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Geochemical Characterization of Soils in A Semi-Urban Extension Area of Minna, Northcentral Nigeria Using EDXRF Instrumental Analysis

Jimoh Rafiu Atanda[1]*, Ogungbade Olubukola Emmanuel[2], Adeniji Moradeyo Asifat[3], Okoli Ezindu Ebuka[4], Olaleye Oluwatobi Solomon[5], Salami Jamiu Ademola[6]

[1]Department of Water Resources Management and Agrometeorology, Federal University of Abeokuta, Ogun State, Nigeria
[2]Department of Earth Science, Faculty of Science, Olabisi Onabanjo University, Ago Iwoye, Ogun State, Nigeria
[3]Department of Physical Sciences, School of Science, Yaba College of Technology, Lagos State, Nigeria
[4]Department of Civil Engineering, Federal Polytechnic, Oko, Anambra State, Nigeria
[5]Department of Water Resources and Agrometeorology, Faculty of Agriculture, Federal University Oye Ekiti, Ekiti State, Nigeria
[6]Department of Physics, School of Physical Sciences, Federal University of Technology,Minna,Niger State Nigeria

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Contact
*Jimoh Rafiu Atanda
geomodgeoexploreconsultants@gmail.com (JRA)

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Abstract
A study on pedogeochemistry and agrogeochemistry was conducted on an open Farm field to evaluate the trace and macro elements in the soil and their effects on Dioscorea rotundata (white yam) yield. Twenty soil samples were collected at predetermined depths and distances across the farm and analyzed using Energy Dispersive X-ray Fluorescence (EDXRF) focusing on soil geochemical anomalies and their impact on yam yield in Chanchaga Local Government Area, Niger State, Nigeria. Results showed that high potassium absorption led to impaired yield, harvest loss, and premature crop death. The mean concentrations of key elements were potassium (1.8%), calcium (1.5%), iron (1.4%), magnesium (0.42%), copper (127 ppm), zinc (127 ppm), and manganese (739 ppm), following the order K > Ca > Fe > Mg for minor elements and Mn > Zn for major elements. These values were compared with Alloway (1995) standards for essential nutrients in yam cultivation. Excessive potassium absorption negatively affects yam yield, while imbalanced element proportions can impact crop health and human consumption. Ensuring optimal soil geochemistry is crucial for sustainable yam production and food safety.

Keywords
Pedogeochemistry, agrogeochemistry, white yam, minor, major, energy dispersive X-ray Fluorescence

Abbreviations

IEM: Ion exchange membrane technology
ICP-MS: Inductive coupled plasma-mass spectrometry
XRF: X-ray fluorescence
ICP-AES: Inductive coupled plasma atomic emission spectroscopy
EDXRF: Energy dispersive X-ray fluorescence
WDXRF: Wave dispersive X-ray fluorescence
GPS: Global Positioning System
E-T: Emission-Transmission

1. Introduction

Soil represents the loose, unconsolidated material covering the Earth's crust, differing from bedrock in its structural and compositional characteristics, structural integrity, and ability to sustain agricultural activities. It acts as a vital avenue for agricultural yield, supplying essential nutrients and water (Adeola et al.,2015).Elemental analysis has emerged as a crucial method for evaluating soil composition and assessing earth materials on a global scale. In intensive agricultural systems, the primary objective is to ensure that nutrient availability does not hinder crop yields (Riedel et al., 2015). This requires that crops have access to all necessary mineral nutrients, with the rate of nutrient supply meeting or surpassing the crop's demand.

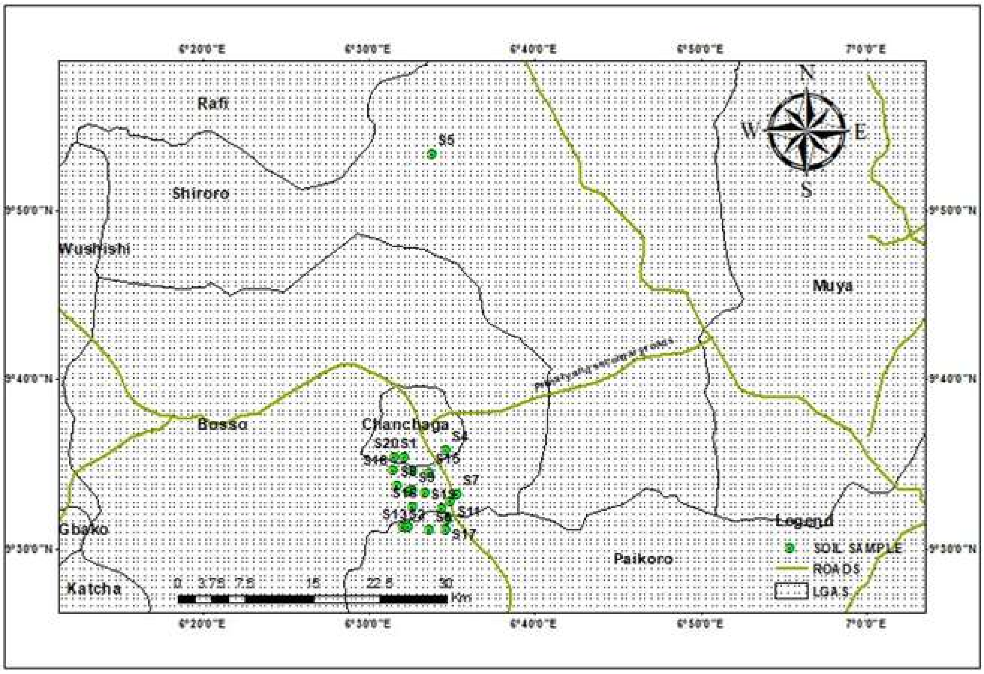

Fig. 1. Spatial layout of the soil sampling points within the study area (Author)

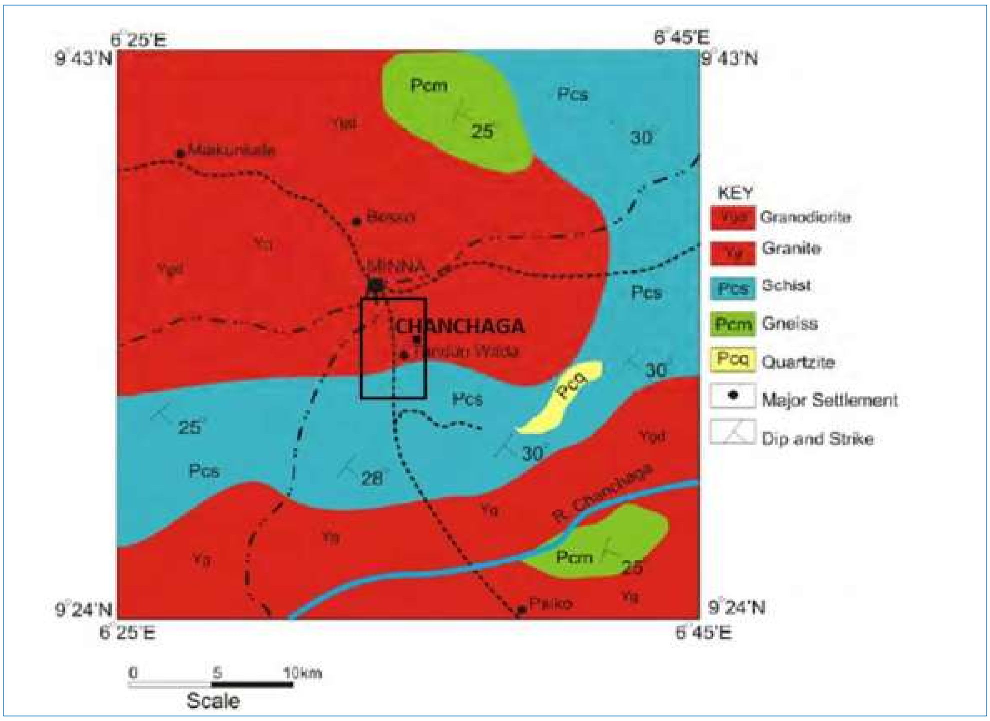

Fig. 2. Geological Map of part of chancaga, Minna, Niger State (Nda et al., 2015)

Consequently, soil chemistry plays a central role in determining the nutrient needs of crops, ensuring sustainable agricultural practices. The optimal composition of soil is critical for crop development, making comprehensive multi-elemental soil studies essential for improving agricultural productivity (Kabata and Pendias, 2001). Geochemistry involves the study of the dispersion (types and concentrations) of elements within the earth's life-support system, including Geological materials, Substrate, Hydrosphere, Flora and Gaseous envelope. It also examines the reaction pathway and pathway that control the constituents and interactions of these elements across different states (Kabata and Pendias, 2001).

In soil science, geochemistry focuses on trace elements, their movement, spatial trends, and outcome in flora and earth, encompassing both natural and human-introduced sources (Roberts et al., 2005). Trace elements, often referred to as minor elements, micronutrients, or microelements, are present in soils and plants in small ratios, generally indicated in proportion of million. These elements are essential for flora development and animal nutrition, although their specific requirements vary among species.

Over time, additional elements have been identified as important, with over twelve minor elements, including boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), sodium (Na), and zinc (Zn), now recognized as important for flora development and animal health (Kihara et al.,2020).

Table 4. Synopsis of Geographic data of the soil samples in the study area

No	Sample No (S1-S20)	Sample Medium	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Elevation (ft)
1	S1	Soil	9.5908°N	6.5258°E	758
2	S2	Soil	9.5211°N	6.5342°E	715
3	S3	Soil	9.5292°N	6.5792°E	702
4	S4	Soil	9.5975°N	6.5769°E	883
5	S5	Soil	9.8894°N	6.5631°E	866
6	S6	Soil	9.5183°N	6.5611°E	755
7	S7	Soil	9.5544°N	6.5892°E	745
8	S8	Soil	9.5628°N	6.5292°E	758
9	S9	Soil	9.5575°N	6.5436°E	794
10	S10	Soil	9.5781°N	6.5436°E	791
11	S11	Soil	9.5469°N	6.5817°E	758
12	S12	Soil	9.5400°N	6.5739°E	833
13	S13	Soil	9.5211°N	6.5403°E	715
14	S14	Soil	9.5569°N	6.5406°E	738
15	S15	Soil	9.5750°N	6.5611°E	820
16	S16	Soil	9.5417°N	6.5417°E	699
17	S17	Soil	9.5194°N	6.5778°E	764
18	S18	Soil	9.5750°N	6.5250°E	787
19	S19	Soil	9.5556°N	6.5569°E	702
20	S20	Soil	9.5908°N	6.5353°E	755

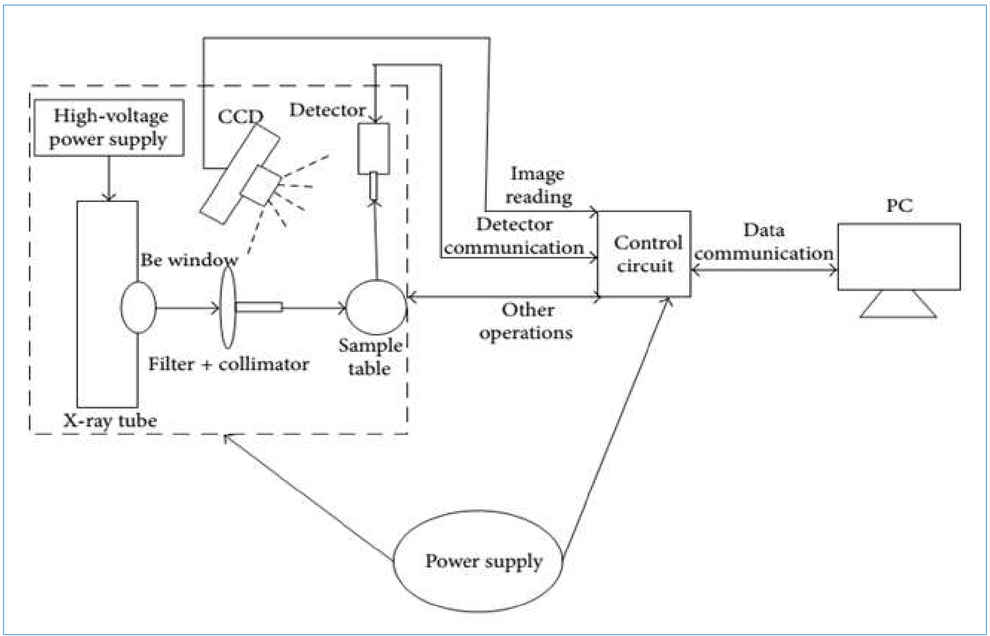

Fig. 3.The Conceptual diagram of the EDXRF spectrometer's structural configuration

Minor elements commonly found in soils include boron (B), zinc (Zn), manganese (Mn), copper (Cu), molybdenum (Mo), iron (Fe), and chloride (Cl). Major elements, on the other hand, made of fundamental nutrients such as nitrogen (N), phosphorus (P), and potassium (K), as well as ancillary nutrients like calcium (Ca), magnesium (Mg), and sulfur (S) (Kabata and Pendias, 2001; Mohammed,2019). Seventeen trace elements are considered essential for plants due to their specific biochemical roles. Among these, essential trace elements e.g. boron, copper, chlorine, iron, manganese, molybdenum, and zinc are particularly important. Deficiencies in these elements can result in significant reductions in plant development, yield, and agricultural performance. Some soils naturally lack adequate quantities of these nutrients needed to meet the for the crops to grow, necessitating external supplementation (Chand et al., 2011; Njinga 2013).

Chanchaga, is the experimented agricultural field located in north central part of Nigeria and is characterized by high agricultural potential. Understanding the chemical properties of its soils is essential for optimizing land use and promoting crop productivity.

A variety of analytical methods have been employed globally for soil analysis, each with its unique advantages. These include ion exchange membrane technology (IEM) (Zaher, 2012), inductive coupled plasma-mass spectrometry (ICP-MS) (Smart et al., 2017; Markl et al., 2014; Riedel et al., 2015; Bzour et al., 2016), inductive coupled plasma atomic emission spectroscopy (ICP-AES) (Xiangdong and Thornton, 2001; Burke et al., 2015), and X-ray fluorescence (XRF) (Towett et al., 2015; Arcadius et al.,2023).

Energy dispersive X-ray fluorescence (EDXRF) has been widely used for elemental analysis due to its efficiency and accuracy (Sudhakaran et al., 2018; Thomas et al., 2016; Idris et al., 2004). Additionally, wave dispersive X-ray fluorescence (WDXRF) has been utilized for detailed soil characterization (Grosheva et al., 2007). The primary motive of this study is to conduct soil sampling from chosen agricultural plots, analyze the soil for macroelements and microelements, and evaluate the impact of these elements on the yield and output of yam (Dioscorea rotundata). By understanding the geochemical composition of the soils in the study area, this research aims to provide insights into optimizing soil nutrient management for improved agricultural productivity.

Table 2. Overview of Soil samples findings

Samples	Mg (%)	K (%)	Ca (%)	Fe (%)	Cu (PPm)	Zn (PPm)	Mn (PPm)
S1	0.521	0.939	0.722	1.48	73.3	45.8	373
S2	0.035	3.56	2.62	2.49	134	103	844
S3	0.031	2.85	1.44	1.67	124	87.3	628
S4	0.049	0.294	0.403	0.078	60.6	37.8	199
S5	0.035	0.896	0.611	0.151	74.4	43.8	278
S6	0.462	1.24	0.93	1.27	138	744	3050
S7	3.42	3.50	2.31	8.36	412	334	1450
S8	0.424	5.85	1.36	0.215	147	127	748
S9	2.08	0.375	1.05	0.020	42.3	30.7	134
S10	0.030	2.23	1.47	0.153	353	203	1250
S11	0.217	3.43	1.59	2.40	-	90.2	753
S12	0.409	2.57	1.94	0.372	232	210	1510
S13	0.032	1.50	1.28	0.729	111	73.9	488
S14	0.038	1.44	1.21	0.889	153	74.5	503
S15	0.045	0.601	0.502	0.939	51.9	44.5	245
S16	0.045	0.723	0.616	2.32	79.1	56.3	338
S17	0.037	0.769	0.591	1.77	119	54.2	355
S18	0.051	1.61	0.836	0.217	161	59.6	418
S19	0.462	0.797	0.577	1.56	93.3	69.8	322
S20	0.049	0.437	7.53	1.24	----	56.5	898
Average	0.42	1.8	1.5	1.4	127	127	739

2. Study Area and Regional Geological Settings

The experimented field used for the research work is situated within the Chanchaga Local Government Area of Niger State, Nigeria, and is geographically adjacent to the Bosso Local Government Area. It spans latitudes 9° 31' E to 9° 38' E and longitudes 6° 31' N to 6° 36' N, covering an approximate area of 100 km², as depicted on a 1:35,000 scale map (Fig. 1).

This region is part of the Minna Sheet 164 SW bounded by Barikin Sale to the north, Chanchaga to the south, Gongwapi to the west, and Sabon Gari to the east. It is well-connected to neighboring villages, settlements, and farmlands through an extensive network of footpaths, minor roads, and major highways, facilitating accessibility and transportation.

Agriculture is the predominant land use in the area, with the soil primarily consisting of sandy loam, which is highly conducive to farming activities. However, during the study period, certain sections of the area were observed to be waterlogged, while others exhibited clayey soil properties (Edegbene et al., 2023).

Table 3. Average levels of major and minor elements in the soil samples

Element	Mean Values
Major Elements	
Mg	0.42%
K	1.8%
Ca	1.5%
Fe	1.4%
Minor Elements	
Cu	127ppm
Zn	127ppm
Mn	739ppm

Table 4.The concentration of essential elements (Alloway, 1995)

The region supports the cultivation of major crops such as yam (Dioscorea spp.), rice (Oryza sativa), groundnut (Arachis hypogaea), and maize (Zea mays), which are integral to the local economy and food security. The study area benefits from a well-developed dendritic drainage system, characterized by numerous rivers and streams that promote soil health and support crop output rate.

Plants	Typical Soil Contents	
	Mean	Range
Major Nutrients		
Carbon	2.0%	0.7-50%
Nitrogen	0.2%	<0.002- >2.5%
Phosphorus	0.04%	0.002-0.6%
Potassium	1.8%	0.005-7.9%
Sulphur	433%	3.0-8200ppm
Calcium	2.0%	0.1-32%
Magnesium	0.83%	0.005-16%
Micronutrients		
Boron	38ppm	0.9-1000ppm
Chlorine	485ppm	18-806ppm
Copper	26ppm	2.5-60ppm
Iron	3.2%	0.01-21%
Manganese	761ppm	<1-18300ppm
Molybdenum	1.9%	0.07-5ppm
Zinc	60ppm	1.5-2000ppm

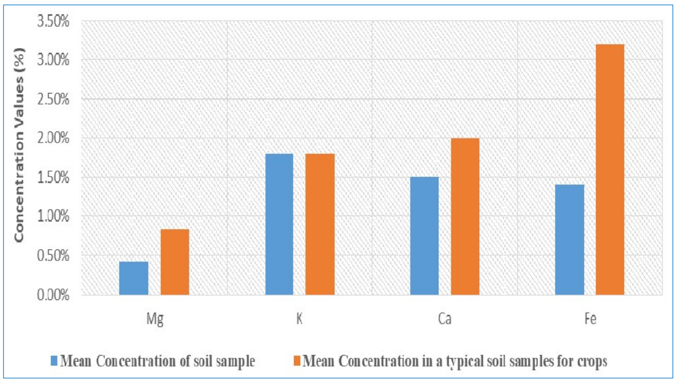

Fig. 4. Bar chart comparing mean concentrations of magnesium (Mg), potassium (K), calcium (Ca), and iron (Fe) in soil samples from the study area with standard reference values for crop cultivation

This natural drainage network is crucial in maintaining environmental harmony and promoting long-term viability farming practices in the region. The drainage system in the area exhibits a dendritic pattern, indicative of a relatively uniform geological structure. The region is predominantly drained by the Chanchaga River to the southeast, along with other significant rivers, including the Suka River to the north, and the Sauke, Guduko, and Gora Rivers and these rivers appear to originate from the highlands within the area, with their tributaries ultimately converging and discharging into the Chanchaga River (Edegbene et al., 2023).

The region is underlain by the crystalline Basement Complex, characterized by hard rock terrains (Fig. 2). The primary lithological units consist of granites covering approximately 80% of the region, mainly exposed in the western part of the town, and gneisses, which occupy about 20% of the area to the east (Idris et al., 2015).

Granites are typically coarse-grained and often form high batholithic structures, exhibiting features such as jointing, fracturing, foliation, and, in certain locations, boulder-like appearances. Gneisses are fine-grained rocks with light bands of quartz and feldspar and dark bands of biotite mica (Idris et al., 2015) (Fig. 2).

2.1. Review of Related Literature on Geochemical Characterization of Soils in Semi-Urban Extension Areas Using EDXRF Instrumental Analysis

Understanding the geochemical constituents of agricultural soils is crucial for assessing soil fertility, crop productivity, and potential contamination from trace elements. Numerous studies have applied energy-dispersive X-ray fluorescence (EDXRF) spectroscopy to assess soil chemistry, particularly in semi-urban agricultural areas where human activities significantly influence soil quality and crop yields, including yam production.

Ikoko et al. (2022) acquired Soil samples from Bayelsa State in the Niger Delta and analyzed the samples .The experimental field were partitioned into eight grids, with two samples per grid acquired systematically in each grid to the depth of 900 mm and findings pinpointed a high concentration result in some samples higher than that of the elemental concentrations in soils. In addendum, Aluminum, Strontium, Barium, Gallium have a very high value that is higher than that of the worldwide mean range upper limit values in crustal soil.

Haifei et al. (2020) conducted research on soil health and carbon increase from a single biochar amendment in a rice farm trial. The study concluded that one-time addition of biochar to paddy soils results in sustained enhancement in soil health and increased carbon threshold, enhancing higher rice production and long-period farming sustainability.

Muhammad et al. (2019) embarked on research on trace element analysis of soil samples from Fika, Yobe State, using MP-AES showed all elements below international benchmarks, except Pb, which was above the threshold.

Essiett and Bede (2016) carried out a study on Analysis of soil components from Ikot Abasi Local Government Area, Nigeria Using EDXRF. Evaluation of the result showed that Sr is diminished in the soil .The values were normalized to the Clarke value, with K, Ti, Co, Zn, and Nb exhibiting higher concentrations.

Similarly, Abou et al. (2019) explored the elemental properties of farmland soils in Assiut Governorate, Egypt. The study concluded that chemistry of the soil is affected majorly by agricultural practices and that soil needs further elemental studies to assess soil health and enhance crop yield.

Meanwhile, Louise et al. (2014) explored the resolving elemental and stratigraphic complexity: A procedure for using handheld X-ray fluorescence in mineral resource discovery. The reviewed studies collectively underscore the significance of geochemical assessments in agricultural lands, especially in semi-urban expansion areas where human activities alter soil composition.

EDXRF continues to be a valuable technique for soil characterization, facilitating informed land-use planning and improved yum productivity

3. Materials and Methods

The methodology was deployed to investigate the soil properties and elemental composition in Chanchaga area of Minna, Niger State, using both fieldwork and laboratory-based analytical techniques. The approach involved a systematic field investigation that included traversing various terrains, such as footpaths, roads, streams, and rivers, to collect soil samples from key locations across the study area. Precise geographical data, including elevation, longitude, and latitude, were recorded for each sampling point using a Global Positioning System (GPS), as shown in Table 1. This enabled accurate location tracking and spatial analysis of the sample distribution. In total, 20 soil samples were collected using random sampling techniques (Fig. 1) which ensured representative selection across the study area. Sampling was conducted along different traverses, and the site chosen was mainly agricultural plot, which was thought to be representative of the area's soil composition.

Soil samples were taken from the B-horizon, the layer beneath the A-horizon, as this horizon is recognized as the zone of accumulation, where significant concentrations of elements are typically found (Margui, 2022) Samples were collected at an average depth of 1.5 meters from the soil profile, which is generally the depth where mineralization occurs and can provide more accurate geochemical data. The process of soil sampling involves using digging tools, such as shovels and hand diggers, to extract the soil from the specified depth. The collected samples, weighing approximately 1 kg each, were carefully packaged in labeled polythene bags to maintain sample integrity and ensure proper identification for laboratory analysis. The samples were then distributed across the study area to cover a wide geographical span, ensuring the inclusion of various soil types and conditions.

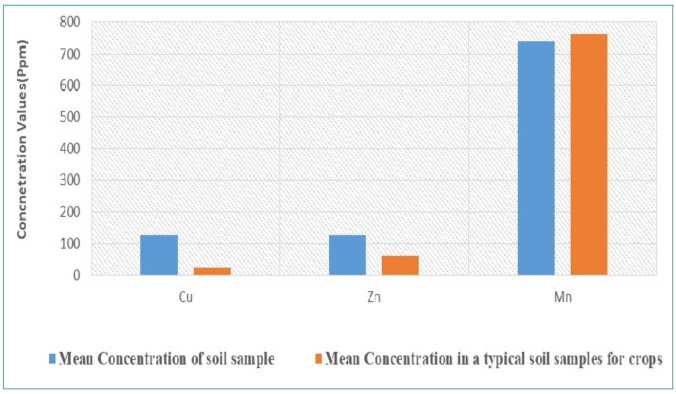

Fig. 5. Bar chart illustrating mean concentrations of copper (Cu), zinc (Zn), and manganese (Mn) in soil samples from the study area compared to typical soil concentrations for crop cultivation

After the soil field sampling, the samples were later transported for analsyis. The EDXRF elemental analysis was carried out at the Centre for Energy Research and Training Institute laboratory in Zaria, Nigeria on the samples. The Energy Dispersive X-ray Fluorescence (EDXRF) technique was employed, which is a well-established and highly effective technique for evaluating both macro and micro elements in a typical soil (Funtua, 2015). EDXRF analysis is particularly advantageous due to its non-destructive nature, quick turnaround time, and the ability to analyze a wide range of elements with high accuracy (Shackley, 2021).

The technique (Fig. 3) utilized the Emission-Transmission (E-T) method for quantitative elemental analysis, a methodology extensively validated in prior studies for the examination of soil and geological samples (Panagiotis et al., 2024; Markl et al., 2014). A 109Cd radioactive source was employed to excite the soil samples, facilitating the detection and quantification of several critical elements, including potassium (K), calcium (Ca), titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), magnesium (Mg), and molybdenum (Mo). This approach ensures accurate and reproducible determination of elemental concentrations, making it a reliable tool for geochemical and environmental analyses. This technique is capable of detecting elements in the range of 10 ppm to less than 1 ppm, ensuring the sensitivity and accuracy of the analysis (Margui, 2022).

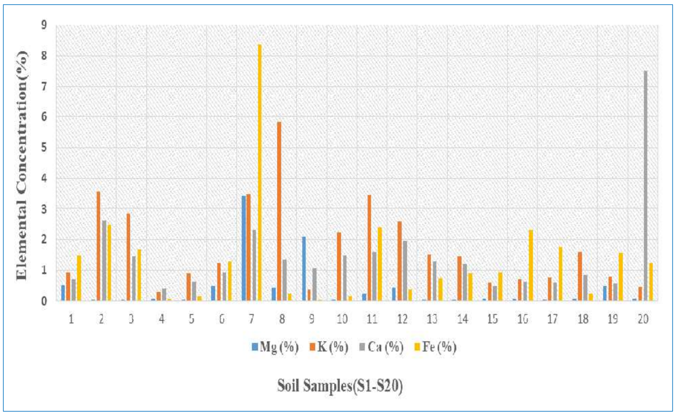

Fig. 6. Bar chart showing the elemental concentration of Mg, K,Ca and Fe in the soil samples (S1-S20) in percentage (%)

The EDXRF results were analyzed and interpreted to offer understanding of the elemental composition, which is critical for understanding the mineralization patterns and the geochemical behavior of the study area. The elemental concentrations were used to evaluate the soil potency in reference to agricultural productivity, mineral exploration, and other environmental considerations. The data obtained from the analysis were also compared to other regional geochemical studies to provide a broader context and to help identify any significant anomalies or trends in the soil composition. The conceptual diagram of the EDXRF spectrometer's structural configuration (Fig. 3).

4. Results and Discussion

The findings of the soil sample interpretation, including mean concentrations and essential element levels as described by Alloway (1995), are presented in Tables 2-4. Magnesium concentrations were generally low in samples 1, 2, 3, 4, 5, 8, and 10 to 20, except for samples 7 and 9, which recorded higher values of 3.42% and 2.08%, respectively. These elevated levels, when compared to the Alloway standard of 0.83% (Table 4), may result in chlorosis due to reduced chlorophyll synthesis, significantly lowering yam yield. Potassium levels were notably high in sample 2 (2.62%), sample 3 (1.44%), sample 11 (3.43%), and sample 18 (1.61%) (Fig. 6), surpassing the standard value of 0.83%. Excessive potassium can weaken yam roots, impair yield and cause harvest losses.

Manganese concentrations were also irregular, with sample 10 at 1250 ppm and sample 6 at 3050 ppm (Table 2 and Fig. 7), significantly exceeding the Alloway standard of 761 ppm (Table 4). Such high levels can lead to chlorosis, further restricting yam production. Additionally, all samples showed elevated copper levels (Fig. 5 and 7), which may induce chlorosis and disrupt critical growth processes, severely affecting yield. Iron levels were particularly high in sample 7 (8.36%) (Fig. 4 and 6), while other samples exhibited very low concentrations. Given iron's role in chlorophyll formation, its deficiency can cause chlorosis and reduce crop yield.

A comparative analysis of the soil sample results and the Alloway (1995) standards is illustrated in bar charts (Fig. 4 and 5), emphasizing significant deviations in elemental concentrations and their potential effects on yam production. These findings highlight the importance of balanced soil nutrient levels for optimal agricultural productivity.

The study involved analyzing twenty (20) soil samples collected from various locations, as outlined in Table 1, to assess the level of key elements, including magnesium (Mg), potassium (K), calcium (Ca), iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn). The mean concentrations of the minor elements were calculated and ranked as follows: Mg (0.42%) < Fe (1.4%) < Ca (1.5%) < K (1.8%). For the major elements, the order was Zn (127 ppm) < Mn (739 ppm).

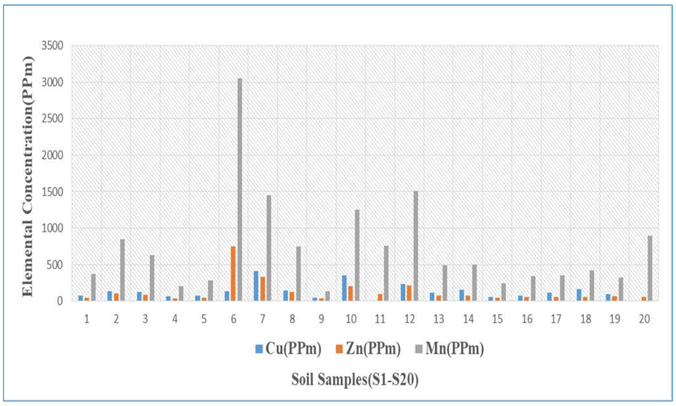

Fig. 7. Bar chart showing the elemental concentration of Cu, Zn and Mn in the soil samples (S1-S20) in Part per million (PPm)

Significant variations in elemental concentrations were observed across the sampling locations. These mean concentrations were compared to the standard values for typical soil contents as defined by Alloway (1995), with the findings demonstrated in a bar chart (Fig. 3). Insufficiency in certain elements were noted due to their low concentrations, while abnormally high levels of other elements were also identified, both of which could significantly impact the growth and yield of yam production.

Fig. 6 and 7 illustrate the spatial distribution of minor and major elements across the study area, revealing that manganese (Mn) and copper (Cu) were present in high concentrations at all locations. This suggests a geochemical anomaly, which could adversely affect yam yield. Notably, magnesium (Mg) concentrations were consistently low across all locations, despite its critical role in crop development. This deficiency is likely to hinder yam production, as the necessary elements are not present in the required proportions. The mean concentration of magnesium (0.42%) was significantly lower compared to potassium (1.8%), calcium (1.5%), and iron (1.4%).

Additionally, the mean concentration of manganese (739 ppm) exceeded the standard requirement of 761 ppm as per Alloway (1995) (Table 3), potentially impacting yam yield. Calcium concentrations, with a mean value of 1.5%, were slightly below the standard requirement of 2.0%, further highlighting potential challenges for optimal crop growth. These findings underscore the importance of maintaining balanced soil nutrient levels to ensure sustainable agricultural productivity.

5. Conclusion

The development and efficiency of yam is a function of availability of both minor and major elements. While these elements are highly significant for soil fertility and yam cultivation, imbalances in their concentrations can significantly impact yield. The chemical analysis results of all soil samples were compared to the standard concentrations of essential elements as outlined by Alloway (1995).

For instance, the magnesium concentration in sample 1 was 0.521%, which is below the Alloway standard of 0.83%. This deficiency can lead to chlorosis due to insufficient chlorophyll production, ultimately reducing yam yield and overall productivity. Similarly, the potassium concentration in sample 1 was 0.90%, compared to the Alloway standard of 1.8%. This deficiency weakens the yam's root system, resulting in impaired yields and harvest losses. Conversely, excessive potassium levels can cause premature crop death. Additionally, the calcium concentration in sample 1 was 0.722%, while the Alloway standard ranges from 0.01% to 32%, with an optimal value of 2%. This deficiency can hinder the development of the root system, further diminishing yam production. These findings underscore the importance of maintaining balanced soil nutrient levels to support optimal yam growth and maximize yield.

Conflict of Interest

All authors mentioned in this paper do hereby declare that there are no known conflicting financial interests or any other financial hindrance that could arise to have any effect on the research reported in this paper.

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