

BASLINE DETERMINATION OF MICRONUTRIENTS IN THE SOILS OF SELECTED FARMS IN LOKOJA AND ITS ENVIRONS, KOGI STATE: A PATHWAY TO ADDRESSING HIDDEN HUNGER-RELATED ISSUES

Dallatu Ephraim Musa, *Sunday Ojonuyo Okwoli, Anthony Ugbedeajo Atumeyi, Aloysius Akangee Pam

Department of Chemistry, Federal University Lokoja, Lokoja, Kogi State, Nigeria

*Corresponding Author Email Address: sundayokwoli@gmail.com

ABSTRACT

Three agricultural farms in Lokoja, Kogi State, Nigeria - Federal University Lokoja (FUL), Kogi State Polytechnic (KSP), and the Kogi State Ministry of Agriculture (KSM) - were the subjects of this study, which created a baseline evaluation of the soil micronutrient status. Significant differences were found when key physicochemical properties were analyzed: FUL and KSP soils were moderately acidic to near neutral (pH 5.18- 6.43), whereas KSM soils were highly acidic (pH 2.70- 3.72 via the KCl method). KSM soils had the highest soil organic matter (SOM) and cation exchange capacity (CEC), reaching up to 12.26% and 60.69 cmol_c/Kg, respectively. Principal Component Analysis confirmed that SOM and CEC were the main factors differentiating the soils and controlling micronutrient retention. For example, zinc (Zn) levels ranged from 8.54 to 44.23 mg/kg, while some nickel (Ni) concentrations (98.82 mg/kg) exceeded the 50 mg/kg toxicity threshold. Atomic Absorption Spectrometry revealed correspondingly high concentrations of Iron (up to 126,410.55 mg/kg) and Copper (211.32 mg/kg) in KSM soils, due to their high SOM and CEC. The results establish a crucial baseline for soil health, showing that KSM soils need pH amelioration to increase availability and reduce possible nickel toxicity, even though they are rich in some micronutrients. To maximize crop productivity in the area, site-specific soil management is advised.

Keywords: soil micronutrients; cation exchange capacity; soil acidity; organic matter; hidden hunger.

INTRODUCTION

Soil is the topmost layer of the earth's surface, where plants, trees, animals, and other organisms can grow. (Gavrilescu, 2021). He further reported that soil is a complex heterogeneous medium made up of minerals, organic materials, and gaseous and aqueous constituents. It is one of the most vital natural resources for sustaining life on Earth. (Dewangan *et al.*, 2023). Soil provides nutrients to plants; hence, it forms the foundation of our food systems. (Dewangan *et al.*, 2023). Micronutrients are involved in many aspects of plant metabolism, including the regulation of nutrition, the production of chlorophyll, the retention of flowers, the growth of reproductive organs, and the development of fruit and seeds. (Monib *et al.*, 2023; Javed *et al.*, 2022) categorized nutrients into two groups as i. micronutrients and ii. Macronutrients. Micronutrients, which include iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), and nickel (Ni), are crucial for regulating various microbial processes, including respiration,

photosynthesis, biomolecule synthesis, redox homeostasis, cell development, and immune system function. (Dai *et al.*, 2023).

Micronutrient deficiencies severely restrict the growth and biological functions of organisms, even though they only need a small amount of essential nutrients. (Dai *et al.*, 2023). For instance, iron (Fe) is the building block of numerous enzymatic processes, making it more than just a simple element. (Ahmed *et al.*, 2024). Its existence guarantees the effective operation of processes like respiration, nitrogen metabolism, and photosynthesis. (Li *et al.*, 2022). Lower concentrations might interfere with these processes, reducing the vitality of plants. (Herlihy *et al.*, 2020). Zinc, which is necessary for every facet of cellular function, including DNA synthesis and glucose metabolism, is another participant in this field. (Balandrán-Valladares *et al.*, 2021). Every trace element promotes intricate processes that prioritize development and growth. (Ahmed *et al.*, 2024). For example, boron controls the formation of pollen tubes and aids in the absorption of calcium. (Ahmed *et al.*, 2024). Manganese is used in the synthesis of chemicals that give cells their structural integrity. (Schmidt and Husted, 2019). Micronutrients are essential for human growth, development, and physiology, even though they are found in minuscule amounts. Deficits can result in anaemia from low iron. (Mahadea *et al.*, 2021) and neurological problems from copper imbalances (Ahmed *et al.*, 2024). Although plants are our main source of these vital elements, many crops lack the nutrients that people require in their natural state.

According to Prusty *et al.*, zinc enhances seed viability and seedling vigour, regulates auxin concentration in plants, supports photosynthesis and nitrogen metabolism, and provides defense against biotic and abiotic stressors. Zinc deficiencies in plants can cause reduced energy, chlorotic leaves, parallel white streaks on the leaf blade, slow development, and reduced synthesis of RNA and proteins (Prusty *et al.*, 2022). Copper keeps plants healthy, increases male flower fertility and reduces iron oxidation in plants (Prusty *et al.*, 2022). Reduced growth, ragged leaves, and decomposing and dead leaf tips are signs of copper deficiency in plants (Monib *et al.*, 2023). Iron, a component of ferredoxin, which aids in nitrogen fixation, is present in leguminous root nodule haemoglobin (Ahmed *et al.*, 2024). Deficiency symptoms include interveinal apical leaves, creamy chlorosis, stunted shoots, and decreased yield (Prusty *et al.*, 2022). Manganese participates in the tricarboxylic acid cycle through oxidation and reduction reactions. It also activates enzymes such as oxidoreductases,

hydrolases, and lyases. It also catalyzes the enzymatic activities of glycoaminase, isocitrate dehydrogenase, and malic dehydrogenase (Ahmed *et al.*, 2024). Deficiency symptoms may include a yellow cast, stunted plants, interveinal chlorosis in leaves, and decreased quality and productivity. Reduction of nitrate metabolism, inhibition of lateral root development, reduced cold hardness, and death of basal leaves (Monib *et al.*, 2023). (Prusty *et al.*, 2022) claim that boron promotes pollen tube elongation and germination, flower output, retention, seed and fruit development, and cell wall thickness. Additionally, it encourages photosynthetic translocation. Stunted roots, short internodes in rosette leaves, thick, leathery leaves, excessive branching, short, twisted, and/or torn petioles, undersized, malformed, or absent fruits with cork patches, chlorosis, and limited nitrogen metabolism are some of the symptoms that the plant exhibits (Monib *et al.*, 2023). Molybdenum facilitates the production of ascorbic acid, alleviates excesses of copper, manganese, and zinc, and encourages the growth of pollen and anthers (Monib *et al.*, 2023). The symptoms and deficiencies include twisted stalks, pale green leaves, and a necrotic area in the middle of the leaf between the veins and around the edges (Prusty *et al.*, 2022). Chlorine stimulates enzymes that use starch, influencing energy transfer and germination. Chlorine helps move and retain water in cells under moisture stress. Additionally, chlorine regulates the opening and closing of leaf surface stomata (Prusty *et al.*, 2022). Symptoms of chlorine deficiency include stubby roots, interveinal chlorosis, wilting, non-succulent tissue, and stunted or limited growth. Plants depend on the micronutrient nickel for essential functions, such as activating urease, which controls senescence and is critical for nitrogen metabolism. In addition to supporting iron absorption, nickel can act as a cofactor in certain enzyme reactions in place of zinc and iron (Monib *et al.*, 2023). The absence of nickel, on the other hand, can cause nitrogen-fixing plants to necrotize their leaf tips and reduce nitrogen fixation efficiency by delaying nodulation in leguminous vegetable crops (Monib *et al.*, 2023).

(Dewangan *et al.*, 2023) reported that reduced agricultural yields, stunted growth, and lower-quality crops can result from a lack of micronutrients in the soil. Iron and manganese are needed to maintain soil pH; they help lower soil acidity, which is crucial for crop development. Dewangan *et al.* (2023); Angelaki *et al.* (2022); Foroughi and Weil, (2025) reported that copper and zinc determine the texture and structure of soil by increasing the aeration, water-holding capacity and porosity of soil. According to Dewangan *et al.* (2023); Sukran and Yeliz, (2024) soil's water balance is maintained by boron, which controls the flow of water through soil and avoids waterlogging. Legumes need molybdenum in order to fix nitrogen, which is necessary to preserve soil fertility. (Dewangan *et al.*, 2023; Yang and Wang, 2024). Micronutrients are essential to maintaining and sustaining soil health, which is a key component of environmental sustainability. (Khambalkar *et al.*, 2025; Topa *et al.*, 2025). Natural ecosystems that support agricultural growth may be destroyed when crop yields are decreased as a result of a lack of micronutrients in the soil. (Sun *et al.*, 2024; Kopittke *et al.*, 2024).

Gashu *et al.* (2021) reported that micronutrient deficiencies have led to the emergence of "hidden hunger," which is becoming more widespread worldwide, particularly in several sub-Saharan African nations. The term "hidden hunger" refers to micronutrient deficiencies that harm plant and human growth and development

(Gallina *et al.*, 2025; Kam, 2025). However, macronutrients (such as N and P) have received more attention than soil micronutrients, which are the primary source of micronutrients for both humans and plants (Peng *et al.*, 2023). Understanding the spatial distribution of soil micronutrients across different agricultural domains is crucial for improving crop yield and quality (Peng *et al.*, 2023). Over two billion people worldwide suffer from one or more micronutrient deficiencies, with Sub-Saharan Africa (SSA) having higher rates than most other regions. It will be difficult to achieve the UN Sustainable Development Goal 2 (zero hunger) by 2030 because of these micronutrient deficiencies (MNDs), which are also referred to as "hidden hunger" (Lowe, 2021; Gashu *et al.*, 2021).

Scholars have carried out various studies on micronutrients in Nigeria, among which are: "Characterization of physio-chemical properties and micronutrient status of soil development on Anantigha Coastal Marine sediment in Calabar" by (Aki and Isong, 2018). Orobator *et al.* (2023) conducted a study, "Comparative Assessment of Selected Micronutrients Under Three Different Land Use Systems in Odighi, Edo State, Nigeria," to ascertain concentrations of specific micronutrients in each of the three land use systems, assess distribution of these micronutrients across the three land use systems, and investigate effects of the three land use systems on the selected micronutrients. (Harrison *et al.*, 2024) In "Evaluation of Soil Micronutrients in Madagali Local Government Area of Adamawa State, Nigeria," the study determined micronutrient variability across the study region; the collected soil samples were subjected to laboratory examination using appropriate techniques and descriptive statistics. In the study "Comparison of AAS and D.C.-ARC Techniques for Micronutrients Determination in the Soil" carried out by (Dallatu *et al.*, 2016) Sensitivity and selectivity of the two techniques for the determination of micronutrients in the soil of the Teaching and Research Farm of the Federal University of Agriculture, Makurdi, Benue State, Nigeria. A field study on the "Distribution and Status of Soil-available Micronutrients along a Hillslope at Ekpi Ibami in the Akamkpa Local Government Area of Cross River State, Nigeria" was conducted by (John *et al.*, 2019). So far, no record exists of determining micronutrients in soils from farms in Lokoja, Kogi State, and this has received little attention in the last ten years.

Micronutrient deficiencies in soil threaten plants and human health. Zinc deficiencies in plants can cause reduced energy, chlorotic leaves, parallel white streaks on the leaf blade, slow development, and reduced synthesis of RNA and proteins (Prusty *et al.*, 2022). Copper keeps plants healthy, increases male flower fertility and reduces iron oxidation in plants (Prusty *et al.*, 2022). Reduced growth, ragged leaves, and decomposing and dead leaf tips are signs of copper deficiency in plants (Monib *et al.*, 2023). Iron, a component of ferredoxin, which aids in nitrogen fixation, is present in leguminous root nodule haemoglobin (Ahmed *et al.*, 2024). Deficiency symptoms include interveinal apical leaves, creamy chlorosis, stunted shoots, and decreased yield (Prusty *et al.*, 2022). Manganese participates in the tricarboxylic acid cycle through oxidation and reduction reactions. It also activates enzymes, including oxidoreductases, hydrolases, and lyases. It also catalyzes the enzymatic activities of glycoaminase, isocitrate dehydrogenase, and malic dehydrogenase (Ahmed *et al.*, 2024). Deficiency symptoms may include a yellow cast, stunted plants,

interveinal chlorosis in leaves, and decreased quality and productivity. Reduction of nitrate metabolism, inhibition of lateral root development, reduced cold hardiness, and death of basal leaves (Monib *et al.*, 2023). Prusty *et al.* (2022) claim that boron promotes pollen tube elongation and germination, flower output, retention, seed and fruit development, and cell wall thickness. Additionally, it encourages photosynthetic translocation. Stunted roots, short internodes in rosette leaves, thick, leathery leaves, excessive branching, short, twisted, and/or torn petioles, undersized, malformed, or absent fruits with cork patches, chlorosis, and limited nitrogen metabolism are some of the symptoms that the plant exhibits (Monib *et al.*, 2023). Molybdenum facilitates the production of ascorbic acid, alleviates excesses of copper, manganese, and zinc, and encourages the growth of pollen and anthers (Monib *et al.*, 2023). The symptoms and deficiencies include twisted stalks, pale green leaves, and a necrotic area in the middle of the leaf between the veins and around the edges (Prusty

et al., 2022). Chlorine stimulates enzymes that use starch, affecting energy transfer and germination. Chlorine helps move and retain water in cells under moisture stress. Additionally, chlorine regulates the opening and closing of leaf surface stomata (Prusty *et al.*, 2022). Symptoms of chlorine deficiency include stubby roots, interveinal chlorosis, wilting, non-succulent tissue, and stunted or limited growth. Plants depend on the micronutrient nickel for essential functions, such as activating urease, which controls senescence and is critical for nitrogen metabolism. In addition to supporting iron absorption, nickel can act as a cofactor in certain enzyme reactions in place of zinc and iron (Monib *et al.*, 2023). The absence of nickel, on the other hand, can cause nitrogen-fixing plants to necrotize their leaf tips and reduce nitrogen fixation efficiency by delaying nodulation in leguminous vegetable crops (Monib *et al.*, 2023). Figure 1 illustrates symptoms of deficiencies of micronutrients in plants.

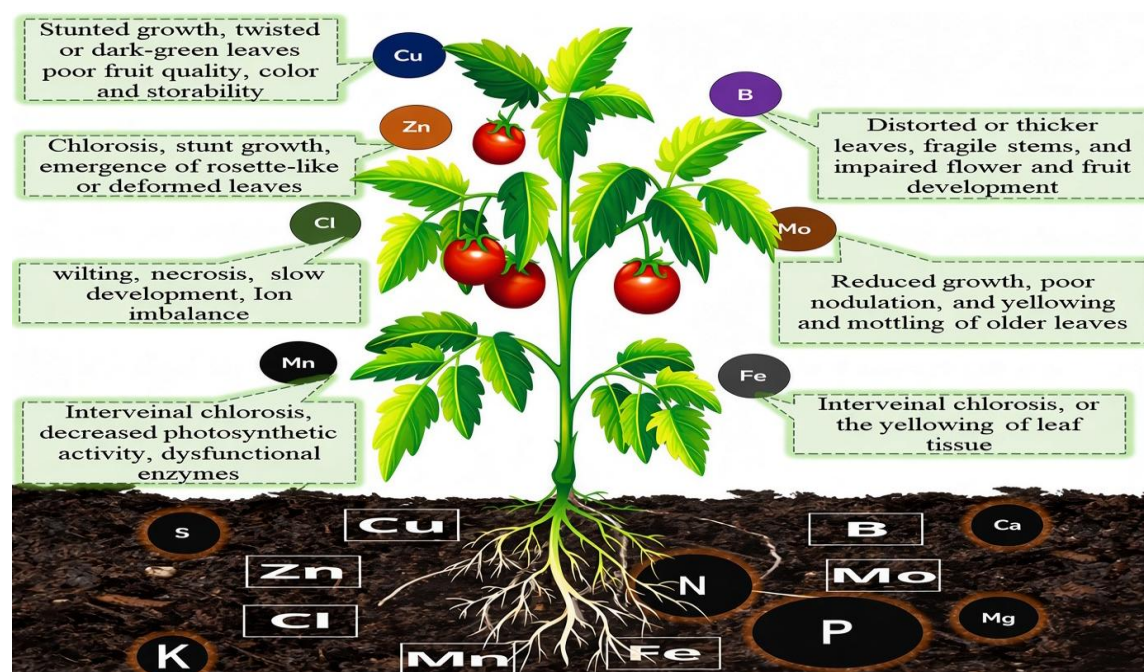


Figure 1: Visual Indicators of Micronutrient Deficiencies in Horticultural Crops.
Source: Ahmed *et al.*, 2024

Micronutrient deficiencies in soil are equally threatening to humans. (Ahmed *et al.*, 2024) reported that a zinc deficiency in humans results in inadequate immunity, genetic abnormalities, organ malfunctions, and more than 0.4 million deaths globally each year. Iron deficiency, according to Von Brackel and Oheim (2024) and Fehsel, causes skeletal deformities, epilepsy, persistent neurological disorders, mood and cognitive abnormalities, reproductive disorders, decreased fertility, and neurological disorders that are linked to Alzheimer's disease. Copper also

increases the risk of cardiovascular problems, causes neurological disorders that are linked to Alzheimer's disease, and causes Menkes disease, a genetic ailment of copper insufficiency that involves a variety of symptoms (Datta & Bose, 2024; Liu & Miao, 2022). Growth retardation, hormone abnormalities, skeletal abnormalities that affect bone health, and disturbances in reproductive and other bodily processes are all signs of human boron deficiencies (Nielsen, 2014). Figure 2 illustrates symptoms of micronutrient deficiencies in humans.

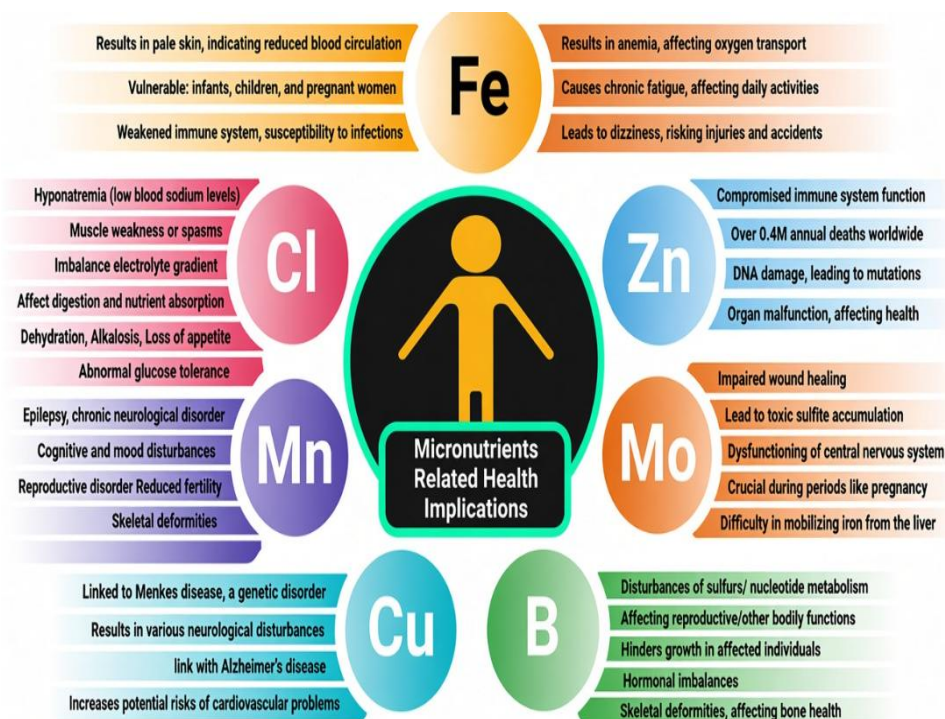


Figure 2: Deficiencies of Micronutrients in Soil as a Threat to Human Beings
Source: Ahmed *et al.*, 2024

MATERIALS AND METHODS

Site Location and Sampling

Three farmlands cultivated by resourceful persons within and outside the Federal University Lokoja (FUL), Kogi State Polytechnic Lokoja (KSP), and the Kogi State Ministry of Agriculture research (KSMA) Felele - Lokoja, all of which are in Lokoja Local Government Area and the capital of Kogi State, Nigeria, were selected for this study.

Lokoja lies between the Greenwich Meridian's longitudes of 6° 41' E and 6° 45' E and the equator's latitudes of 7° 45' N and 7° 51' N. At a height of 45 to 125 meters above sea level, with the River Niger forming its western border (Ebiloma, 2019; Isah and Aliyu, 2024). Hills encircle Lokoja, with Patti Ridge being the highest point. About 107 meters below sea level, the flat region typically experiences undulations. (Jimoh and Salami, 2020). Because of anthropogenic activities like bush clearance, burning, and lumbering, only resistant vegetation still predominates in the study area, which is classified as being inside the Guinea Savannah Belt. (Jimoh and Salami, 2020). Lokoja's climate has wet and dry seasons and is classified by Köppen as a tropical wet and dry climate. With an average yearly rainfall of roughly 1000 mm and a relative humidity of 60%, the rainy season lasts from May to October (Orimoloye, 2016). Between December and April, the highest recorded daytime temperature is 37.9 °C on average (Jimoh and Salami, 2020). Figures 3 and 4 are the maps of the study area.



Figure 3: Map of Kogi State showing the study site, Lokoja
Source: (Olorunfemi, 2021)



Figure 4: Map of Kogi State showing the study site, Lokoja
Source: Google Map

Sampling

This was done in line with the procedure reported by (Dallatu *et al.*,

2016; Rahman *et al.*, 2021) Soil samples were collected randomly from three crop-growing farms and uncultivated (fallow) land as control samples per sampling area. Grasses on the surface of sampling points were weeded off, and seven soil samples were collected to a depth of 10 cm using a soil auger along a triangular transect (Figure 5) at an interval of 210 cm (2.1 m). The samples were placed in separate black polythene bags, washed and rinsed with distilled and deionized water, labeled and transported to the laboratory for analysis.

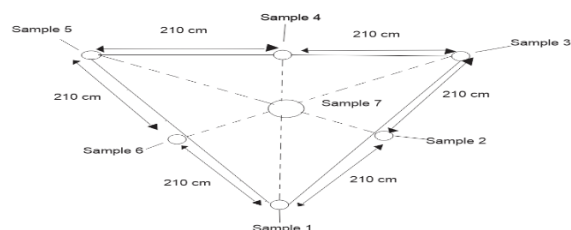


Figure 5: Schematic Description of Field Sampling Plan

Laboratory Methodology

Sample Treatment

This was done according to the method used by (Dallatu *et al.*, 2016; Rahman *et al.*, 2021). Soil samples from each site (200 grams each) were combined and thoroughly mixed to form composite samples: Federal University Lokoja soil (FULs), Kogi State Polytechnic soil (KPs), and Kogi State Farm soil (KSFs). Each composite sample was then spread on a Formica surface board in a dust-free environment to air-dry. The samples were redistributed twice daily for effective drying, after which each sample was gently crushed in a mortar (without grinding) and sieved through a 2 mm plastic sieve into plastic containers. The < 2.00 mm fraction was stored for subsequent analyses.

Routine analysis

Determination of soil moisture content

This was conducted using the thermogravimetric method, also known as the oven - drying method, reported by (Li *et al.*, 2022; Schoonover and Crim, 2015). The weight of moisture was deduced, and Equation 1 was used to calculate the percentage moisture content of the samples.

$$\% \text{ moisture content} = \frac{\text{loss in weight of soil}}{\text{weight of air dried soil}} \times 100 \quad (1)$$

Determination of soil pH by the water method

This was conducted according to the procedure reported by (FAO, 2021). We weighed 10.0 g of each sample into 50 cm³ beakers, added 25 cm³ of deionized water, stirred for 60 minutes, and then allowed it to stand for another 60 minutes. The pH was measured in triplicate.

Determination of soil pH by salt method

This was conducted according to the procedure reported by (FAO, 2021). We weighed 10.0 g of each sample into 100 cm³ polyethylene bottles, added 50 cm³ of potassium chloride solution, stirred for 60 minutes and allowed it to stand for 60 minutes. pH of the supernatant was measured at 25°C. This was done in triplicate.

Estimation of soil organic matter content: combustion method

This was done according to the procedure reported by (Schoonover and Crim, 2015). Loss in weight on ignition measures organic carbon. Oven - dried samples were ignited in a furnace at 360°C for 5 and a half hours. The difference in weight between oven-dried and ignited samples provides the soil's organic matter content. Equation 2 was used to estimate the percentage (%) organic matter content.

Calculation

$$\begin{aligned} \text{Percentage organic matter content} \\ &= \frac{\text{weight of organic matter}}{\text{mass of oven dried soil}} \\ &\times 100 \quad (2) \end{aligned}$$

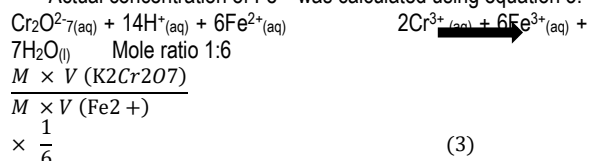
Estimation of soil organic matter content: Walkley-Black wet oxidation method

This was done in line with the method reported by (Palma-López *et al.*, 2024; Bhardwaj *et al.*, 2024). About 1.00 g of air-dried sample was placed in a 500 cm³ Erlenmeyer flask. About 10 mL of 0.167 M K₂Cr₂O₇ and 20 cm³ concentrated H₂SO₄ were added. The mixture was stirred for one minute and allowed to stand in a fume hood for 30 minutes. Then, 200 mL of water was added to the flask, and the suspension was filtered through acid-resistant filter paper (Whatman No. 540). O-phenanthroline indicator was added to a 0.5 M (NH₄)₂Fe(SO₄)₂·6H₂O solution, titrated until the color changed from green to dark green, and then ferrous sulfate heptahydrate was added to standardize the solution.

Calculations

A. Actual concentration of iron(ii) solution

Actual concentration of Fe²⁺ was calculated using equation 3.



M_{Fe} (actual concentration of Fe²⁺ was calculated)

B. Organic matter

Given that 1cm³ 0.167 M K₂Cr₂O₇ = 3 mg carbon = 0.003g carbon

% Organic carbon = (B - T) × M × 0.003g × 1.33 × 100/W

Where:

B = Blank titre value

T = Sample titre value

M = Molarity of titrant

% Organic matter = % organic carbon × 1.724

Determination of cation exchange capacity (CEC)

We adopted the method described by Estafan *et al.* (2013). We accurately weighed 5 g of the sampled soil on an analytical balance and transferred it to a 50 cm³ centrifuge tube. Add 25 cm³ of 1.0 M sodium acetate solution to the tube, cover it with a stopper, and shake in a mechanical shaker for 5 minutes. Then centrifuge at 2000rpm for 5 minutes to clear the supernatant. The liquid was decanted completely, and the extraction procedure was repeated three more times. Instead of Sodium acetate, ethanol was used to reduce the electrical conductivity to less than 40 mS/cm. To displace the sodium adsorbent, 1.0 M ammonium acetate was used. After shaking and centrifuging three times with ammonium acetate, the supernatant was collected through filtration into a 100 cm³ volumetric flask and made up to volume with ammonium

acetate solution. The sodium concentration was determined using a flame photometer (JENWAY Model: PFP 7 flame photometer) after calibration with a series of known sodium concentrations in the range of 1-10 ppm (Estafan *et al.*, 2013).

The ammonium acetate-extractable sodium that is exchangeable Na in ng/100g soil = b

$$\frac{Na \text{ Con. of extract in } \frac{Meq}{litre(Y)} \times 100}{Wt. of soil in g(5)} \times \frac{Vol. of extract in ml(100)}{1000} = \frac{Y \times 10}{5} = 2Y \quad (4)$$

Soil Characterization and Elemental Analysis Using SEM-EDX Methods

This was done in line with the method reported by (Akhtar *et al.*, 2023a). The SEM-EDX method identifies possible constituents and streamlines the description of soil morphology by analyzing minute traces (Akhtar *et al.*, 2023). Each sample image was 1280 by 960 pixels (19.84 pixels).

Analysis for micronutrients using Atomic Absorption spectrometry (AAS)

This was done in line with the method reported by (FAO, 2023 ; Dai *et al.*, 2023 ; Mao *et al.*, 2017). We weighed about 0.5 g of each sample into a 100 cm³ beaker. We added 10 cm³ of 37% HCl and 5 cm³ of 65% HNO₃ to the sample and covered it with a watch glass. Boil the mixture at 95 to 105 °C for 3 hours. The watch glass was removed and dried. Add about 25 cm³ of 5% HCl, heat for about 10 minutes, then cool to room temperature. The mixture was then filtered into a 100 cm³ flask. The filtrate was made up to the mark with deionized (demineralized) water and analyzed for Fe, Mn, Cu, Zn, Mo, and Ni. The concentrations of total micronutrients were measured using AAS (ICCP 6300, Thermo Scientific, USA)

RESULTS AND DISCUSSION

Tables 1, 2, 3, 4, 5 and 6 show percentage moisture content, soil pH (water method), soil pH (KCl method), organic matter by ignition, organic matter by Walkley-Black wet method, cation exchange capacity (CEC), characterization of soil particle size by pipette method, characterization of soil particle size by SEM-EDX and concentration (mg/Kg) of Zn, Fe, Cu, Ni and Mn in the soil samples of FCS KSPCS and KMASA

Table 1: Percentage Moisture Content of the Sampled Soils.

Sample	Moisture Content (g)	% Moisture Content
FCS	0.345 ± 0.001	3.45 ± 0.001
KSPCS	0.037 ± 0.002	0.37 ± 0.002
KMACS	0.215 ± 0.001	2.15 ± 0.001
FS _A	0.191 ± 0.001	1.19 ± 0.001
KSPS _A	0.043 ± 0.001	0.43 ± 0.001
KMAS _A	1.954 ± 0.002	19.54 ± 0.002
FS _B	0.249 ± 0.001	2.49 ± 0.001
KSPS _B	0.047 ± 0.001	0.47 ± 0.001
KMS _B	0.895 ± 0.002	8.95 ± 0.002
FS _C	0.217 ± 0.001	2.17 ± 0.001
KSPS _C	0.045 ± 0.002	0.45 ± 0.002
KMAS _C	0.632 ± 0.002	6.31 ± 0.002

Table note:

FCS = Federal University Farm's control sample
KSPCS = Kogi State Polytechnic farm's control sample
KMACS = Kogi State Ministry of Agriculture farm's control sample
S_A = Sample A
S_B = Sample B
S_C = Sample

DISCUSSION OF RESULTS

Percentage moisture content of the sampled soils

Table 1 shows the samples' moisture content (%). The moisture content was 19.54 ± 0.002% for KMASC and 0.37 ± 0.002% for KSPCS. Soil moisture content varied widely; the lowest was 0.037 ± 0.002 g (KSPCS), while the highest was 1.954 ± 0.002 g

(KMASA). KSMASA (sample A) soils with higher moisture content will have better micronutrient mobility and solubility, which will enhance plant absorption (Brady and Weil, 2016). Moisture content

affects the rate of nutrient diffusion and microbial activity, which controls nutrient release. (Lal and Shukla, 2004).

Table 2: pH of the Soil samples by the water method.

Samples	pH of the sampled soils by the H ₂ O method			X ± SD
	First	Second	Third	
FCS	5.78	5.79	5.79	5.79 ± 0.01
KSPC	6.32	6.34	6.36	6.34 ± 0.02
KMACS	3.63	3.55	3.58	3.59 ± 0.04
FSA	6.40	6.48	6.42	6.43 ± 0.04
KSPSA	4.95	4.93	4.91	4.93 ± 0.02
KMASA	3.53	3.71	3.52	3.59 ± 0.11
FSB	5.49	5.46	5.46	5.47 ± 0.02
KSPSB	6.02	6.02	5.99	6.01 ± 0.02
KMSB	3.60	3.64	3.67	3.63 ± 0.04
FSC	5.83	5.85	5.87	5.85 ± 0.02
	6.33	6.30	6.34	6.32 ± 0.02
KSPSC	3.70	3.74	3.72	3.72 ± 0.02
KMASC				

pH of the Sampled Soils by Water Method

Table 2 shows the pH values of the sampled soils. The pH values of the soil samples vary from slightly acidic KSPC (6.34 ± 0.02) to highly acidic KMASC (3.72 ± 0.02). The KMASC (3.72 ± 0.02) was highly acidic, the KSPC (6.34 ± 0.02) was somewhat acidic, and the FSA (6.43 ± 0.04) was ideal for most crops. These values indicated that the soils were either acidic or moderately acidic. At pH values below 5.5, more Fe, Mn, Zn, and Cu dissolve, but they can become dangerous without buffering. (Sposito, 2016).

It is claimed that KSPSC and FSA soils with moderate acidity have good plant nutrient availability and support micronutrient uptake for plant growth. (Jamal *et al.*, 2024). Soils that are acidic ($\text{pH} < 5.5$): The KMACS, KMSB, and KMASA samples had distinctly acidic pH values (3.53–3.74). Although acidic soils make iron and manganese (Mn) more soluble and phosphorus (P) and molybdenum (Mo) less available, they can also make these metals more toxic. (Kopittke *et al.*, 2019). Near-neutral soils (pH 5.5–6.5): Most samples fell into this range, which is frequently optimal for

micronutrient availability (e.g., FCS, KSPCS, FSA, KSPSB, FSC, KSPSC). White and Brown (2010) State that a nearly neutral pH promotes balanced absorption of Zn, Cu, and B (boron). The increased KMASA variation (3.59 ± 0.11) suggests localised soil heterogeneity, which may result from organic matter decomposition or human inputs. This variability emphasises the need for site-specific soil management strategies to address micronutrient surpluses or shortages. (Bünemann *et al.*, 2018). The pH data can serve as a reference for interpreting micronutrient concentration measurements made by atomic absorption spectrophotometry (AAS). Alloway (2013) suggests that while acidic soils (KMACS, KMASA) may have higher Fe/Mn ratios, near-neutral soils (FSA, KSPSC) may have the best Zn/Cu availability. To assess deviations and recommend corrective measures, compare these pH values to global standards (such as FAO guidelines) or regional benchmarks (such as Nigerian savanna soils). For example, the majority of crops may require supplements if they are grown in soils with a pH of less than 4.5 (Sposito, 2016).

Table 3: pH of Sampled Soils by Salt (KCl) Method.

Samples	pH of the sampled soils by the salt (KCl) method			
	First	Second	Third	X ± SD
FCS	5.49	5.45	5.49	5.48 ± 0.01
KSPCS	5.72	5.73	5.72	5.72 ± 0.01
KMACS	2.83	2.92	2.93	2.89 ± 0.06
FSA	6.26	6.23	6.28	6.26 ± 0.02
KSPSA	4.40	4.39	4.38	4.39 ± 0.01
KMASA	2.85	2.83	2.87	2.85 ± 0.02
FSB	5.21	5.12	5.21	5.18 ± 0.02
KSPSB	5.52	5.56	5.55	5.54 ± 0.02
KMSB	2.68	2.72	2.74	2.71 ± 0.03
FSC	5.57	5.57	5.59	5.56 ± 0.01
KSPSC	5.81	5.82	5.82	5.82 ± 0.01
KMASC	2.63	2.75	2.71	2.70 ± 0.06

pH of the Sampled Soils by Salt Method

Table 3 shows the pH values of the sampled soils. The pH values of the soil samples vary from slightly acidic KSPC (6.34 ± 0.02) to highly acidic KMACS (3.72 ± 0.02). Moderate acidity was indicated by KSPC (5.72 ± 0.01), appropriate acidity for most crops was indicated by FSA (6.43 ± 0.04), and severely acidic soils were indicated by KMACS (2.70 ± 0.06). It was claimed that moderately acidic KSPSC and FSA soils have adequate plant nutrient availability and support micronutrient uptake for plant growth. Because K^+ ions displace exchangeable H^+ and Al^{3+} , the pH of KCl is typically 0.3–1.0 units lower than that of water. (Brady and Weil, 2016) (Lal and Shukla, 2004) The pH values of soil samples obtained using the salt (KCl) method from Federal University Lokoja (FUL), Kogi State Ministry of Agriculture (KSMA), and Kogi State Polytechnic (KSP) provide crucial details regarding the potential acidity and exchangeable ion dynamics in the soils (Table 3). The KCl method shows the "reserve acidity" of soils and typically yields lower pH values than the water approach because K^+ ions displace exchangeable Al^{3+} and H^+ ions (Thomas, 2018; Sposito, 2016). Understanding micronutrient bioavailability requires an understanding of how pH affects the solubility, speciation, and plant uptake of essential micronutrients such as Fe, Zn, and Mn. (Alloway, 2013).

Samples from KMACS (2.89 ± 0.06), KMASA (2.85 ± 0.02), KMSB (2.71 ± 0.03), and KMACS (2.70 ± 0.06) showed extreme acidity. (Kopittke *et al.*, 2019) This suggests that low pH values indicate increased solubility of Al^{3+} and Mn^{2+} , which can be detrimental to plants and impede root development. These conditions may limit P and Mo availability while increasing Fe/Mn intake to potentially hazardous levels. (White and Brown, 2010). In terms of micronutrient availability, most samples (e.g., FCS: 5.48 ± 0.01 ; KSPCS: 5.72 ± 0.01 ; FSA: 6.26 ± 0.02) fell within this range, which is generally favourable. For instance, 5.5 to 6.5 is the ideal pH range for Zn and Cu availability. (Alloway, 2013).

Table 4a: Percentage Soil Organic Matter Content of the Sampled Soils by Ignition Method.

Sample	Organic content (g)	% Organic matter content
FCS	0.432 ± 0.001	4.47 ± 0.001
KSPCS	0.080 ± 0.010	0.80 ± 0.010
KMACS	2.979 ± 0.001	30.44 ± 0.001
FSA	0.351 ± 0.001	3.57 ± 0.001
KSPSA	0.109 ± 0.001	1.09 ± 0.001
KMASA	0.557 ± 0.001	6.94 ± 0.001
FSB	0.388 ± 0.001	3.98 ± 0.001
KSPSB	0.140 ± 0.001	1.41 ± 0.001
KMASB	0.445 ± 0.002	4.89 ± 0.002
FSC	0.345 ± 0.001	3.53 ± 0.001

KSPSC	0.129 ± 0.001	1.30 ± 0.001
KMACS	0.366 ± 0.002	3.91 ± 0.002

Percentage Soil Organic Matter Content by Ignition Method

Table 4a shows significant variation in soil organic matter (SOM) content among soils sampled from Federal University Lokoja (FUL), Kogi State Ministry of Agriculture (KMA), and Kogi State Polytechnic (KSP). Because it affects microbial activity, water retention, and nutrient cycling, organic matter is a crucial indicator of soil health. (Lal, 2020). According to the data, KSPCS (Kogi State Polytechnic Control Sample) has the lowest organic matter content ($0.80 \pm 0.010\%$), while KMACS (Kogi State Ministry of Agriculture Control Sample) has the highest ($30.44 \pm 0.001\%$). The low SOM in KSPCS (0.80%) and KSPSA (1.09%) may indicate soil deterioration, possibly due to erosion or overcultivation, consistent with research linking intensive farming to SOM depletion. (Xu *et al.*, 2023).

Soils containing less than 2% SOM are often associated with lower agricultural yields and nutritional deficiencies. (Lehmann and Kleber, 2015). The KMACS's exceptionally high SOM indicates fertile soil conditions, likely from organic additions or minimal disturbance. This is consistent with research by (Batiano *et al.*, 2007), which found that composting and other agricultural practices encourage SOM accumulation. According to (Six *et al.*, 2004), these percentages correspond to the 20–40% range that characterizes soils with high levels of organic matter in tropical agroecosystems.

Table 4b: Percentage Soil Organic Matter Content by Wet Oxidation Method of the Sampled Soils.

Sample	% Organic Carbon	% Organic matter content
FCS	5.69 ± 0.10	9.80 ± 0.10
KSPCS	6.96 ± 0.04	12.00 ± 0.04
KMACS	2.25 ± 0.02	3.89 ± 0.02
FSA	4.32 ± 0.05	7.44 ± 0.05
KSPSA	1.60 ± 0.02	2.75 ± 0.02
KMASA	1.42 ± 0.04	2.44 ± 0.04
FSB	7.11 ± 0.03	12.26 ± 0.03
KSPSB	2.55 ± 0.20	4.40 ± 0.20
KMASB	4.30 ± 0.02	7.41 ± 0.02
FSC	5.57 ± 0.09	9.60 ± 0.09
KSPSC	2.47 ± 0.03	4.26 ± 0.03
KMACS	3.41 ± 0.03	5.88 ± 0.03

Percentage Soil Organic Matter Content by Walkley-Black Wet Oxidation Method

The percentage of soil organic matter (SOM) and soil organic carbon (SOC) in soil samples collected using the Walkley-Black wet oxidation method from different locations is shown in Table 4 b. Differences in land use, management techniques, and environmental factors explain the wide range of SOM across the sites under investigation. The following provides a comprehensive analysis aligned with the study's goals: SOM content varies significantly by region, ranging from 2.44% (KMASA) to 12.26% (FSB). While low values (such as KMASA and KSPSA) may suggest degraded or heavily farmed soils, high values (such as FSB and KSPCS) indicate rich soils with strong nutrient-retention

capacity.

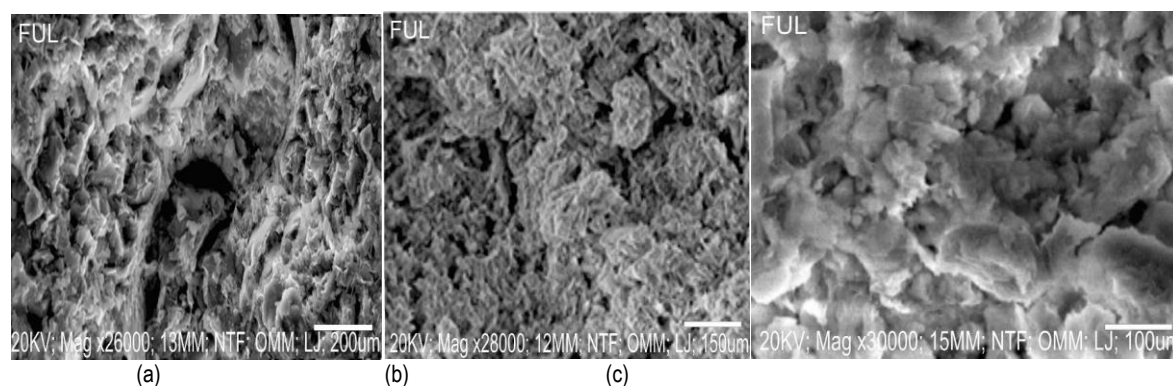
The Walkley-Black method, which assumes that organic matter contains about 58% carbon, is compatible with the conversion factor of 1.72 (from SOC to SOM), according to Nelson and Sommers (1996). KMASA and KSPSA have the lowest SOM (2.44% and 2.75%, respectively), which may result from erosion or overcultivation. FSB and KSPCS have the highest SOM (12.26% and 12.00%, respectively), likely due to organic amendments or minimal disturbance (Six *et al.*, 2004). Micronutrient absorption depends on SOM. High SOM (like FSB) enhances chelation of metals such as Zn, Fe, and Cu, reducing leaching and increasing plant uptake (Bolan *et al.*, 2014). However, fertilization may be necessary to address micronutrient deficiencies (like KMASA) caused by low SOM. The two highest SOMs, KSPCS (12.00%) and FSB (12.26%), suggest either low tillage or high organic inputs (such as crop residues and manure) to maintain carbon (Xu *et al.*, 2023). Lowest SOM: According to KSPSA (2.75%) and KMASA (2.44%), erosion, overcultivation, or sandy textures can all lead to degradation issues (Choudhury *et al.*, 2021). Use of Land and SOM: A 2023 study in Geoderma found that conservation agriculture, which uses less tillage and cover crops, increases SOM by 15–30% compared with conventional farming (Xu *et al.*, 2023). A 2024 Science of the Total Environment study found that adding SOM to tropical soils above 5% lowers zinc leaching by 40% (Li *et al.*, 2022). Deficiency Thresholds: Research in Agriculture, Ecosystems and Environment (2023) states that SOM below 3% is linked to decreased Fe/Mn bioavailability (Bolan *et al.*, 2014). Trends in Global SOM: A 2022 study found that sustainable practices can quadruple SOM in tropical farm soils, which typically average 3.5%. Specifics for Nigeria: A 2021 study published in Soil and Tillage Research found that SOM in Nigerian savanna soils ranged from 2.8 to 11.4% (Lombardo *et al.*, 2022). Nature Communications published a meta-analysis (Lombardo *et al.*, 2022).

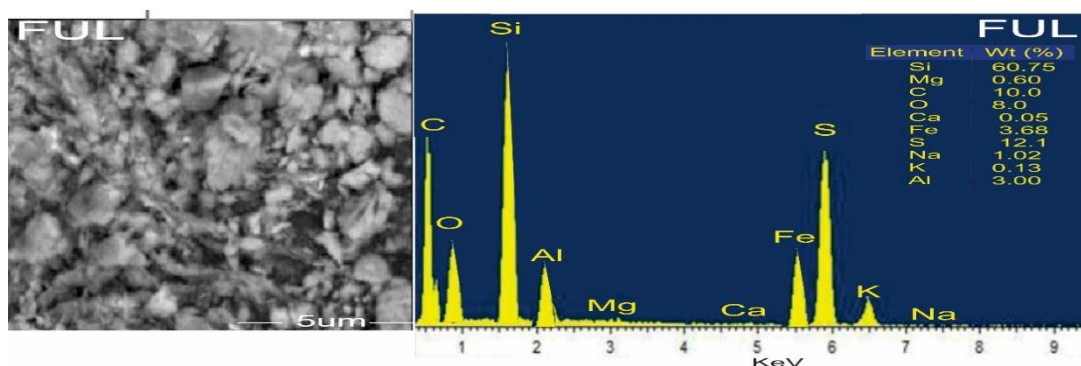
Table 5: Cation Exchange Capacity of the Sampled Soils

Sample	Metal concentration(mg/l)	CEC (Cmol _c /Kg)
FCS	26.14	52.27
KSPCS	9.56	19.13
KMACS	26.28	52.56
FSA	28.32	56.64
KSPSA	15.52	31.05
KMASA	30.34	60.69
FSB	27.60	55.20
KSPSB	14.21	28.42
KMASB	29.89	59.78
FSC	27.39	54.79
KSPSC	18.08	36.15
KMASC	29.93	59.87

Cation Exchange Capacity of the Sampled Soils

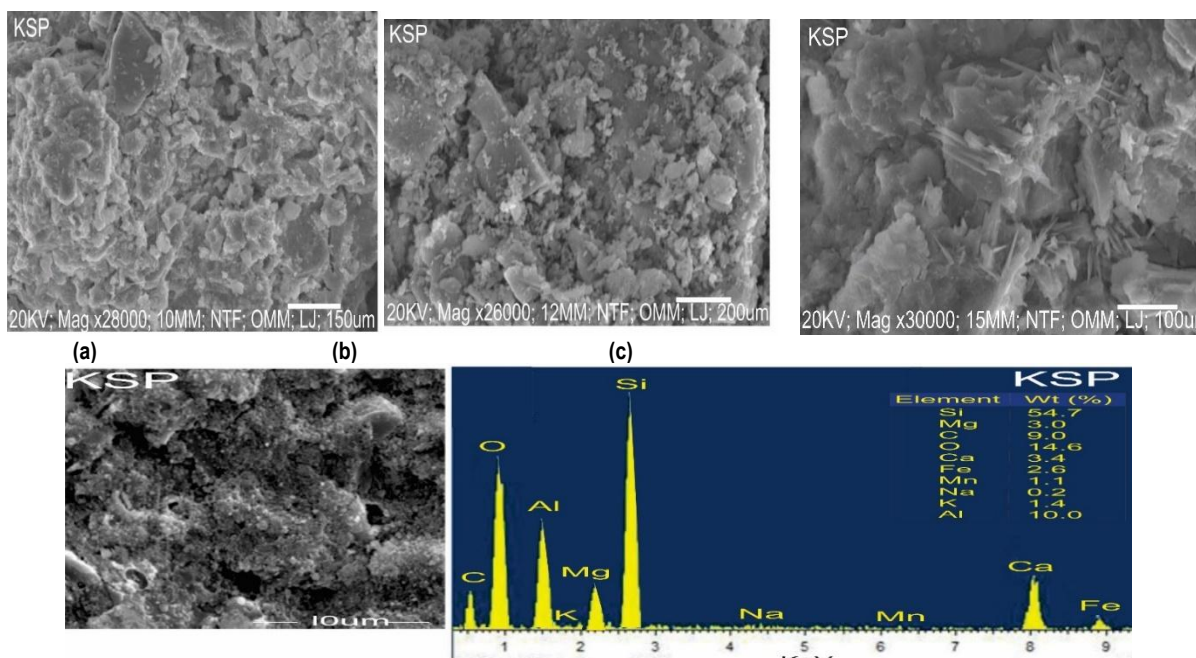
Micronutrient control is significantly impacted by the notable variations in observed CEC values (19.13–60.69 cmol_c/kg across sampling locations. "High CEC soils (FSA: 56.64; KMASA: 60.69) exhibit a significant potential to retain nutrients, which is typical of soils rich in clay or organic matter," according to (John *et al.*, 2019). However, strong binding with exchange sites caused by high CEC may result in micronutrient immobilisation, particularly for Zn and Cu (Hervilly *et al.*, 2021). Micronutrient leaching is more likely in sand or heavily worn soils with low CEC (KSPCS: 19.13; KSPSB: 28.42) due to reduced nutrient retention. (Saha *et al.*, 2017).





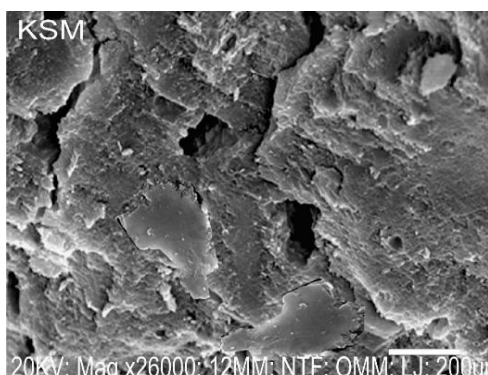
(d)

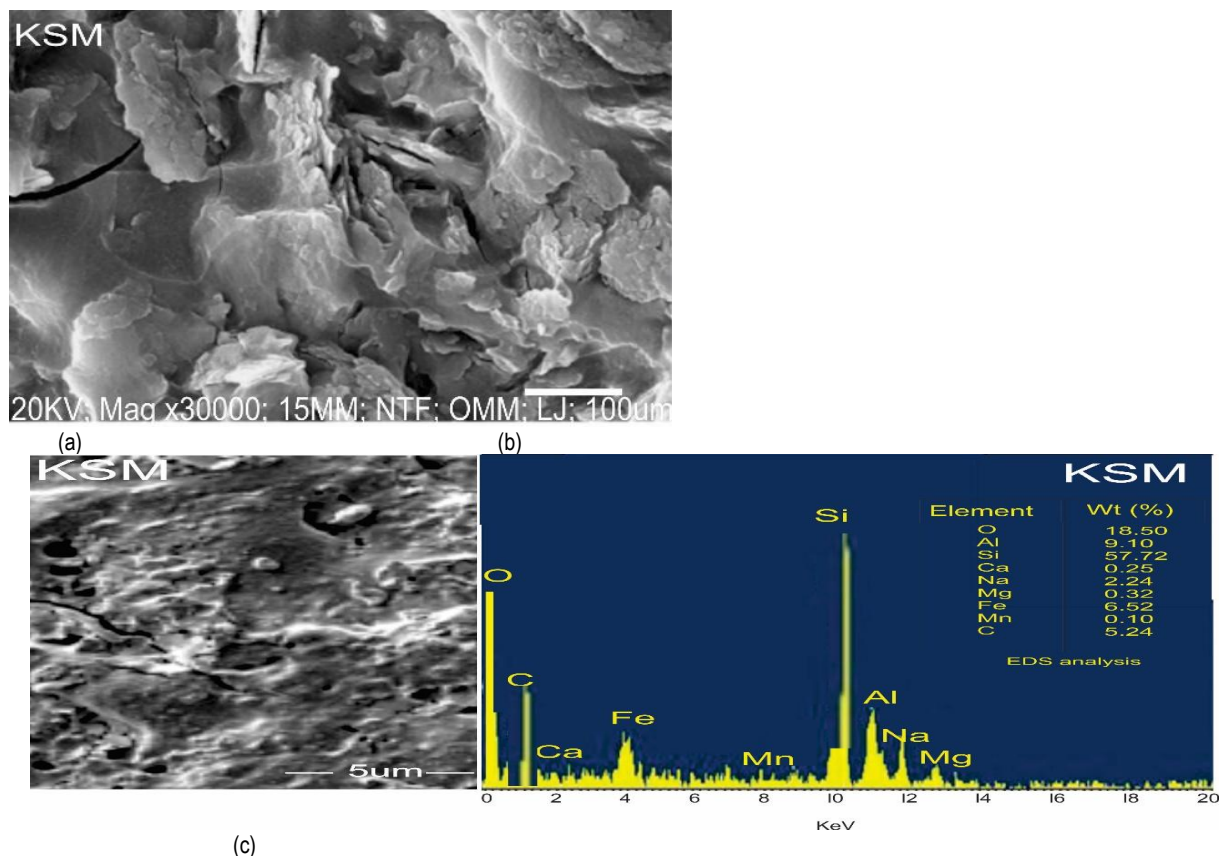
Plate 1: SEM images of FUL sampled soils



(d)

Plate 2: SEM images of KSP sampled soil





(c)
Plate 3: SEM images of KSM sampled soils

Characterization of Soil Particle Distribution by Scanning Electron Microscope EDX

Plate 1 (a, b, c and d)

The FUL SEM micrograph of the soil sample (plate iv x 30000) shows a very uneven, porous structure with a wide range of particle sizes and many micro voids. This shape type indicates a high surface area, which explains the soil's ability to absorb and retain micronutrients for plant growth. (Das *et al.*, 2019). Because the soil matrix is porous, it provides more active sites for micronutrient binding, increasing the availability of Fe, Mn, Zn, and Cu elements. (Das *et al.*, 2019)

The heterogeneity of soil texture is also reflected in the presence of small and coarse particles, with finer fractions (like clay minerals) having higher nutrient sorption capacities because of their higher surface reactivity and cation exchange properties. (Akhtar *et al.*, 2023b). Because they preserve the fundamental levels of micronutrients that plants can access, these characteristics are essential for soils used in sustainable agriculture (Bhowmik *et al.*, 2022).

The SEM image shows a high surface roughness, sharp, angular particles, and a crumbly, highly porous structure. A highly worn mineral soil containing primary and secondary minerals is indicated by this microtopography, which is known to improve micronutrient adsorption through increased surface area and charge site interaction. (Wang *et al.*, 2022). Interconnected pores allow for longer agricultural production because they enhance nutrient

exchange and retention. (Zhou *et al.*, 2024).

This micrograph shows plate-shaped particles that are more layered and dense. These characterize clay minerals like montmorillonite and kaolinite. According to (Zhou *et al.*, 2024), clays show improved micronutrient retention because of their high cation exchange capacity (CEC) and strong affinity for metal ions. According to (Aftab and Hakeem, 2020), this morphology supports the idea that soils in these regions may hold and gradually release micronutrients essential to plant health.

The morphological differences between the two samples suggest that changes in soil porosity and mineralogy may explain variation in micronutrient content between measured locations. For example, clay soils retain micronutrients better than sandy or silty soils (Zhang *et al.*, 2019).

Plate 2 (a, b, c and d)

A heterogeneous mixture of particles with varying sizes and shapes is clearly visible in the KSP SEM images, as shown on plates a, b, c and d. This is supported by the fact that soils frequently contain a range of particle sizes, from sand to clay. (Lal, 2020). Some particles are rounded or sub-angular, but many are angular and platy. The soil's parent material and weathering processes control the morphological variation. (White and Brown, 2010). The presence of both larger sand-sized grains and finer, silt-sized particles suggests a polydisperse system, a defining feature used to categorize soil textures.

The soil's texture, which influences aeration, nutrient availability, and water-holding capacity, is determined by the proportions of sand, silt, and clay. (Alloway, 2013). The observed range of particle sizes in the SEM image suggests the soil is likely a mixed textural class, which may affect farm productivity.

At a $\times 26000$ magnification, the KSP soil sample's SEM picture reveals a denser and less porous character than that of FUL. Sand-sized particles predominate, as shown by the granular, coarse texture. Micronutrient availability and water-holding capacity would be diminished by relatively low porosity, which is typically associated with sandy or loamy sand soils. (Xu *et al.*, 2023). Angular particles reflect mechanical deterioration, which could result from erosion or human activity.

The micrographs primarily show the platy, sheet-like shape of KSM clay minerals, as seen in plates l, j and k above (Xu *et al.*, 2023). The individual platelets are more widely distributed in some areas, while the clay particles are observed to be closely packed in aggregates in other areas. The degree of aggregation and alignment of these clay particles greatly affects the soil's physical properties, such as its porosity, aeration, and water-holding capacity. Plant nutrient availability can also be influenced by these traits (Lombardo *et al.*, 2022). The presence of these closely packed clay formations would also affect the soil's capacity to hold onto micronutrients. Clay minerals' large surface area and negative charge allow them to adsorb and retain positively charged micronutrients through cation exchange reactions (Sparks, 2020). Therefore, the type of clay minerals that are present would determine the soil's capacity to hold onto nutrients.

Plates 3 (a, b, c)

Table 6: Concentrations of Zn, Ni, Cu, Mn and Fe in mg/Kg of the sampled soils

Concentrations of the Micronutrients in mg/Kg					
Samples	Zn	Ni	Cu	Mn	Fe
FSC	24.92 $\pm$ 0.014	11.03 $\pm$ 0.014	123.53 $\pm$ 0.021	230.66 $\pm$ 0.014	25846.07 $\pm$ 0.057
KSPCS	21.11 $\pm$ 0.021	89.37 $\pm$ 0.007	86.66 $\pm$ 0.014	277.52 $\pm$ 0.007	34046.62 $\pm$ 0.021
KMACS	30.36 $\pm$ 0.021	98.82 $\pm$ 0.028	131.09 $\pm$ 0.028	236.26 $\pm$ 0.028	52326.70 $\pm$ 0.021
FSA	8.54 $\pm$ 0.057	21.26 $\pm$ 0.014	28.54 $\pm$ 0.028	225.63 $\pm$ 0.014	21559.41 $\pm$ 0.007
KSPSA	26.57 $\pm$ 0.014	80.84 $\pm$ 0.014	74.97 $\pm$ 0.007	331.52 $\pm$ 0.007	102408.95 $\pm$ 0.007
KMASA	44.23 $\pm$ 0.014	86.49 $\pm$ 0.014	204.23 $\pm$ 0.028	312.92 $\pm$ 0.014	117791.75 $\pm$ 0.028
FSB	23.70 $\pm$ 0.021	54.43 $\pm$ 0.007	64.67 $\pm$ 0.028	208.48 $\pm$ 0.014	32466.47 $\pm$ 0.035
KSPSB	27.18 $\pm$ 0.035	50.66 $\pm$ 0.014	109.84 $\pm$ 0.035	308.44 $\pm$ 0.057	61624.35 $\pm$ 0.007
KMASB	40.97 $\pm$ 0.014	17.31 $\pm$ 0.007	211.32 $\pm$ 0.021	345.76 $\pm$ 0.007	126410.55 $\pm$ 0.021
FSC	24.24 $\pm$ 0.028	94.76 $\pm$ 0.014	55.56 $\pm$ 0.042	249.13 $\pm$ 0.007	34046.60 $\pm$ 0.028
KSPSC	32.12 $\pm$ 0.028	79.71 $\pm$ 0.021	91.57 $\pm$ 0.021	210.92 $\pm$ 0.014	52326.71 $\pm$ 0.028
KMASC	41.75 $\pm$ 0.007	42.91 $\pm$ 0.035	171.41 $\pm$ 0.021	316.27 $\pm$ 0.007	88424.07 $\pm$ 0.014

Concentrations of Zn, Ni, Cu, Mn and Fe in mg/Kg of the sampled soils

Determining soil fertility and directing sustainable farming practices require an analysis of the micronutrient concentrations in agricultural soils. The levels of zinc (Zn), nickel (Ni), copper (Cu), manganese (Mn), and iron (Fe) in various soil samples from farms connected to Federal University Lokoja (FUL), Kogi State Ministry of Agriculture (KMA), and Kogi State Polytechnic (KSP) vary noticeably, according to the data shown in Table 6. These findings are in line with international studies that emphasise the significance of micronutrients for soil health and crop productivity (Alloway, 2013).

Crucial Findings and analysis

Iron (Fe) Dominance: The soils' iron contents ranged from 126,410.55 mg/kg (KMAB) to 21,559.41 mg/kg (FSA), which is a very high amount. Lateralization processes are responsible for the high levels of iron in tropical soils (Mir, 2025). On the other hand, too much iron can cause nutritional imbalances and interfere with the absorption of other micronutrients, like zinc (Assunção *et al.*, 2022).

Zinc (Zn) Variability: The Zn concentrations ranged from 8.54 to 44.23 mg/kg, with KMASA having the highest value and FSA having the lowest. For most crops, 10–50 mg/kg is the adequate range (Assunção *et al.*, 2022). According to (Shiwakoti *et al.*, 2019), the fluctuation could be caused by changes in the amount of organic matter or previous fertilizer applications.

The ranges for Cu and Ni were 11.03 mg/kg (FSC) to 98.82 mg/kg (KMACS) and 28.54 mg/kg (FSA) to 211.32 mg/kg (KMAB), respectively. Both geological parent materials and human inputs may contribute to the high Ni levels in KMACS and KMAMA soils (Adriano, 2001). Because of their possible toxicity, Cu levels over 100 mg/kg (such as KMAB) might need to be monitored (Adriano, 2001).

Some samples had elevated Ni levels (11.03–98.82 mg/kg) above the 50 mg/kg threshold for uncontaminated soils, which raised concerns about toxicity risks (Mir, 2025). Similar findings in Hawaii linked road sediments and agricultural runoff to anthropogenic sources of Ni and Cu pollution (Sutherland, 2002); and Cu levels in the sampled soils (28.54–211.32 mg/kg) were higher than those reported in Kashmir Valley (10–59 mg/kg) (Mir, 2025), suggesting localized enrichment, possibly from agrochemicals or industrial activities.

Consistency of Manganese (Mn)

Since manganese is abundant in acidic soils, its concentrations (208.48–345.76 mg/kg) were comparatively consistent across samples (Kochian *et al.*, 2021). According to (Hervilly *et al.*, 2021), these concentrations are adequate for plant growth and are non-toxic. Since manganese (Mn) and boron (B) are abundant in acidic soils, Mn levels (208.48–345.76 mg/kg) were comparatively constant across samples (Assunção *et al.*, 2022). But long-term research in the Pacific Northwest showed that soils subjected to constant wheat-fallow rotations experienced Mn depletion, highlighting the importance of organic amendments in Mn restoration (Shiwakoti *et al.*, 2019).

Comparative Evaluation Using Benchmarks

The findings were compared to the guidelines for agricultural soils provided by the Food and Agriculture Organisation (FAO) and the World Health Organisation (WHO). While Zn and Cu levels mostly stayed within advised ranges (FAO, 2020), Fe and Mn levels were above global norms (WHO, 2019). According to Kabata-Pendias (2010), Ni values in certain samples (such as KMACS) were higher than the 50 mg/kg threshold for uncontaminated soils, indicating localized enrichment.

Table 7: tables for the principal component analysis

Extracted Eigenvectors			
	Coefficient s of PC1	Coefficients of PC2	
% Moisture content	-0.39	0.4654 8	
% O.M ignition	-0.3151	0.1782 8	
% SOC	0.58841	0.3462 3	
% SOM	0.58841	0.346	
CEC	-0.2371	0.71	

Table 8: Eigen values of the correlated Matrix

Eigenvalues of the Correlation Matrix			
	Eigenvalue	Percentage of Variance	Cumulative
1	2.34778	46.96%	46.96%
2	1.44866	28.97%	75.93%
3	0.91162	18.23%	94.16%
4	0.29195	5.84%	100.00%
5	1.00E-06	0.00%	100.00%

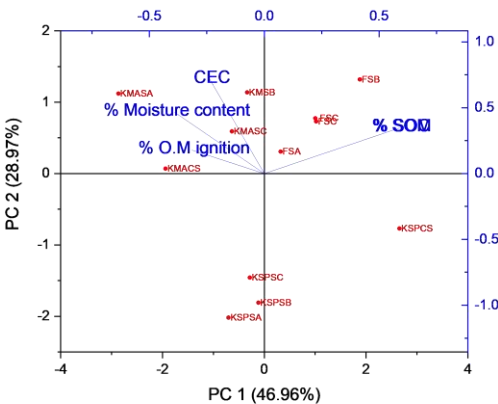


Figure 6: Bi - Plots of the Principal Component Analysis (PCA) for Micronutrients and its Physicochemical Parameters in the Sampled Soils From FUL, KSP and KSM Lokoja Kogi State.

Examining Principal Component Analysis (PCA) Bi-plot in Relation to Micronutrient Management and Soil Fertility

The Principal Component Analysis (PCA) biplot that is produced offers a potent multivariate overview of the connections between soil characteristics and sample locations, answering the research goals of comparing soils and incorporating standard analysis according to the data shown on Tables 6 and 7, illustrated on the Figure 6 respectively.

Soil Types Clearly Delineated by Source Institution

The obvious grouping of samples according to their institutional source is the most important result. The close clustering of Kogi State Ministry of Agriculture (KMAS) samples (KMASA, KMASB, and KMACS) suggests that the parent material or management practices used on these farms are uniform, indicating a high degree of homogeneity in their soil properties. The isolated Federal University Lokoja (FUL) sample and the Kogi State Polytechnic (KSP) cluster, on the other hand, show that the soils from these three institutions are pedologically different. In soil science, this type of spatial clustering is a typical and potent result of PCA, successfully achieving the goal of comparing these soils to one another (Lehmann and Kleber, 2015).

The Role of Soil Organic Matter and Cation Exchange Capacity in Micronutrient Retention

According to the biplot, Cation Exchange Capacity (CEC) and Soil Organic Matter (SOM) are closely related to the main driver of soil differentiation (along PC1). High SOM and CEC are the distinguishing features of these soils, as indicated by the KMA cluster's tight alignment with these vectors. When analysing the preliminary micronutrient concentration data, this discovery is essential.

SOM, CEC, and the retention of cationic micronutrients are known to be mechanistically related. Numerous exchange sites found in soil organic matter bind and hold onto positively charged ions, increasing the soil's total CEC and lowering nutrient leaching (Brady and Weil, 2016). This directly explains why the initial concentration table showed exceptionally high levels of Fe and

other metals in the KMAS samples (e.g., KMASA Fe = 117791.75 mg/kg). These micronutrients are accumulated and stabilized by the high SOM content in these soils, which serves as a reservoir. SOM is one of the most important factors influencing the bioavailability and sequestration of heavy metals in soils, especially iron and copper, according to recent studies (Lehmann and Kleber, 2015).

Soil Moisture's Impact on Nutrient Dynamics

The KSP cluster is associated with the second principal component (PC2), which seems to be affected by the moisture content. The solubility and chemical speciation of nutrients like Mn and Fe are determined by redox conditions and microbial activity, both of which are significantly influenced by soil moisture (Shaheen *et al.*, 2016). The reduction of Mn⁴⁺ and Fe³⁺ to more soluble and bioavailable forms (Mn²⁺ and Fe²⁺) due to fluctuating moisture levels may have an impact on their mobility and plant uptake. This implies that one of the main ways that the KSP soils differ from the others may be through water management techniques.

Conclusion

In conclusion, the PCA biplot offers a useful interpretation of the soil data that goes beyond descriptive statistics. It proves that; the three institutions' soils differ greatly from one another. The elevated micronutrient levels at the KMA sites are likely not due to contamination but are a direct result of naturally high soil fertility characterized by abundant organic matter and a high cation exchange capacity. The moisture content characteristics of the KSP soils set them apart and may have an impact on nutrient availability via various pathways. In order to provide a solid, evidence-based comparison, this analysis effectively connects the routine soil properties to the micronutrient data, establishing a useful baseline for upcoming environmental monitoring and agricultural management.

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