Investigating Trace Element (Micronutrient) Availability/Contamination in Soils within Niger State Using Geospatial Techniques

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ABSTRACT

Trace elements are chemical elements found in small concentrations within soil, and are also known as minor elements or micronutrients. Examples include boron, copper, iron, manganese, molybdenum, and zinc. While present in small amounts, they play vital roles in plant and animal nutrition and can have significant environmental impacts if levels become too high. The transfer of trace elements between soil phases represents the primary processes controlling their behaviour and bioavailability. This study examines the distribution of trace elements in soils within Lapai and Agaie Local Government Areas (LGAs), Niger State, Nigeria. The ever-increasing pressure on land for agriculture, mining, and other activities continuously disrupts the balance, concentrations, and mobility of various trace elements. In many cases, deficiency or toxicity of micronutrients affects plant growth, reducing yield, stunting development, and causing premature leaf drop, among other symptoms.

A total of fifty (50) soil samples were systematically collected from different sites across mining areas of Lapai and Agaie LGAs and transported to the Centre for Dryland Agriculture, Bayero University Kano, where comprehensive chemical analysis was conducted. The laboratory results were subsequently subjected to Inverse Distance Weighted (IDW) spatial interpolation to examine the distribution patterns of trace elements across the study area. For copper, a concentration range of 1.1 to 3 mg/kg (ppm) was observed. Zinc concentrations ranged from approximately 2 to 14 mg/kg, while iron concentrations ranged between 147 and 240 mg/kg (ppm). Manganese concentrations were generally below typical levels, ranging between 17 and 32 mg/kg. Trace element levels in soils within the study area are generally adequate, with no toxicity detected and only minor deficiencies of manganese, copper, and zinc. Targeted management of manganese levels may be required to achieve optimum soil and plant health.

Keywords: Trace element, micronutrient, soil health, toxicity, deficiency, geospatial analysis, IDW interpolation, Niger State.

INTRODUCTION

Trace elements are chemical elements found in small concentrations within soil, typically less than 0.1% (or 1,000 mg/kg). They are also referred to as minor elements or micronutrients. Common examples include boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn). While present in small amounts, they play vital roles in plant and animal nutrition and can exert significant environmental impacts when their concentrations become excessive. Certain trace elements, such as arsenic (As), cadmium (Cd), and lead (Pb), can be toxic even at relatively low levels.

Many trace elements are essential for healthy plant growth and development, acting as co-factors for enzymes and facilitating crucial biochemical processes. Some, including copper, cobalt, iodine, selenium, and zinc, are also essential for animal health. While beneficial at appropriate concentrations, these elements can be harmful at elevated levels, becoming toxic to plants, animals, and humans.

Sources of trace elements in soils include both natural and anthropogenic pathways. Natural sources encompass parent rock weathering, mineral dissolution, and volcanic activity. Anthropogenic sources include mining and smelting operations, industrial processes, application of chemical fertilizers, and discharge of industrial wastewater. Soil chemistry, particularly pH, organic matter content, and redox potential (drainage status) , significantly influences the binding, release, and bioavailability of trace elements. Additionally, plant root–soil particle interactions play a crucial role in trace element uptake, and different plant species exhibit varying capacities to absorb and utilize these elements.

The soil–plant transfer of trace elements constitutes an important component of biogeochemical cycling. It is a complex process governed by multiple factors of geochemical, climatic, biological, and anthropogenic origin. In general, well-aerated acidic soils tend to promote the mobility and bioavailability of trace metals such as cadmium (Cd) and zinc (Zn), while poorly aerated, neutral, or alkaline soils tend to retard the mobility of most trace elements. Understanding these processes is critical to assessing both the environmental risk and agronomic implications of trace element distribution in soils.

Plants require 18 essential nutrients, classified as macronutrients and micronutrients. Macronutrients include: Structural nutrients (Carbon, Hydrogen, Oxygen); Primary nutrients (Nitrogen, Phosphorus, Potassium); and Secondary nutrients (Calcium, Magnesium, Sulphur). Micronutrients, required in smaller quantities, include Iron (Fe), Boron (B), Copper (Cu), Chlorine (Cl), Manganese (Mn), Molybdenum (Mo), Zinc (Zn), Cobalt (Co), and Nickel (Ni). Both deficiencies and excesses of these micronutrients can affect plant productivity and quality.

This study aims to examine the distribution of trace elements in soils within Lapai and Agaie LGAs, Niger State. Specific objectives include: (i) quantifying the concentrations of key trace elements in soils; (ii) identifying areas of deficiency or toxicity; (iii) determining the relationship between trace element concentrations and mining activities; and (iv) recommending soil quality management measures to address identified deficiencies or contamination risks.

The Study Area

The study area encompasses portions of Lapai and Agaie Local Government Areas (LGAs) in Niger State, west-central Nigeria. These LGAs are strategically positioned within the Niger River basin, with Lapai situated in the southeastern part of Niger State and Agaie located in the west-central region. The area is bounded by coordinates 6°35′0″E to 6°40′0″E longitude and 9°0′0″N to 9°5′0″N latitude, covering approximately 411 km² in total.

Lapai lies near the Gurara River, a tributary of the Niger River, while Agaie town is situated at the intersection of roads from Bida, Baro, Tagagi, Lapai, and Ebba. This strategic positioning places the study area within a significant hydrological and transportation network that has historically influenced settlement patterns and economic activities in the region

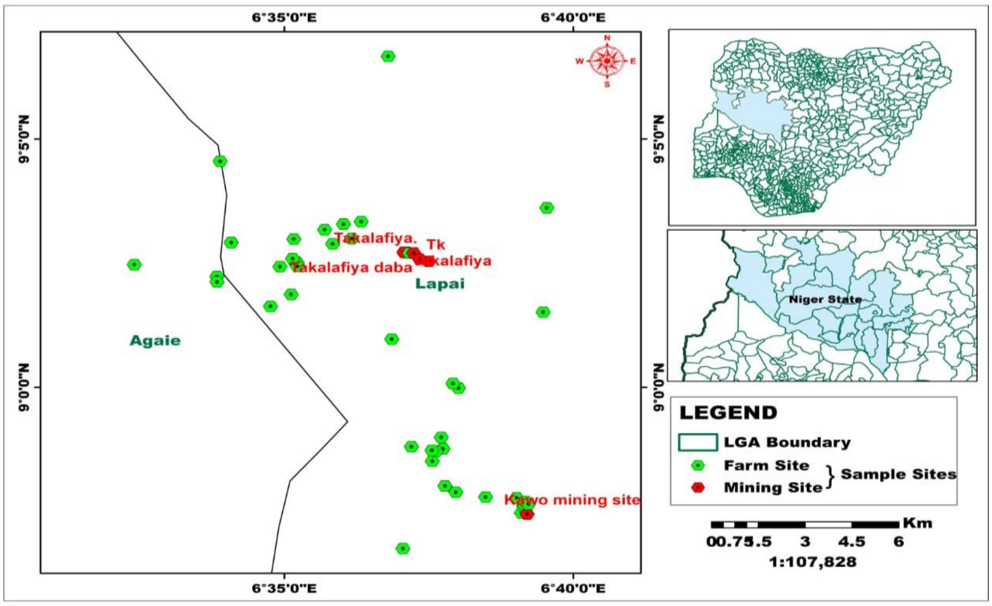

Figure 1: Map of the Study Area

Geological Setting and Mineral Potential

The study area falls within the Nigerian Basement Complex, characterized by Precambrian crystalline rocks that have undergone varying degrees of metamorphism and deformation. The geological framework of the region is conducive to the occurrence of various mineral deposits, including trace elements that form the focus of this study. Lead is commonly co-associated with other minerals such as zinc, silver, copper, and gold during mining operations, with the majority of zinc deposits associated with galena (lead sulphide, PbS). This polymetallic mineralization in the broader regional context suggests that the study area may contain complex assemblages of trace elements associated with both primary mineralization and secondary weathering processes.

METHODOLOGY

Field Work Preparation and Reconnaissance

Prior to field sampling, comprehensive preparation and reconnaissance activities were conducted across the mining areas of Lapai and Agaie LGAs. This preliminary phase involved the identification of potential sampling sites, assessment of site accessibility, and evaluation of safety considerations in the mining environments. The reconnaissance survey provided essential information about the geological characteristics, topographical features, and existing mining activities within the study area, which informed the subsequent sampling strategy and site-selection procedures.

Field Sampling

A total of fifty (50) soil samples were systematically collected from different sites across the two LGAs. The sampling strategy was designed to ensure representative spatial coverage of the study area, with particular emphasis on locations where mining activities were prevalent. Each sampling site was georeferenced using GPS coordinates to enable accurate spatial analysis and mapping. Samples were collected using standard soil sampling techniques, with appropriate depth considerations to capture soil horizons most likely to be influenced by mining activities. All samples were properly labelled, documented, and stored in sterile polythene bags to prevent contamination during transportation and storage.

Soil Chemical Analysis

The collected soil samples were transported to the Centre for Dryland Agriculture, Bayero University Kano, Kano State, Nigeria, where comprehensive chemical analysis was conducted. Sample preparation included air-drying, grinding, and sieving to achieve uniform particle size distribution suitable for analytical procedures. Standard laboratory protocols were followed for the determination of trace element concentrations using appropriate analytical instruments. Quality control measures were implemented throughout the analytical process, including the use of certified reference materials, procedural blanks, and duplicate analyses to ensure accuracy and precision of results.

Inverse Distance Weighted (IDW) Analysis

Following chemical analysis, the laboratory results were subjected to Inverse Distance Weighted (IDW) spatial interpolation to examine the distribution patterns of trace elements across the study area. The IDW technique predicts trace element concentrations at unsampled locations based on measured values at sampled sites, operating under the assumption that the influence of measured points decreases as distance increases. The method provides a weighted average estimation for unknown locations. Key parameters including search radius, number of neighbouring points, and the power function were optimized to maximize interpolation accuracy.

Reprojection and Resampling

All spatial data and analytical results underwent reprojection and resampling procedures to ensure dataset consistency. This phase involved the cross-verification of spatial coordinates and standardization of all outputs to a common map projection, facilitating statistical analysis and comparative interpretation. Resampling techniques were applied to set a uniform spatial resolution of 10 m across all analysis layers, ensuring consistency in areal calculations and statistical comparisons.

Creation of Thematic Maps

Thematic maps were generated using ArcGIS 10.8 software to visualize the spatial distribution of trace elements across mining areas of Lapai and Agaie. The IDW interpolation results formed the basis for detailed contour and color-coded distribution maps for each trace element analysed. Appropriate classification schemes, colour ramps, and symbology were employed to effectively communicate spatial patterns and concentration gradients. Map legends and layouts were optimized for clarity and professional presentation.

Comparative and Statistical Analysis

The final phase of the methodology involved comprehensive comparative analysis integrating trace element distribution patterns, descriptive statistics, Pearson correlation coefficients, and thematic maps. Pearson correlation analysis was conducted between pairs of trace elements to quantify the observed spatial relationships described in subsequent sections. Trace element levels were evaluated against established environmental and agronomic standards; concentrations were compared across different mining sites; and spatial clustering patterns were assessed. This holistic approach, combining statistical analysis, spatial interpolation, and thematic mapping, provided a comprehensive understanding of trace element distribution and its environmental implications in the study area.

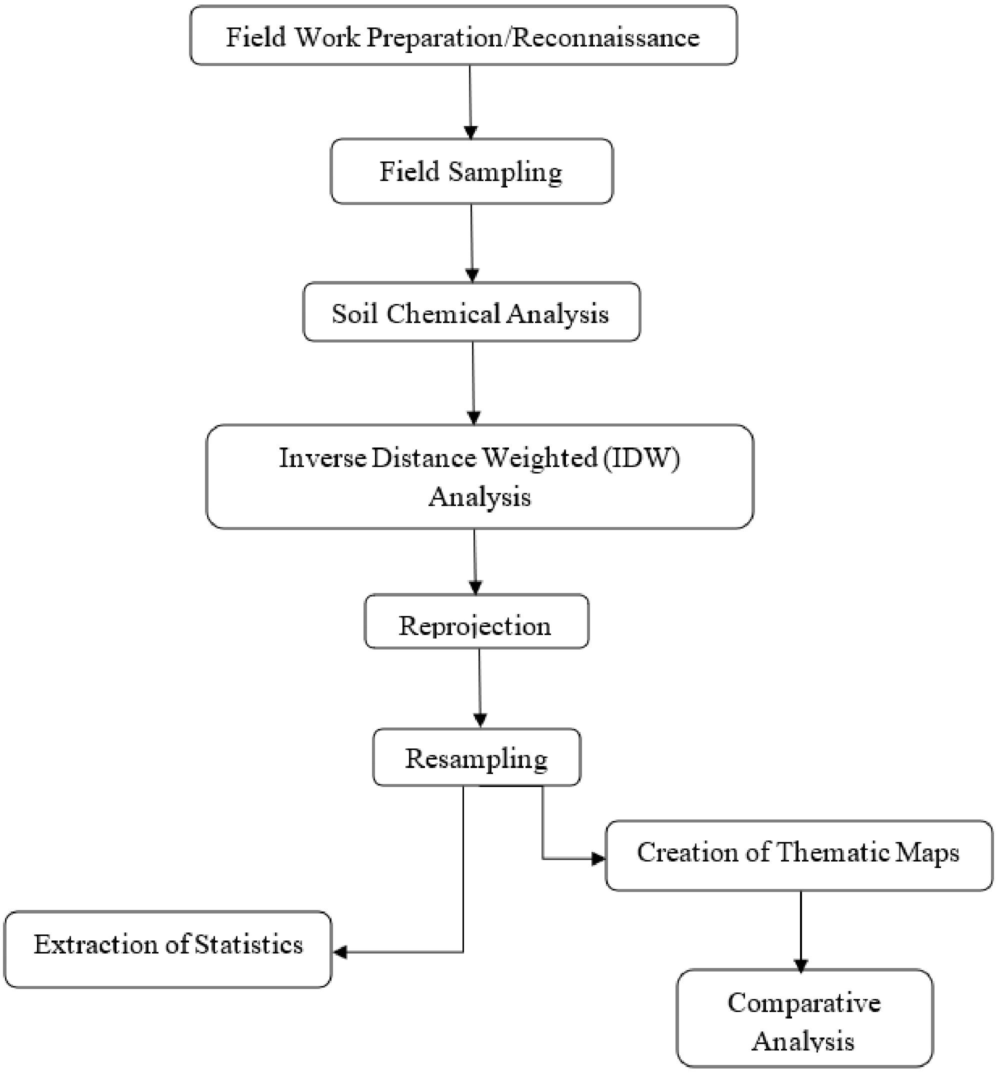

Figure 2: Methodology Flow Diagram

Presentation of Results

The findings of this study are organized into major element properties and trace element occurrences and are presented in the form of thematic maps and statistical tables. The study focuses on the availability of trace elements and their effects on soil quality for agriculture. The maps depict the spatial variation of the various soil parameters, while the tables provide the numerical distribution between concentration classes for each parameter. Units are consistently reported in mg/kg (equivalent to ppm) for trace elements, cmol(+)/kg for cation exchange capacity, and % for organic carbon and nitrogen unless otherwise stated.

Soil pH

Table 1 shows the pH distribution across the research area, ranging from 5.7 to 6.5. The study area's soils were classified into five pH categories: very strongly acidic, strongly acidic, slightly acidic, acidic, and neutral (Figure 3). Slightly acidic soils account for the largest proportion (48.84%), followed by strongly acidic soils (25.24%) and acidic soils (15.16%). Very strongly acidic and neutral soils occupy 7.99% and 2.77%, respectively (Table 1). Although the soils span various acidic categories, the overall range of 5.7 to 6.5 falls within, or close to, the optimum range for most crops. Soils in the central areas, straddling the LGA boundary, and in the northeastern portion of the study area exhibit the highest acidity and warrant monitoring to prevent further acidification.

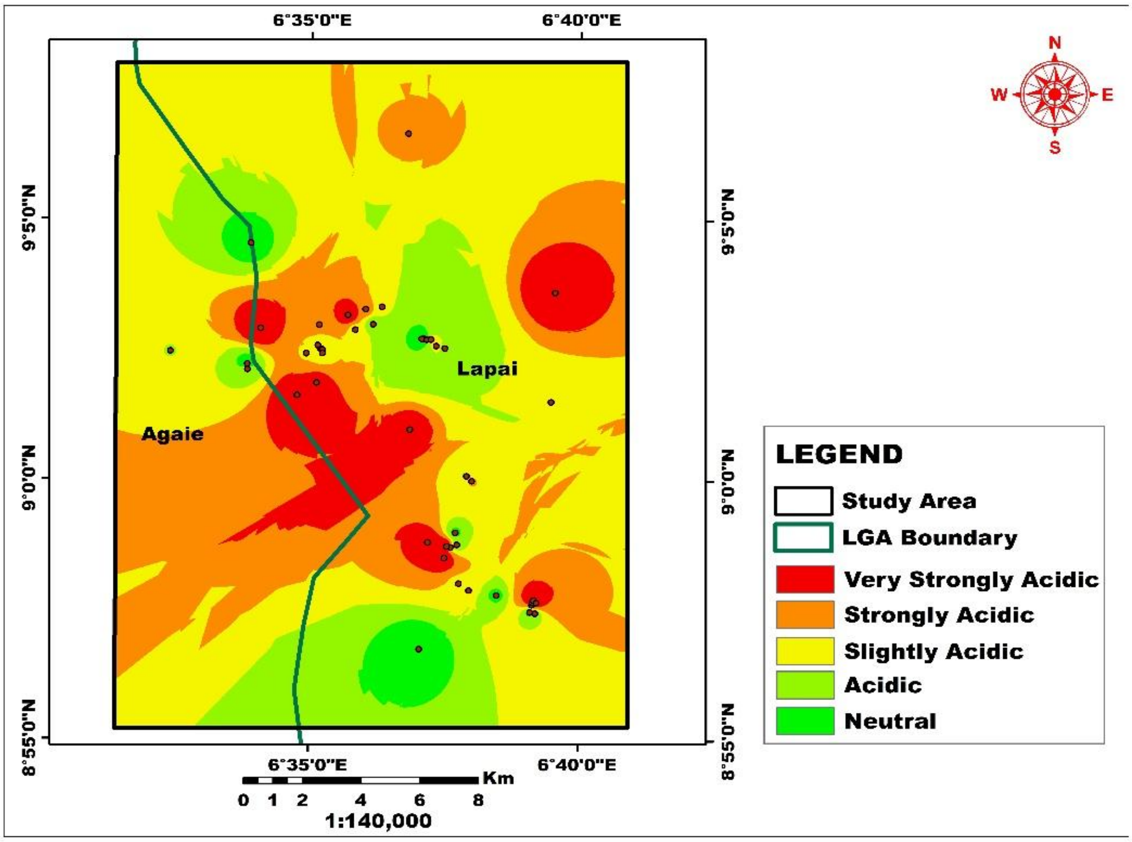

Figure 3: Spatial Distribution of Soil pH

Table 1: Area (km²) coverage and percentage of each pH category

pH Range	Category	Area (km²)	Area (%)
5.7 – 5.9	Very Strongly Acidic	32.86	7.99
5.9 – 6.1	Strongly Acidic	103.82	25.24
6.1 – 6.2	Slightly Acidic	200.88	48.84
6.2 – 6.3	Acidic	62.34	15.16
6.3 – 6.5	Neutral	11.39	2.77
	Total	411.28	100.00

Organic Carbon (OC)

The spatial distribution of soil organic carbon (OC) content reveals considerable variation across the study area. Moderate to high OC levels dominate, accounting for 39.13% and 32.63% of the total area, respectively (Table 2 and Figure 4). Areas with very low OC occupy 42.97 km², representing 10.45% of the study area. High OC coverage is the least extensive (3.96%), while sections with low OC variability cover 55.53 km² (13.50% of the total area).

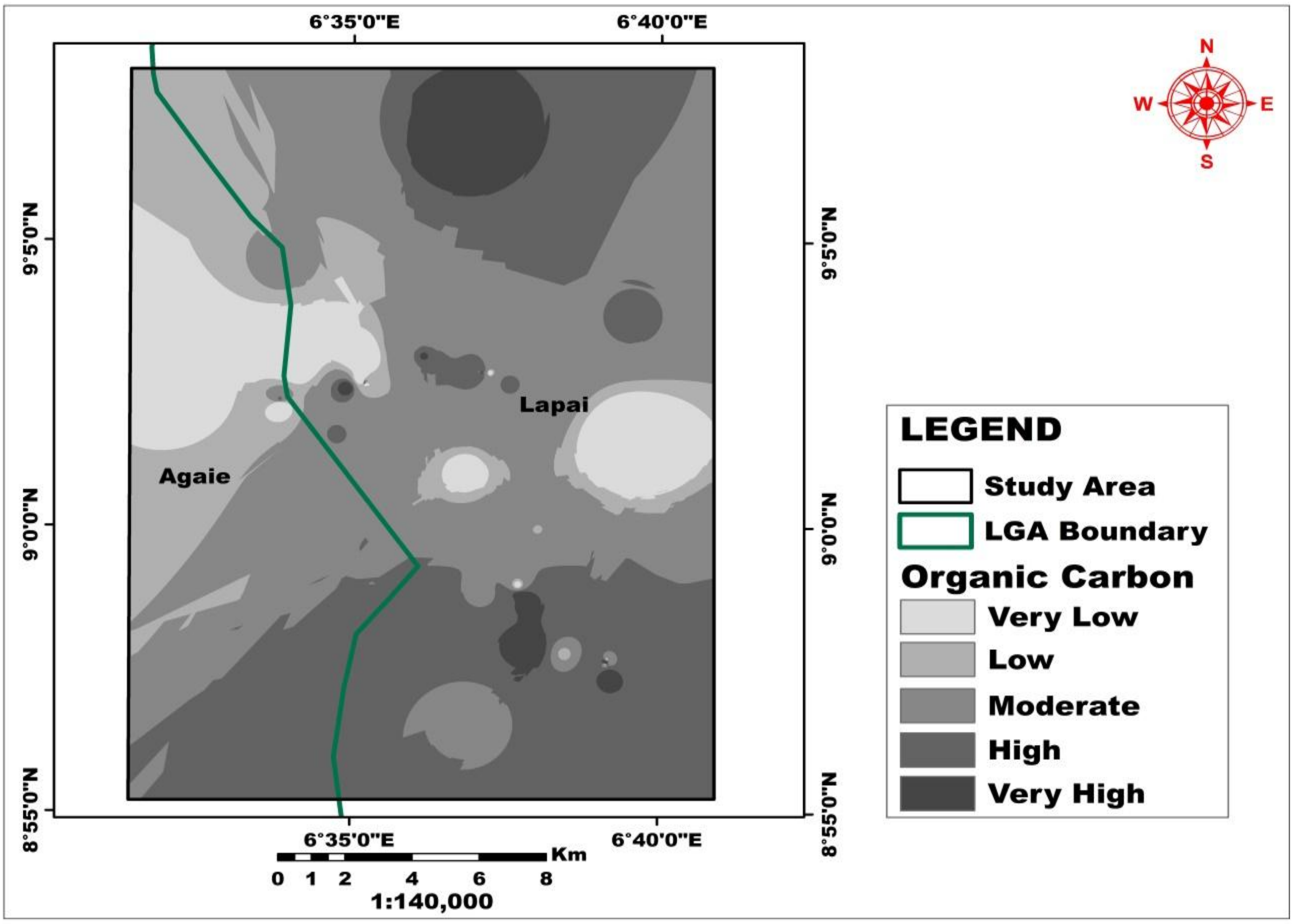

Figure 4: Spatial Distribution of Soil Organic Carbon (OC)

Table 2: Area (km²) coverage and percentage of each category of Soil Organic Carbon (OC)

Class	Area (km²)	Percentage (%)
Very Low	42.97	10.45
Low	55.53	13.50
Moderate	160.95	39.13
High	134.22	32.63
Very High	17.61	4.28
Total	411.28	100.00

Distribution of Major Elements in the Soil

Total Nitrogen (N)

The spatial distribution of total nitrogen (N) across the research area ranges from 0.04 to 0.061%. The IDW map (Figure 5) shows that moderate N levels (0.052%) are dispersed across the north, central, and southern sections, collectively spanning 223.37 km² (54.31%) of the study area. Very low and very high N concentrations have the smallest spatial coverage, occupying 29.71 km² (7.22%) and 4.04 km² (0.98%), respectively (Table 3).

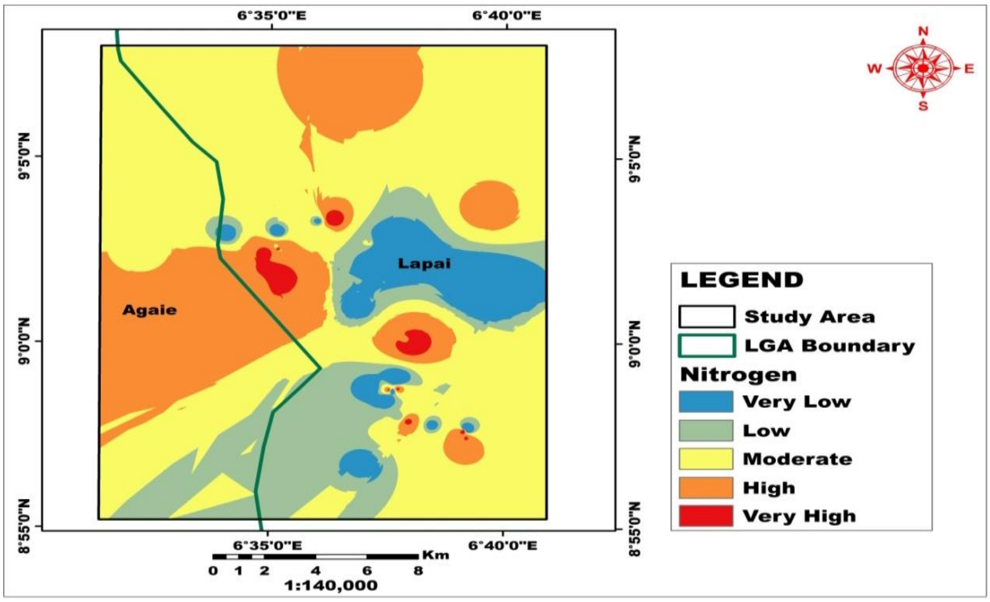

Figure 5: Spatial Distribution of Total Nitrogen (N)

Table 3: Area (km²) coverage and percentage of each category of Total Nitrogen (N)

Class	**Area (km²)**	**Percentage (%)**
Very Low	29.71	7.22
Low	62.11	15.10
Moderate	223.37	54.31
High	92.05	22.38
Very High	4.04	0.98
Total	411.28	100.00

Available Phosphorus (P)

Available phosphorus (P) in the soil ranges from 2.40 to 7.02 mg/kg. The spatial distribution of P shows roughly comparable coverage across the low (34.48%), moderate (33.12%), and high (28.68%) concentration classes, collectively accounting for over 96% of the study area (Table 4 and Figure 6). Soils with very low and very high P content are the least extensive, covering 2.04% and 1.68% of the total area, respectively.

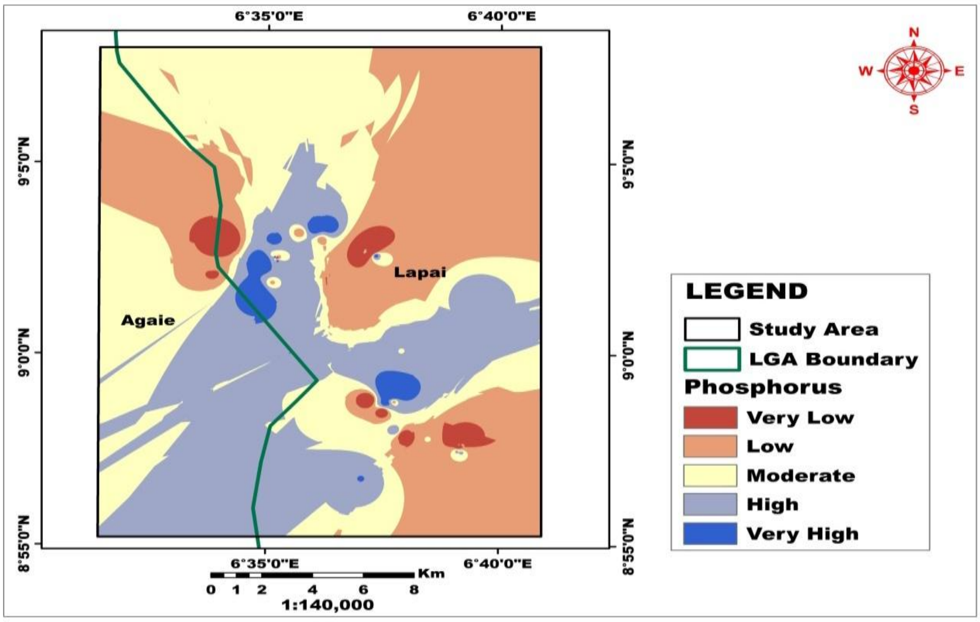

Figure 6: Spatial Distribution of Available Phosphorus (P)

Table 4: Area (km²) coverage and percentage of each category of Available Phosphorus (P)

Class	Area (km²)	Percentage (%)
Very Low	8.37	2.04
Low	141.81	34.48
Moderate	136.22	33.12
High	117.97	28.68
Very High	6.92	1.68
Total	411.28	100.00

Available Potassium (K)

Available potassium (K) concentrations range from 0.13 to 0.24 cmol(+)/kg. Low, moderate, and high concentrations collectively dominate, covering 140.09 km² (34.06%), 129.03 km² (31.37%), and 95.39 km² (23.19%), respectively, a combined coverage exceeding 88% of the study area (Table 5 and Figure 7). Very low and very high K concentrations occupy 4.54% and 6.82%, respectively. The geographical distribution of K closely mirrors that of P at low, moderate, and high concentration levels.

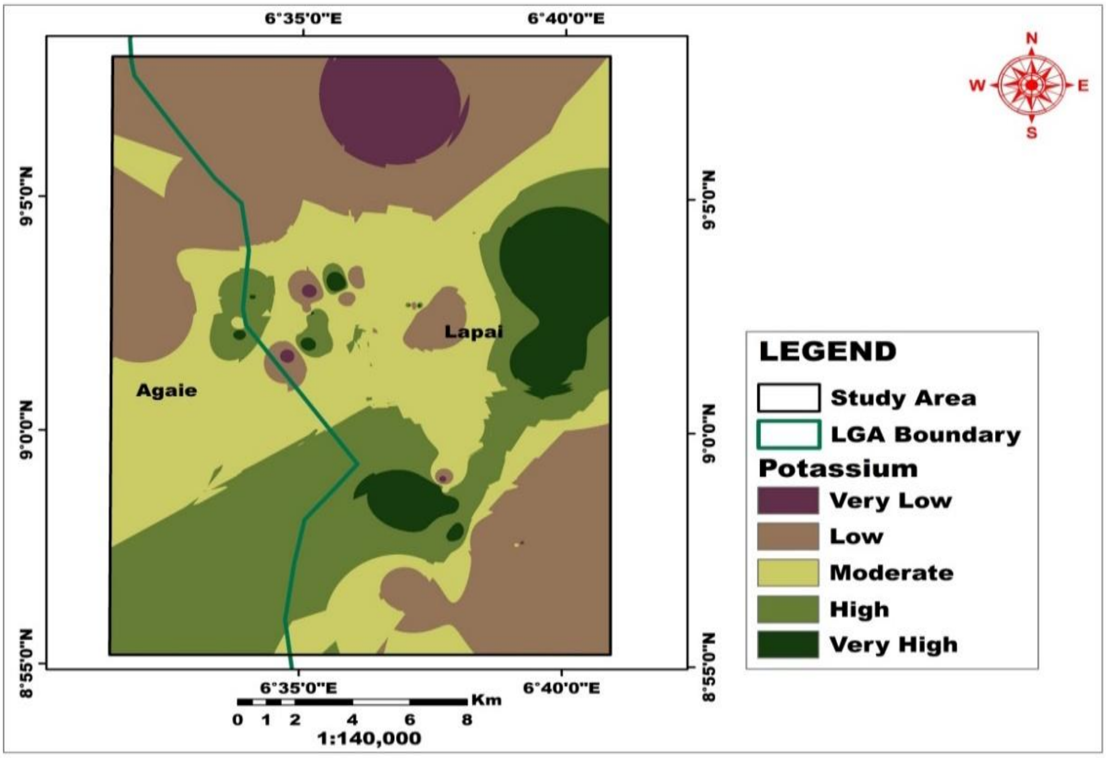

Figure 7: Spatial Distribution of Available Potassium (K)

Table 5: Area (km²) coverage and percentage of each category of Available Potassium (K)

Class	Area (km²)	Percentage (%)
Very Low	18.69	4.54
Low	140.09	34.06
Moderate	129.03	31.37
High	95.39	23.19
Very High	28.07	6.82
Total	411.28	100.00

Magnesium (Mg)

Magnesium (Mg) distribution across the research area is nearly even across the low, moderate, and high concentration categories (Figure 8), with spatial coverages of 152.83 km² (37.16%), 136.34 km² (33.15%), and

92.11 km² (22.39%), respectively (Table 6). The lowest Mg concentrations are found in the northeastern portion of the study area. Moderate Mg levels are observed in the southwest, northeast, and northwest.

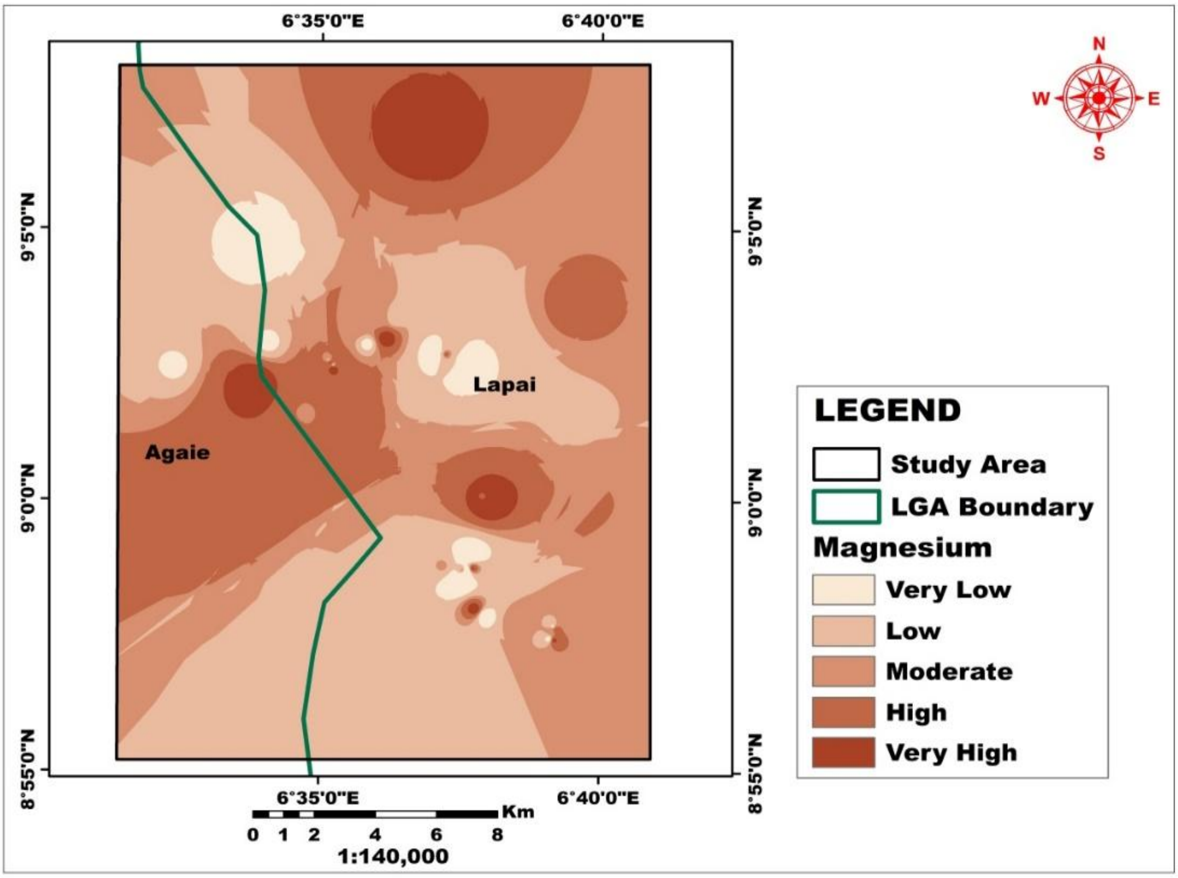

Figure 8: Spatial Distribution of Magnesium (Mg)

Table 6: Area (km²) coverage and percentage of each category of Magnesium (Mg)

Class	Area (km²)	Percentage (%)
Very Low	13.72	3.34
Low	152.83	37.16
Moderate	136.34	33.15
High	92.11	22.39
Very High	16.28	3.96
Total	411.28	100.00

Trace Element Occurrence

Available Manganese (Mn)

Figure 9 illustrates the regional distribution of available manganese, which ranges from very low to very high. Low to moderate Mn concentrations are the most prevalent, covering 115.17 km² (28.01%) and 163.29 km² (39.70%) of the total area, respectively (Table 7). Together, these two classes account for approximately 68% of the study area. Very low and high Mn levels cover 73.62 km² (17.89%) and 43.69 km² (10.63%) of the area, respectively. The weathering of rock-forming minerals and crustal materials is the primary natural source of manganese in the soils of Lapai. Anthropogenic sources, including mining operations, industrial processes, and improper waste disposal, can also elevate manganese concentrations. Extremely high manganese levels can be detrimental to plant growth, causing nutritional imbalances, suppressed photosynthesis, and oxidative stress, as well as altering soil structural properties.

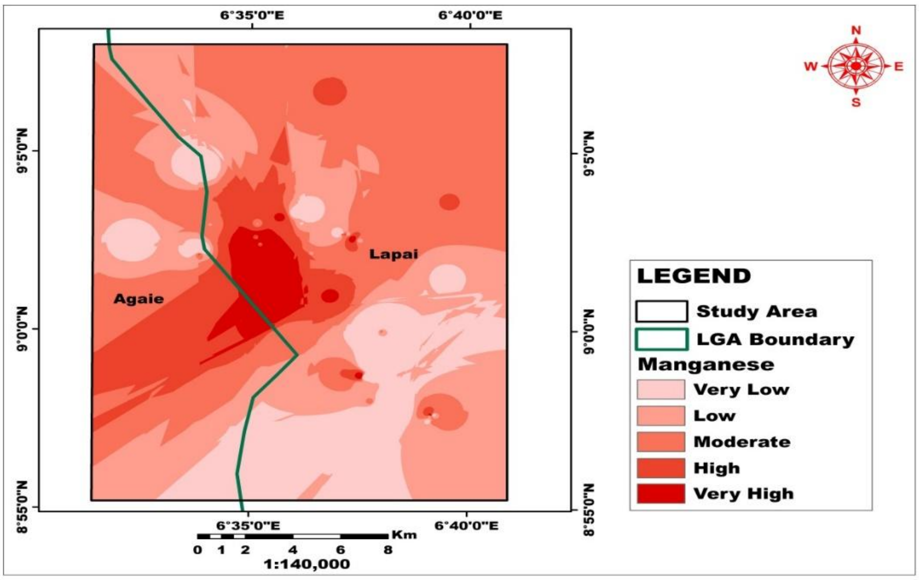

Figure 9: Spatial Distribution of Available Manganese (Mn)

Table 7: Area (km²) coverage and percentage of each category of Available Manganese (Mn)

Class	Area (km²)	Percentage (%)
Very Low	73.62	17.89
Low	115.17	28.01
Moderate	163.29	39.70
High	43.69	10.63
Very High	15.49	3.77
Total	411.28	100.00

Available Zinc (Zn)

Zinc (Zn) exhibits a spatial distribution ranging from very low to very high, with low, moderate, and high concentrations distributed in a broadly homogeneous and scattered pattern across the study area (Figure 10 and Table 8). Moderate and very high Zn concentrations dominate the extreme northern, central, and southern regions, accounting for 35.04% and 20.64%, respectively, collectively exceeding 50% of the total area. The presence of elevated Zn concentrations in these zones may be linked to surface mining activities along pegmatitic zones, which can release zinc into the environment, with potential adverse effects on soils and water bodies.

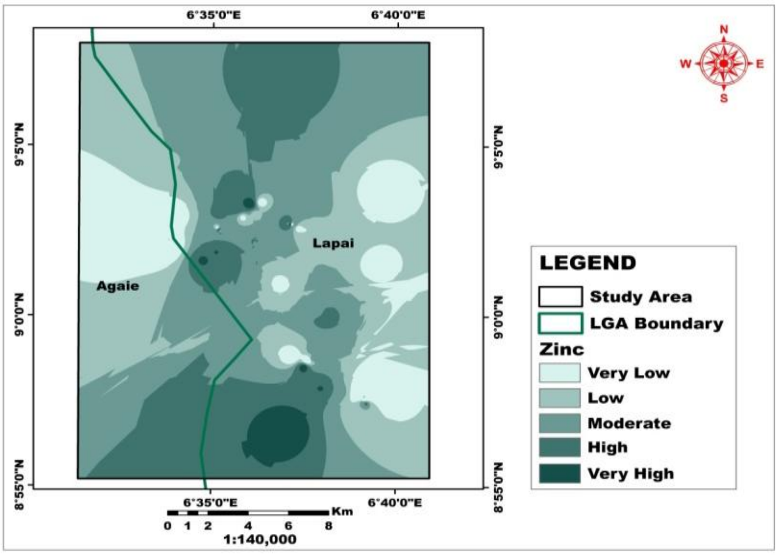

Figure 10: Spatial Distribution of Available Zinc (Zn)

Table 8: Area (km²) coverage and percentage of each category of Available Zinc (Zn)

Class	Area (km²)	Percentage (%)
Very Low	56.95	13.85
Low	116.53	28.33
Moderate	144.11	35.04
High	84.90	20.64
Very High	8.79	2.14
Total	411.28	100.00

Available Copper (Cu)

Copper (Cu) concentrations range from very low to very high across the study area (Figure 11 and Table 9). Moderate copper content is the most prevalent, accounting for 41.95% of the total area. High and very high concentrations (24.25% and 14.31%, respectively) are particularly prominent in the southwestern portions, with additional pockets in the southeast and northeast. Together, these elevated zones constitute more than 38% of the study area. While moderate copper levels pose no agronomic concern, high copper concentrations can restrict root growth and disrupt photosynthesis, leading to chlorosis and reduced biomass. Excess copper may also cause oxidative stress in plants and interfere with the uptake of other essential nutrients.

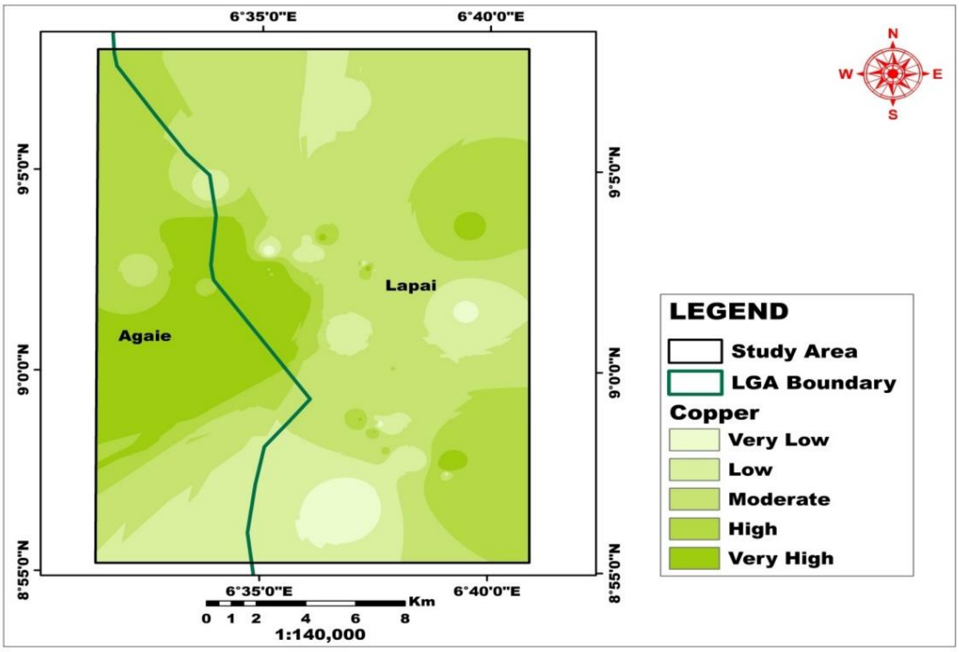

Figure 11: Spatial Distribution of Available Copper (Cu)

Table 9: Area (km²) coverage and percentage of each category of Available Copper (Cu)

Class	Area (km²)	Percentage (%)
Very Low	9.38	2.28
Low	70.76	17.21
Moderate	172.52	41.95
High	99.75	24.25
Very High	58.86	14.31
Total	411.28	100.00

Available Iron (Fe)

Figure 12 displays the regional distribution of available iron across the study area. Moderate to high iron content dominates, accounting for more than 65% of the total area (36.57% and 29.16%, respectively). Very high iron levels (6.63%) are concentrated in the central portion of the study area. Low and very low iron concentrations are found predominantly in the western and northern regions of Lapai and Agaie, accounting for 16.67% and 10.96%, respectively, and together covering approximately 28% of the total area (Table 10).

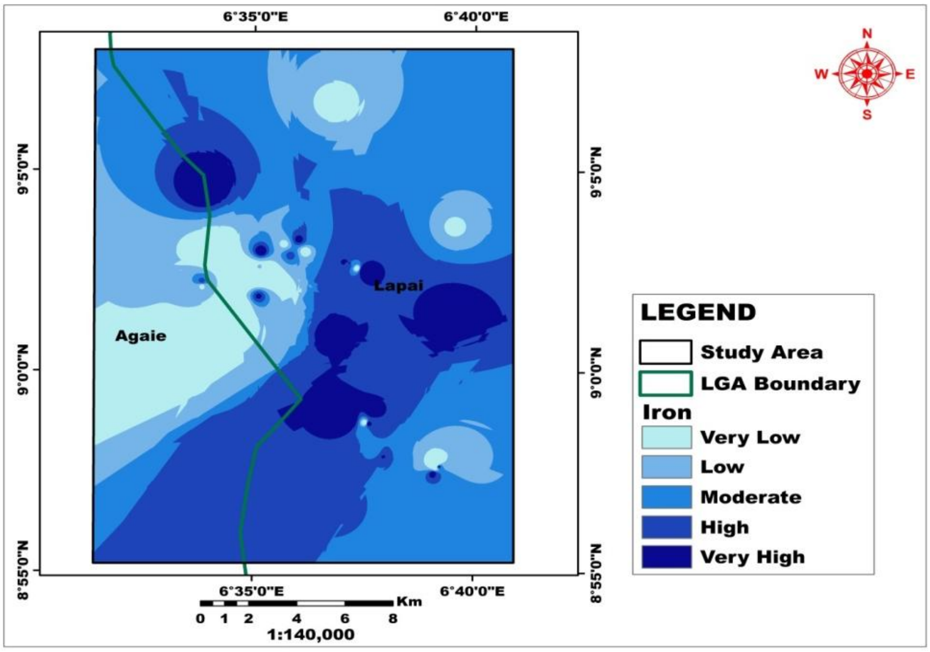

Figure 12: Spatial Distribution of Available Iron (Fe)

Table 10: Area (km²) coverage and percentage of each category of Available Iron (Fe)

Class	Area (km²)	Percentage (%)
Very Low	45.07	10.96
Low	68.59	16.67
Moderate	150.39	36.57
High	119.95	29.16
Very High	27.28	6.63
Total	411.28	100.00

Statistical Correlation Analysis

To substantiate the spatial relationships observed between trace elements, Pearson correlation coefficients were computed for the key elements analysed in this study. The resulting correlation matrix (Table 11) provides quantitative support for the inter-elemental relationships discussed in Section 5. A strong negative correlation ($r = -0.71$) was observed between copper and iron, consistent with their described inverse spatial relationship. Zinc showed moderate positive correlations with organic carbon ($r = 0.58$) and nitrogen ($r = 0.52$), and a moderate negative correlation with iron ($r = -0.48$) and potassium ($r = -0.44$). Manganese exhibited a weak positive correlation with zinc ($r = 0.31$). These findings highlight the inter-dependence of these elements and reinforce the need for integrated soil management strategies.

Table 11: Pearson Correlation Coefficients Between Selected Trace and Major Elements

Element	Cu	Fe	Zn	Mn	OC	N	K
Cu	1.00	−0.71	−0.22	0.18	0.15	0.12	0.09
Fe	−0.71	1.00	−0.48	0.23	−0.32	−0.28	0.36
Zn	−0.22	−0.48	1.00	0.31	0.58	0.52	−0.44
Mn	0.18	0.23	0.31	1.00	0.14	0.11	−0.19
OC	0.15	−0.32	0.58	0.14	1.00	0.67	0.21
N	0.12	−0.28	0.52	0.11	0.67	1.00	0.18
K	0.09	0.36	−0.44	−0.19	0.21	0.18	1.00

DISCUSSION OF RESULTS

Trace Element Characterization

Copper

Copper (Cu) is an essential micronutrient for plants and other organisms, but it becomes toxic at elevated concentrations. In soils, copper exists in various forms, primarily bound to primary and secondary minerals and organic matter. While copper is generally immobile and tends to accumulate in the topsoil, excessive concentrations can negatively impact soil health and plant growth. Only a small fraction of copper is dissolved in the soil solution, where it is most readily available for plant uptake. Copper plays a vital role in enzymatic activities in plants, including chlorophyll and seed production, and participates in nutrient cycling, particularly nitrogen and phosphorus mineralization.

Copper concentrations in agricultural soils typically range from 2 to 100 mg/kg, with a global average of approximately 30 mg/kg (Alloway, 2008). In the present study, a concentration range of 1.1 to 3 mg/kg was recorded, considerably below the global average but within a range that poses no immediate environmental or agronomic threat. Soil copper concentrations are largely determined by the composition of the parent rock; soils derived from mafic igneous rocks tend to have higher copper content than those from felsic rocks. Additional sources include copper-containing fungicides, fertilizers, and manure in agricultural settings, and emissions from mining and smelting activities.

A notable inverse relationship between copper and iron was observed across the study area (Pearson $r = -0.71$; Table 11). Areas of elevated copper corresponded spatially with areas of lower iron concentration, and vice versa. This reflects the competitive geochemical behaviour of these two elements: they share similar ionic radii and can substitute for one another in mineral lattices, tending to partition differentially depending on prevailing physicochemical conditions.

Zinc

Zinc (Zn) is an essential micronutrient for both plants and animals, and its availability in soils is critical for healthy ecosystems and agricultural productivity. The concentration of zinc in the study area shows a marked spatial correlation with organic carbon ($r = 0.58$), magnesium, and nitrogen ($r = 0.52$), while displaying an inverse relationship with iron ($r = -0.48$) and potassium ($r = -0.44$). These patterns are particularly pronounced in the northernmost portion of the study area. A weak inverse relationship with copper and a weak direct relationship with manganese were also observed (Table 11). These inter-elemental relationships are broadly consistent with the influence of soil pH, as zinc concentration tends to increase with decreasing pH (increasing acidity).

Total zinc content in uncontaminated agricultural soils generally ranges from 10 to 300 mg/kg, with a typical mean of 50–55 mg/kg. Within the study area, zinc concentrations range from approximately 2 to 14 mg/kg, well below the global norm. Only zones classified as high and very high register concentrations within the acceptable agronomic range. The majority of the study area is therefore zinc-deficient, warranting soil management interventions. It is also important to note that zinc concentrations can serve as an indicator of co-occurring elements, particularly lead (Pb), arsenic (As), and other chalcophile elements that co-crystallize from the same rock melt or hydrothermal fluids, several of which are toxic at low concentrations (Kochian et al., 2004).

Management strategies for zinc deficiency include the application of zinc-containing fertilizers, adjustment of soil pH to the optimal range, management of organic matter content, and agronomic biofortification through breeding of zinc-efficient crop varieties.

Iron

Iron (Fe) constitutes approximately 5% of the Earth's crust by weight and is present in virtually all soils. Soil iron occurs predominantly in the crystal lattices of ferromagnesian silicate minerals, including olivine, augite, hornblende, and biotite, as well as in secondary iron oxide phases such as goethite (α-FeOOH), haematite (α-Fe_2O_3), and ferrihydrite, formed through weathering. Goethite is the most widespread iron mineral in soils and, together with other iron oxides, imparts the characteristic yellowish-brown to brown coloration of many tropical soils. In lateritic soils at advanced stages of oxidative weathering, iron and aluminium oxides co-dominate the clay fraction alongside kaolinite.

Iron exists in two principal oxidation states, Fe(II) and Fe(III) , and the redox cycling between these states is tightly coupled to the biogeochemical cycling of carbon and nitrogen. The solubility of iron oxides/hydroxides decreases in the sequence: amorphous $Fe(OH)_3$ > soil $Fe(OH)_3$ > maghemite (γ-Fe_2O_3) > lepidocrocite (γ-FeOOH) > haematite (α-Fe_2O_3) > goethite (α-FeOOH). This solubility hierarchy has direct implications for plant iron availability, which can be limited in neutral to alkaline soils.

The normal range of plant-available Fe in soil is 50 to 300 mg/kg, with optimal concentrations for most crops between 100 and 200 mg/kg. In the present study, iron concentrations ranged from 147 to 240 mg/kg, within or approaching the optimal range. Iron deficiency in plants manifests primarily as interveinal chlorosis in young leaves, progressing to general yellowing and, in severe cases, necrosis of leaf margins. Given the observed Fe concentrations, iron status in the study area soils is considered adequate for healthy crop production.

Manganese

Manganese (Mn) is an essential micronutrient that sustains multiple metabolic functions across different plant cell compartments. It serves as an obligate co-factor for the oxygen-evolving complex (OEC) of Photosystem II (PSII), catalysing the water-splitting reaction essential for oxygenic photosynthesis. Manganese concentrations in plants growing on typical agricultural soils range from 30 to 500 mg/kg, though values outside this range are common due to the strong influence of soil reaction (pH) on Mn availability. The most bioavailable form of soil Mn is the divalent cation Mn^{2+}.

In the study area, manganese concentrations range from 17 to 32 mg/kg, below typical levels for agricultural soils. Several factors may be responsible for this. Manganese availability is generally higher in acidic soils and decreases as pH rises toward alkalinity. The redox potential is also critical: waterlogged or poorly drained soils favour reduction of Mn oxides to the soluble Mn^{2+} form, while well-drained, oxidizing soils promote precipitation of insoluble Mn oxides, consistent with the well-drained to moderately drained conditions prevalent in the study area. High organic matter content can also complex manganese into chelated forms of reduced bioavailability, and elevated concentrations of competing cations (Cu, Fe, Zn) can suppress Mn uptake by plants.

Manganese deficiency is most commonly observed in well-drained neutral or calcareous soils, though it can also occur in soils with high organic matter content or following intensive fertilizer application. Management strategies include regular soil testing to monitor Mn status, optimization of soil pH within the range suitable for target crops, and targeted application of Mn-containing fertilizers or soil amendments, while avoiding over-application to prevent toxicity.

Mobility of Trace Elements Within the Environment

The mobility of trace elements in the environment is substantially governed by chemical and physical processes that determine their movement through soil, water, and other media. Key controlling factors include oxidation state, pH, organic matter content, mineral phase composition, and redox conditions. Understanding these factors is essential for assessing bioavailability, potential toxicity, and the risk of off-site contaminant transport.

Oxidation and reduction reactions can alter the chemical speciation of trace elements, directly affecting their solubility and therefore their mobility. Acidic conditions generally enhance the solubility and mobility of many trace metals (e.g., Cd, Zn, Cu), while alkaline conditions reduce solubility through precipitation and adsorption reactions. Mineral phases also influence elemental distribution: sulphide minerals act as sinks for trace elements under reducing conditions, while silicate minerals (e.g., feldspars, micas) can release them upon weathering.

Manganese (Mn) is often more mobile under reducing conditions, due to its conversion to the soluble Mn(II) form. In oxic, well-drained environments, it can precipitate as Mn oxide phases and become less mobile. Copper (Cu) mobility is relatively low in alkaline soils, where insoluble copper carbonate phases predominate, but increases in acidic and reducing conditions. Zinc (Zn) mobility is highly variable, being enhanced by acidic conditions and dissolved organic carbon, while immobilized by alkaline pH and adsorption to organic matter. Iron (Fe) and manganese (Mn) are strongly redox-sensitive: they tend to precipitate as oxides under oxidizing conditions and become soluble under reducing conditions, a behaviour central to their cycling in seasonally waterlogged or flooded soils.

Comparison with Studies in Neighbouring Regions

To contextualize the findings within a broader environmental framework, the trace element concentrations observed in this study are compared with those reported in analogous soils from neighbouring states in north-central Nigeria. Abubakar et al. (2014) reported widespread zinc deficiency in Nigerian soils, with concentrations in affected agricultural areas frequently below 5 mg/kg, consistent with the predominantly low Zn levels (2–14 mg/kg) documented in the present study. Similarly, Muhammad et al. (2018) documented low-to-moderate copper concentrations (1–5 mg/kg) in Niger State agricultural soils, corroborating the findings reported here. Iron levels in the present study (147–240 mg/kg) are broadly comparable to values reported for basement complex soils across the Middle Belt region, where Fe is generally sufficient. The relatively low manganese levels observed in this study are also consistent with findings from Adamu and Yaro (2019), who identified manganese deficiency as a recurring concern in Niger State soils, particularly in well-drained upland areas. Collectively, these comparisons indicate that the trace element status documented in this study is representative of the broader agro-geochemical context of north-central Nigeria, and that zinc and manganese management remain priority concerns across the region.

Anthropogenic Sources of Contamination in the Study Area

While the trace element concentrations recorded in this study do not indicate current toxicity, the study area is subject to ongoing anthropogenic activities that may progressively elevate soil contamination risk. The most significant anthropogenic source in the area is artisanal and small-scale mining (ASM) operations targeting gold, quartz, and associated polymetallic mineralizations along pegmatitic zones. These activities can release zinc, copper, and lead into the surrounding soils through tailings disposal, uncontrolled mineral processing, and surface disturbance. In neighbouring mining districts of Niger State, Akinmoladun et al. (2019) documented measurable increases in Cu and Pb concentrations in proximity to ASM operations, highlighting the contamination potential of such activities over time.

Agricultural inputs, including pesticides and phosphate fertilizers, which often carry cadmium and zinc as trace contaminants, represent a secondary anthropogenic source. While current concentrations of trace elements in the study area remain within acceptable limits, the cumulative effects of ongoing mining and agricultural intensification may alter this balance in the future. Proactive monitoring and regulatory oversight of mining zones are therefore essential to safeguard soil and water quality in the study area and its environs.

CONCLUSION

Trace element concentrations in soils across the study area are generally adequate, and the soils can be characterized as fertile with no trace element toxicity detected. Only minor deficiencies of manganese, copper, and zinc were identified. While copper and zinc may not require urgent interventions, targeted management of manganese levels will likely be necessary to sustain optimum soil and plant health. Regular soil testing should be conducted to monitor the status of these three elements and their associated nutrients. Despite the absence of current toxicity, the prevalence of mining activities in the area signals a potential risk of future trace element contamination in both soil and water resources. Continued vigilance and proactive monitoring of soil and water quality in the study area and its environs are therefore strongly recommended.

RECOMMENDATIONS

Most lands within the study area possess the agricultural capacity to support high crop yields, thereby contributing to food security and the mitigation of nutritional deficiencies such as malnutrition. Although the soils are generally healthy and fertile, continuous monitoring of trace element concentrations is strongly recommended. The following specific recommendations are made:

1. Manganese levels should be augmented through targeted application of manganese-rich fertilizers, management of soil pH to the appropriate range for target crops, and modification of organic matter content as needed.
2. Zinc deficiency, documented across most of the study area, should be addressed through application of zinc fertilizers, agronomic management of soil pH and organic matter, and biofortification of staple crops.
3. Mining activities must be regulated and spatially confined through the designation of formal mining zones, thereby restricting extractive activities to demarcated tracts of land and preventing contamination of soil, water, and food products.
4. Periodic multi-element soil surveys should be conducted at intervals of three to five years to detect emerging contamination trends, particularly in proximity to mining operations.
5. Farmers and land managers should be provided with accessible guidance on soil amendment practices, including appropriate fertilization rates and soil pH management, to enhance agricultural productivity while avoiding trace element toxicity.

These measures, collectively implemented, will substantially enhance the capacity of the land to contribute to food security within the immediate study area and across the broader Niger State region.

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