationship and variation which exists among the parameters. Pearson's correlation coefficient was used as an indicator to evaluate the statistical relationship among pH, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and CEC. The significance of the correlation was computed and determined when the analysis was run. Analysis of variance (ANOVA) was used to determine the variability among the group mean values, regression helped to establish the effect of changes in the cations on the CEC. Statistical analysis was done using the statistical software Max-Stat lite Version 3.60 2015 and SPSS 16.0 for windows.

2.3.4. Base saturation of the soil

Base saturation shows the percentage of each exchangeable cation relative to the total amount of the CEC as they exist in any given soil. A base saturation of 80% calcium shows good quality of soil as it allows smooth adsorption of nutrients such as Mg, Na, K by the soil. If the base saturation is too low or high, some trace minerals such as manganese and iron may not be easily adsorbed. Base saturation was calculated by dividing the individual CEC values by the total CEC for each type of cation and across all the study areas.

3. RESULTS AND DISCUSSION

3.1. Mean and descriptive statistics of the measured values

The mean values of the physicochemical parameters of the soils measured in this study for the two consecutive dry seasons are displayed in Tables 1 and 2. Tables 3–6 show the descriptive statistics of the measured values for the first and second dry seasons, respectively.

3.2. ANOVA, Pearson's correlation coefficient, regression, and base saturation of the soils

ANOVA results (Tables 7 and 8) for the first and second seasons showed considerable variability in group mean values. This was evident in the *p*-values obtained, $p = <0.0001$ at 95% confidence interval which implied that the analyzed samples are from different locations. The Pearson correlation matrices (Tables 9 and 10) displayed the relationship among the different cations to pH and CEC. The results showed that there was a high correlation between Ca, Mg, and CEC but moderately negative to pH. A strong positive correlation was observed between pH and K and low correlation with Na and CEC. The negative correlation suggested that the concentration of

Table 1 | Mean values of physicochemical parameters in the soils (first season)

Sample ID	pH	Ca^{2+} ($cmol_c$/kg)	Mg^{2+} ($cmol_c$/kg)	K^+ ($cmol_c$/kg)	Na^+ ($cmol_c$/kg)	CEC ($cmol_c$/kg)
RM	6.5	3.667	1.802	0.376	0.031	5.876
MY	6.7	4.308	2.183	0.692	0.024	7.207
MK	5.7	4.256	2.158	0.356	0.026	6.796
HA	7.4	3.436	1.752	0.433	0.023	5.644
HJ	6.2	4.026	2.019	0.41	0.021	6.476
MR	7.1	3.718	1.817	0.345	0.029	5.909
MU	7.8	4	1.965	0.462	0.025	6.452
TK	8.0	3.949	1.956	0.385	0.033	6.323
DA	9.9	3.154	1.64	0.43	0.028	5.252
GG	6.8	3.256	1.662	0.379	0.022	5.319

Table 2 | Mean values of physicochemical parameters in the soils (second season)

Sample ID	pH	Ca^{2+} ($cmol_c$/kg)	K^+ ($cmol_c$/kg)	Mg^{2+} ($cmol_c$/kg)	Na^+ ($cmol_c$/kg)	CEC 2 ($cmol_c$/kg)	CEC 1 ($cmol_c$/kg)
RM	6.5	3.769	0.259	1.877	0.033	5.938	5.876
MY	6.6	4.179	0.444	2.108	0.067	6.798	7.207
MK	5.9	4.128	0.350	2.073	0.030	6.581	6.796
HA	7.6	3.641	0.718	1.779	0.043	6.181	5.644
HJ	6.5	3.359	0.211	1.725	0.042	5.337	6.476
MR	7.1	3.872	0.145	1.946	0.024	5.987	5.909
MU	7.6	3.846	0.177	1.937	0.026	5.986	6.452
TK	8.1	4.103	0.467	2.042	0.069	6.681	6.323
DA	9.7	3.359	0.202	1.740	0.040	5.341	5.252
GG	7.2	3.462	0.493	1.690	0.048	5.693	5.319

Table 3 | Descriptive statistics of the first season

	pH	Ca^{2+} ($cmol_c$/kg)	Mg^{2+} ($cmol_c$/kg)	K^+ ($cmol_c$/kg)	Na^+ ($cmol_c$/kg)	CEC ($cmol_c$/kg)
Mean	7.210	3.777	1.895	0.427	0.0026	6.125
Error	0.373	0.127	0.061	0.032	0.001	0.201
Std. dev	1.178	0.401	0.192	0.100	0.004	0.636
Min	5.70	3.154	1.640	0.345	0.021	5.252
Max	9.900	4.308	2.183	0.692	0.033	7.207
sum	72.100	37.770	18.954	4.268	0.262	61.254
CV (%)	16.338	10.606	10.112	23.458	15.139	10.385
Skewness	1.286	−0.288	0.212	2.418	0.429	0.075

Ca and Mg increased when pH decreases and vice versa. Almost all the cations showed strong correlation with CEC. The results are in agreement with most studies including but not limited to Umeri *et al.* (2017) but disagrees with Yirgu *et al.* (2020). The observed variations aligned with the findings of Wu *et al.* (2019).

The results of regression analysis also showed strong coefficient of determination (R^2) when Ca and Mg were made the dependent variables. This implied that the overall changes in the model were significantly affected by changes in Ca and Mg cations. This effect increased when compared with CEC added as a predictor which gave higher result with both seasons' CEC among the predictors in the assessment of the second season results. The observed trend corroborates earlier findings of strong correlation among Ca, Mg and CEC (Tables 11–14).

Table 4 | Descriptive statistics of the second season

	pH	Ca^{2+} (cmol$_c$/kg)	Mg^{2+} (cmol$_c$/kg)	K^+ (cmol$_c$/kg)	Na^+ (cmol$_c$/kg)	CEC (cmol$_c$/kg)
Mean	7.280	3.772	0.347	1.892	0.042	6.052
Error	0.339	0.098	0.058	0.048	0.005	0.164
Std. dev	1.073	0.311	0.182	0.530	0.016	0.518
Min	5.900	3.359	0.145	1.690	0.024	5.337
Max	9.700	4.179	0.718	2.108	0.068	6.798
Sum	72.800	37.718	3.466	18,917	0.422	60.523
CV (%)	14.735	8.252	58.653	8.107	37.046	8.560
Skewness	1.226	−0.102	0.863	0.076	0.793	0.039

Table 5 | Anderson Darling and Shapiro-Wilk tests (first season)

	pH	Ca	Mg	K	Na	CEC
Anderson Darling test *p*-value > 0.05	0.8138	0.9455	0.9429	0.2353	0.9814	0.9803
Pass normality	Yes					
Shapiro-Wilk test *p*-value > 0.05	0.4823	0.6132	0.5955	<0.0001	0.6909	0.7048
Pass normality	Yes	Yes	Yes	No	Yes	Yes

Table 6 | Anderson Darling and Shapiro-Wilk tests (second season)

	pH	Ca	Mg	K	Na	CEC
Anderson Darling test p-value > 0.05	0.7782	0.8716	0.7848	0.8739	0.7600	0.9012
Pass normality	Yes	Yes	Yes	Yes	Yes	Yes
Shapiro-Wilk test p-value > 0.05	0.4643	0.4795	0.4589	0.5198	0.4222	0.5524
Pass normality	Yes	Yes	Yes	Yes	Yes	Yes

Table 7 | Analysis of variance for the physicochemical parameters of the soil samples (first season)

Source of variation	Sum of Square	Number of groups	df	Mean Square	F	F critical	*p*-Value
Between groups	344.586	5	4	86.147	270.069	2.579	0.0001
Within groups	14.354		45	0.319			
Total	358.940		49				
Bartlett test			3				0.0001

Table 8 | Analysis of variance for the physicochemical parameters of the soil samples (second season)

Source of variation	Sum of Square	Number of groups	df	Mean Square	F	F,critical	*p*-Value
Between groups	449.285	6	5	89.857	338.947	2.579	0.0001
Within groups	14.157		54	0.262			
Total	463.443		59				
Bartlett test							0.0001

Table 9 | Pearson's product moment correlation matrix for the physicochemical parameters of the soil samples (first season)

	pH	Ca	Mg	K	Na	CEC
pH		−0.5700	−0.5525	0.0479	0.3229	−0.5158
Ca	0.0854		0.9837	0.3729	−0.0134	0.9847
Mg	0.0977	<0.0001		0.4408	−0.1005	0.9895
K	0.8955	0.2886	0.2023		−0.3063	0.5231
Na	0.3628	0.9706	0.782	0.3895		−0.807
CEC	0.1270	<0.0001	<0.0001	0.1208	0.8246	

Table 10 | Pearson's product moment correlation matrix for the physicochemical parameters of the soil samples (second season)

	pH	Ca	K	Mg	Na	CEC
pH		−0.3937	−0.0334	−0.3478	0.1447	−0.3469
Ca	0.2603		0.1368	0.9776	0.2448	0.9457
K	0.9270	0.7062		−0.0175	0.5575	0.4461
Mg	0.3248	<0.0001	0.9617		0.2179	0.8837
Na	0.6900	0.4955	0.0941	0.5454		0.4381
CEC	0.3261	<0.0001	0.1963	0.0007	0.2054	

Table 11 | Regression analysis for physicochemical parameters of the soil samples with calcium as the response variable (first season)

Variable	Coefficient	*t*-Value	*p*-Value
(Constant)	0.490	−.212	.841
pH	.025	−.662	.537
Mg	.195	10.448	.000
K	.340	−.310	.769
Na	6.930	.988	.369
R^2	0.979		
Adjusted R^2	0.962		
$F(5,45)$	270.069		

Predictors: Constant variable: K, pH, Mg, Na.
Dependent variable: Ca.

Table 12 | Regression analysis for physicochemical parameters of the soil samples with calcium as the response variable (second season)

Variable	Coefficient	*t*-Value	*p*-Value
(Constant)		.000	1.000
pH	.000	.000	1.000
K	−.586	−1.097E7	.000
Mg	−.493	−4.934E6	.000
Na	−.050	−4.565E6	.000
CEC2	1.665	1.486E7	.000
R^2	0.985		
$F(5,54)$	338.947		

Predictors: Constant variable: K, pH, Mg, Na, CEC2.
Dependent variable: Ca.

Table 13 | Regression analysis for physicochemical parameters of the soil samples with magnesium as the response variable (first season)

Variable	Coefficient	*t*-Value	*p*-Value
(Constant)	0.139	.609	.569
pH	.030	.341	.747
K	.049	.591	.580
Na	−.068	−.982	.371
Ca	.981	10.448	.000
R^2	0.979		
Adjusted R^2	0.962		
$F(4, 5)$	57.747		

Predictors: Constant variable: Ca, K, pH, Na.
Dependent variable: Mg.

Table 14 | Regression analysis for physicochemical parameters of the soil samples with magnesium as the response variable (second season)

Variable	Coefficient	*t*-Value	*p*-Value
(Constant)	0.000	–	–
pH	0.000	–	–
Ca	−2.030	–	–
K	−0.190	–	–
Na	−0.102	–	
CEC2	3.379	–	–
CEC1	0.000	–	
R^2	1.000		
Adjusted R^2	1.000		
$F(5,54)$	338.947		

Predictors: Constant variable: Ca, K, pH, Na, CEC1, CEC2.
Dependent variable: Mg.

The base saturation results also showed how much Ca and Mg were in the soils which were observed to be high in the current study (Tables 15 and 16). The trend observed was Ca > Mg > K > Na for both seasons, though values were slightly higher in the first season than the second, which may be related to fluctuations in pH between the seasons. The high percentage of base saturation agrees with the findings of Cui *et al.* (2022) even though this study focuses on the dry season. Yirgu *et al.* (2020) also posited that wetland soils play a critical role in regulating the ecological functions of wetlands, and their physicochemical properties, including base saturation, pH, SOM, and nutrient availability, are important indicators of soil fertility and health which seems to be with agreement with this study especially considering the agricultural activities taking place in the region where the research was carried out.

3.3. pH

The charts showing the relationship between pH, exchangeable bases ($cmol_c$/kg), and CEC across the sampling sites for the first and second seasons are presented in Figures 2 and 3, respectively. The soil samples collected during both dry seasons showed a slightly alkaline pH, which is a typical characteristic of sandy loam soils. According to Leticia *et al.* (2014), this might explain the obtained values for CEC. During the first dry season, the highest pH value (9.9) was recorded at the sampling site DA. However, during the second dry season, this value decreased to 9.7. The sampling site TK had the second-highest pH values, with 8.0 and 8.1 recorded during the two sampling periods, respectively. The pH range for both seasons was 5.7–9.9, with a mean value of 7.280. This mean value is only slightly above neutral, indicating a relatively balanced pH level in the soil

Table 15 | Base saturation of the cations of the first season

Sample ID	Ca^{2+} (%)	Mg^{2+} (%)	K^{+} (%)	Na^{+} (%)
RM	62.4	31	6.4	0.53
MY	59.7	30.3	9.6	0.3
MK	62.6	31.7	5.2	0.38
HA	60.8	31	7.6	0.41
HJ	62	31	6.3	0.32
MR	62.9	30.7	5.8	0.49
MU	61.9	30.5	7.2	0.39
TK	62.5	31	6.1	0.52
DA	60.1	31	8.2	0.5
GG	61	31.2	7.1	0.41

Table 16 | Base saturation of the cations of the second season

Sample ID	Ca^{2+} (%)	Mg^{2+} (%)	K^{+} (%)	Na^{+} (%)
RM	63.50	31.60	4.36	0.60
MY	61.50	31.00	6.50	0.99
MK	62.70	31.50	5.30	0.46
HA	58.90	28.80	11.60	0.70
HJ	62.90	32.30	3.95	0.79
MR	64.70	32.50	2.42	0.40
MU	64.20	32.40	2.95	0.43
TK	61.40	30.50	6.99	1.03
DA	62.90	32.50	3.78	0.75

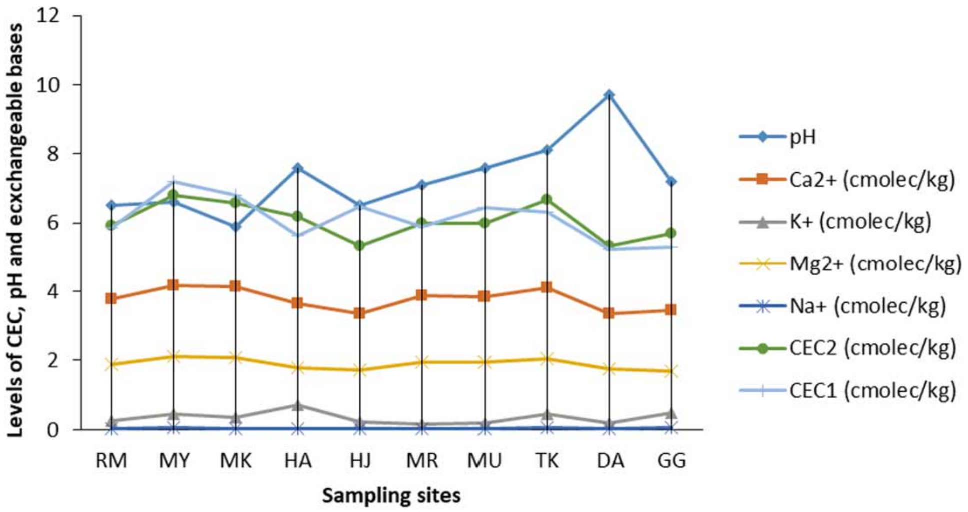


Figure 2 | pH, exchangeable bases ($cmol_c$/kg), and CEC across the sampling sites (first season).

samples. The fact that the majority of the pH values are alkaline could be due to high carbonates and hydroxides in the soil. The coefficient of variation was low for both seasons. This showed high reproducibility and revealed that the data followed a normal distribution as shown by the Shapiro-Wilk test at $p > 0.05$. The skewness

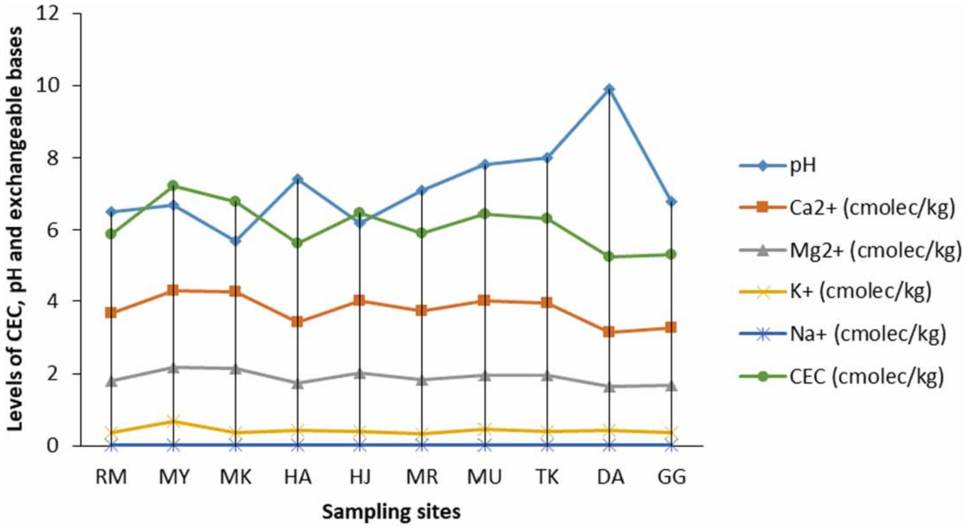


Figure 3 | pH, exchangeable bases (cmol$_c$/kg), and CEC across the sampling sites (second season).

observed from the results also showed higher values for Na and Mg which indicates non symmetry in the set of data (Tables 3 and 4). Shapiro-Wilk test for confirmation of normality also confirmed the normality test performed on the values recorded at $p > 0.05$ with K showing an exception in the first season with a p-value of <0.0001. The difference in group mean values for both seasons was statistically significant at $p < 0.0001$ (Tables 7 and 8). This implied that the null hypothesis that there is no difference in the group mean values will not be accepted; hence, alternative hypothesis is accepted. A strong positive relationship was found in the Pearson product moment correlation matrix between Ca, Mg, CEC, and, to a lesser extent, pH, though negative (Tables 9 and 10). This implied that Ca and Mg may have a similar source which may be in form of carbonates in the soil and may also explain the alkaline pH of the soils. This relationship was further observed in the results of regression where the R^2 value was almost unity when both Ca and Mg were made the dependent variables. In the second season the R^2 value became unity when CEC of the first season was added as a predictor and Mg was made the dependent variable (Tables 11–14).

3.4. Exchangeable cations

Exchangeable cations (calcium, magnesium, potassium, and sodium ions) concentration in the soils for both seasons gave similar values throughout the sampling sites. Pearson's product moment correlation was determined where a strong relationship (0.984 and 0.978) was established between calcium and magnesium ions in the soil samples for both seasons, respectively. This agreed with the result of regression analysis obtained in this study where a high R^2 value of 0.979 was observed when calcium and magnesium were separately used as dependent variables to determine whether their effect on the concentration of other elements in the soil was significant. The results of this study are in agreement but higher than that of Akpan *et al.* (2017) who also reported low values of potassium, sodium, and magnesium in wetland soils. Another study by Aki (2012), however, reported low to moderate values for these cations which are also in agreement with the findings of this research.

The study included the CEC results for one season as predictors in the second season. When Ca was set as the dependent variable, the R^2 value was found to be 0.985. The R^2 value was slightly higher when magnesium was set as the dependent variable and the CEC for both seasons were included, resulting in an R^2 value of 1. This implied that a unit change in magnesium and other predictors resulted in a 0.979 unit change in calcium, and the coefficient of determination (R^2) was even stronger when an additional predictor (CEC) was included in the second dry season analysis. This lends credence to the observation that the presence of Ca influences a soil's CEC as well as Mg in the soil. These manipulations were to further observe and appreciate the relationship which exists among the variables between the dry seasons. Furthermore, the results showed that changes in the concentrations of the ions in the soils are reasonably dependent on changes in the concentrations of other coexisting ions in the soil, and to a greater extent, the CEC of the soil. Variability in group mean values (ANOVA) of pH and cations in soil produced a significant result as well. For the first dry season, $F(5, 45) = 270.069$,

$p = 0.0001$, and for the second dry season, $F(5, 54) = 338.947$, $p = 0.0001$. This indicated that there is a significant difference in the parameters examined across the sampling sites, which led to the rejection of the null hypothesis. The variability among the parameters is noteworthy. The Bartlett's test, which was conducted to verify the ANOVA results, produced a value of 0.0001, indicating that the difference is statistically and homogeneously significant.

3.5. CEC of the soils

The levels of soil CEC for both seasons throughout the sampling sites are presented in Figure 4, whereas, Figure 5 represent the line chart elaborating the amount of CEC across the sampling sites for both seasons. The CEC values of the soils observed were moderate and similar in both seasons. Some variations were observed in the second season which affected the overall CEC values for both seasons. The results of correlation indicated an indirect proportionality between pH and CEC. This showed that an increase in pH led to a decrease in CEC values which are great for the normal functioning of the soil. The exchangeable bases Ca and Mg also played an important role in the CEC value and also the overall outcome of the result. This was evident in the high R^2 values observed when Mg and Ca were made the dependent variables in the multiple regression models. The R^2 values turned higher when CEC values were added to the predictors. This implied that with the exception

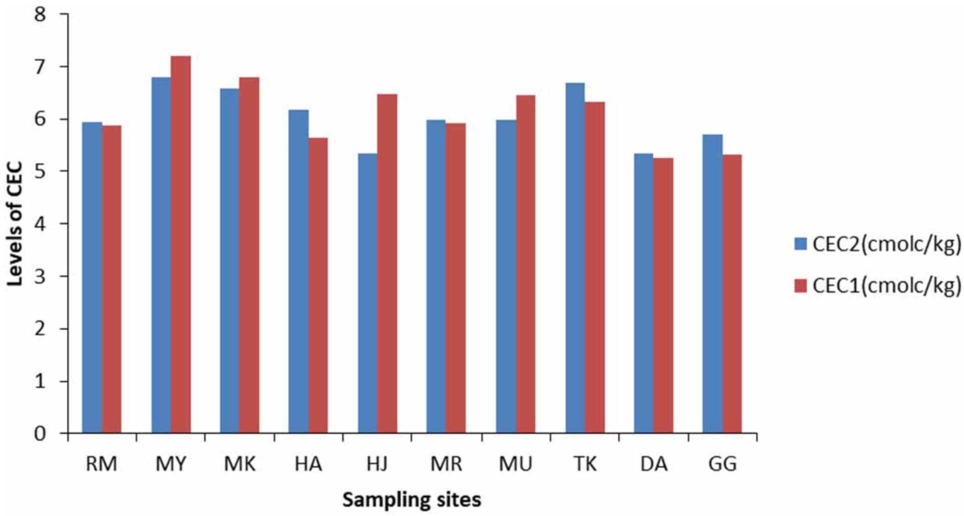


Figure 4 | Levels of soil CEC for both seasons throughout the sampling sites.

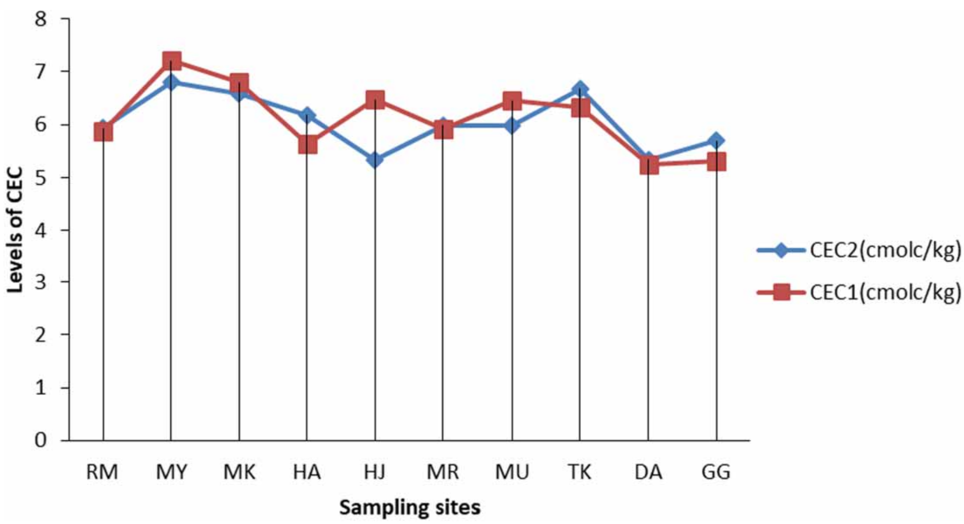


Figure 5 | Line chart elaborating the amount of CEC across the sampling sites for both seasons.

of pH, Mg, Ca, and CEC are all directly proportional to one another in soils as an increase in one would lead to an increase in the other and vice versa. Akpan *et al.* (2017) however, reported low CEC values and high base saturation values which differ from the findings in this study but agree with Aki (2012) in terms of high base saturation and CEC.

The moderate CEC values may be mostly related to the alkaline pH of the soils. When the pH of the soil is low, the adsorption of soil nutrients by the soil is affected, resulting in a higher CEC of that particular soil. This relationship especially that of pH and CEC was reported by Hailegnaw *et al.* (2019) and Leticia *et al.* (2014) but an inverse relationship was observed in this study.

3.6. Base saturation of the soils

From the results obtained, calcium occupied the highest percentage in all the soils in the study areas with more than 60% in most sites followed by magnesium with 30% occupancy. The trend of base saturation is: Ca > Mg > K > Na. Ca^{2+} saturation ranged between 60 and 63.5 in all sampling sites for both seasons, Mg^{2+} had a range of 28 to 32%, K^{+} 2.4 to 11.6, and Na^{+} 0.3 to 1.03. This result further indicated a strong correlation between Ca^{2+} and Mg^{2+} in the sample matrix. There exists a positive relationship between base saturation and pH (Kabala & Labaz 2018) which supported the findings in this study. Base saturation also indicated a direct proportion with CEC as evident in this study. This however differs from Akpan *et al.* (2017) where an inverse relationship between CEC and base saturation was observed. The base saturation of the soils is suitable for most agricultural practices in geographical sites under study. There is the need to explore more by planting other crops and fruits like Irish potatoes, pineapple, apple, and other exotic fruits to determine suitability as this can explore the potential of the soils and boost agricultural activities.

4. CONCLUSION

The Hadejia-Nguru wetlands are home to a diverse range of activities, ranging from fishing and agriculture to tourism and recreation. This wetland complex is an important source of livelihood and resource for local inhabitants, making it a critical part of the local economy. Additionally, it provides habitats for numerous species of flora and fauna, making it ideal for research and conservation efforts. Not only is it ideal for research and conservation efforts, it was recently the subject of this study conducted for two consecutive dry seasons in Nigeria – that yielded valuable insights into the area's ecology and its inhabitants. The physicochemical properties (pH, Ca^{2+}, Mg^{2+}, K^{+}, Na, CEC) of the soil samples analyzed indicated good soil quality for vegetables and cereal crops farming. The pH values were mostly alkaline, which is typical of soils in the study area, and all measured values were within approved standards. The moderately high CEC values of the soils, along with fluctuations in the amount of calcium and magnesium, suggested that the soils are rich in essential nutrients required for plant growth. The significantly positive correlation between calcium and magnesium for both dry seasons and the high coefficient of determination (R^2) for both metals with CEC values as the predictors for both seasons indicated that these metals play a crucial role in determining soil quality. The regression analysis also showed that the changes in CEC and pH levels in the soil were dependent to a large degree on changes in Ca and Mg content of the soil. Additionally, the increase in pH was directly proportional to the CEC and base saturation of the soils, with a higher percentage of calcium than other cations observed from the base saturation of the soils. Overall, these findings suggest that the soil in the study area are suitable for the farming of vegetables and cereal crops and can also be explored for exotic fruits and other crops.

Further studies on the trends that could exist over long periods could be undertaken to reveal unnoticed detail concerning the physicochemical properties of wetlands especially in dry seasons. Exotic farming to include other fruits and vegetables is also encouraged to explore the potential of the study sites.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 21 September 2023; accepted in revised form 25 January 2024. Available online 21 February 2024