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Micronutrient Interactions and their Relationship with Soil Properties in Zagga Savannah Soils, Kebbi State, Nigeria

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ABSTRACT: *Micronutrient deficiencies in savannah soils are a critical constraint to crop production, yet their specific interactions with underlying soil properties are often poorly quantified. This study investigated the relationships between DTPA-extractable micronutrients (Zn, Fe, Cu, Mn) and key soil properties (pH, organic matter, clay content) across eight representative pedons in the Zagga District of Kebbi State, Nigeria, within the Northern Guinea Savannah. Standard laboratory methods were used for soil and micronutrient analysis, and data were examined using descriptive statistics and Pearson correlation analysis. The results revealed distinct control mechanisms: Zn availability showed a moderate positive correlation with clay content (r = +0.46), Fe exhibited a strong negative correlation with pH (r = −0.74), and Cu was strongly positively correlated with organic matter (r = +0.75). Manganese availability was associated with both pH and organic matter (r = +0.64 and +0.42, respectively). These correlations highlight that micronutrient availability in these soils is predominantly governed by specific physicochemical properties—texture, pH, and organic matter—rather than total content alone. The study concludes that effective micronutrient management must transition from a blanket approach to a predictive, soil property-based framework. Recommendations include texture-specific Zn fertilization, pH-aware Fe management, and systematic organic matter enhancement for Cu and Mn sustainability, providing a targeted pathway to improve crop nutrition and productivity in these soils.*

KEYWORDS: *Micronutrients, Soil properties, Interactions, Savannah soils, Kebbi state.*

1. INTRODUCTION

Micronutrients such as zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn) are indispensable for plant metabolic functions, acting as catalysts in critical processes like chlorophyll synthesis and enzyme activation (Sagwal et al., 2023). Their phytoavailability, however, is governed less by total soil content and more by dynamic interactions with soil physicochemical properties, including pH, organic matter (OM), and texture (Brady & Weil, 2016; Kumar et al., 2021). For instance, Zn and Fe solubility is markedly reduced in alkaline conditions, while Cu forms stable complexes with OM, and Mn cycling is heavily influenced by redox potential (Lindsay, 1979; Rengel, 2015). Understanding these property-nutrient relationships is therefore fundamental for diagnosing deficiencies and formulating effective soil management strategies.

In the savannah agro-ecosystems of northern Nigeria, micronutrient limitations pose a growing threat to crop productivity. While widespread Zn deficiency has been documented (Lombin, 1983; Oyinlola & Chude, 2010), the status and drivers of Fe, Cu, and Mn availability remain less predictable and highly variable across landscapes (Shehu et al., 2015; Kolawole et al., 2023). This variability is likely tied to the heterogeneity of key soil properties. The soils of the Zagga District in Kebbi State, situated within the Northern Guinea Savannah, present a pertinent case. Characterized by gradients in texture, acidity, and inherently low OM, this area is typical of the region's agricultural challenges. Previous investigations have noted low Zn levels, but a systematic analysis quantifying how specific soil properties—pH, OM, and clay content—control the availability of the suite of micronutrients (Zn, Fe, Cu, Mn) is lacking.

Such a quantitative correlation study is crucial. It moves beyond general deficiency mapping to provide a mechanistic framework for predicting nutrient availability based on measurable soil characteristics. This study, therefore, aimed to (i) assess the availability of DTPA-extractable Zn, Fe, Cu, and Mn across representative pedons in the Zagga District, and (ii) quantify the statistical relationships between these micronutrients and the key soil properties of pH, organic matter, and clay content. The findings are intended to establish a soil property-based rationale for targeted micronutrient management in these and similar savannah soils.

2. MATERIALS AND METHODS

2.1. STUDY AREA

The study was conducted in Zagga District, Bagudo Local Government Area of Kebbi State, Nigeria (Latitude: 11°27'20"–11°35'30" N; Longitude: 4°00'00"–4°11'32" E) (Figure 1). The climate is hot, semi-arid tropical (AW, Köppen classification), characterized by a distinct wet season (May–October) and a long dry season (November–April). Mean annual rainfall is approximately 650 mm, and mean annual temperature ranges from 16°C to 45°C (Usman *et al.,* 2016). The natural vegetation is Northern Guinea Savannah. For this study, a 170-hectare portion of the larger agrarian landscape was selected for detailed pedological investigation.
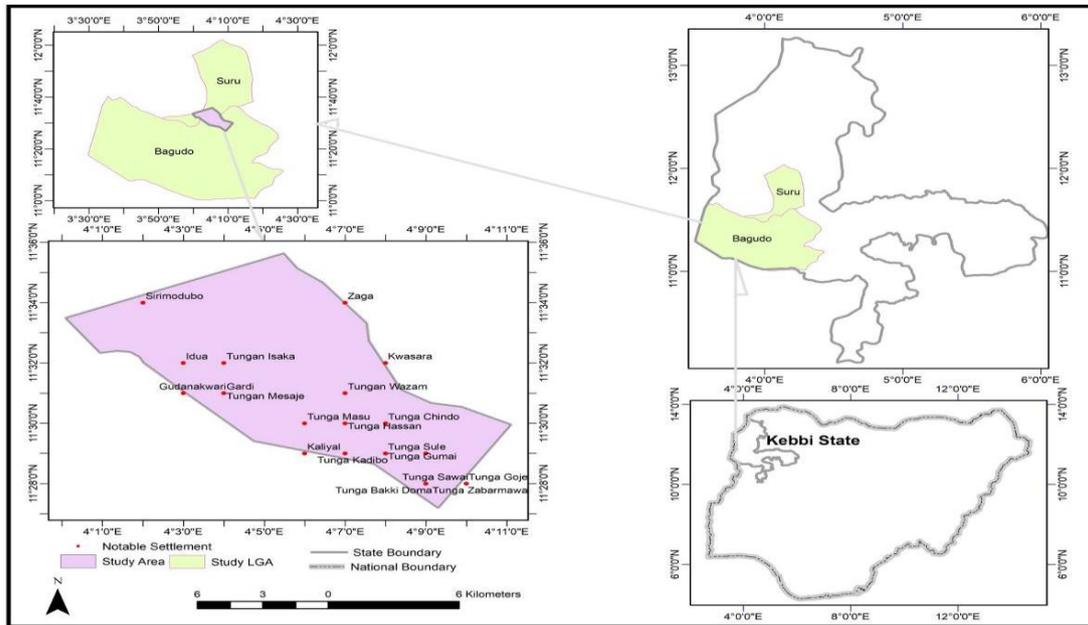

FIGURE 1 Map of Nigeria showing the study area

2.2. SOIL SURVEY, SOIL SAMPLING AND PEDON DESCRIPTION

A semi-detailed soil survey was conducted at a scale of 1:25,000 following conventional survey procedures (Kairis *et al.,* 2020). A systematic grid-based approach was employed, with auger borings at 250-meter intervals to examine soil variability and establish preliminary boundaries. Eight distinct soil mapping units were identified (designated ZG6 to ZG13) in the study area.

A modal profile pit was excavated to a depth of 2 m or until an impermeable layer in the center of each mapping unit. Each profile was described according to FAO (2006) guidelines, noting morphological properties including colour (Munsell chart), texture, structure, consistence, mottling, and horizon boundaries. Soil samples were collected by genetic horizon, air-dried, gently crushed, and passed through a 2-mm sieve prior to laboratory analysis.

2.3. LABORATORY ANALYSIS

All analyses were performed on the <2 mm air-dried soil fraction.

- **Soil pH** was determined potentiometrically in a 1:2.5 soil:water suspension.
- **Particle size distribution** was analyzed using the hydrometer method (Gee & Or, 2002). The percentage of clay (<0.002 mm) was used as an index of soil texture.
- **Organic Carbon (OC)** was determined by the Walkley-Black wet oxidation method (Nelson & Sommers, 1996). Organic Matter (OM) content was estimated by multiplying OC by the conventional factor of 1.724.
- **DTPA-extractable Micronutrients (Zn, Fe, Cu, Mn)** were determined using the method of Lindsay and Norvell (1978). A 10 g soil sample was shaken with 20 ml of 0.005 M DTPA extractant (pH 7.3) for 2 hours. The filtrate was analyzed for Zn, Fe, Cu, and Mn concentrations using an Atomic Absorption Spectrophotometer (AAS).

2.4. STATISTICAL ANALYSIS

Descriptive statistics (mean, range, standard deviation) were computed for all soil properties. Pearson's correlation analysis was performed to evaluate the linear relationships between DTPA-extractable micronutrients (Zn, Fe, Cu, Mn) and the soil properties pH, OM, and clay content. Correlation strength was interpreted as: weak ($|r| < 0.3$), moderate ($0.3 \leq |r| < 0.6$), and strong ($|r| \geq 0.6$). Additionally, to identify the predominant controlling variable for each micronutrient, a stepwise multiple linear regression analysis was performed, with the micronutrient as the dependent variable and pH, OM, and clay as

independent predictors. All statistical analyses were performed at a significance level of *p* < 0.05 using SPSS software (Version 25).

3. RESULTS
3.1. DESCRIPTIVE STATISTICS OF SOIL PROPERTIES AND MICRONUTRIENT STATUS
The physico-chemical characteristics of the studied pedons are summarized in Table 1. The soils were generally acidic to slightly acidic, with pH values ranging from 4.90 to 6.35 (mean: 5.54). Organic matter content was universally low, averaging 0.92 g kg^{-1}. Texture varied from sandy loam to loam, with a mean clay content of 12.6%, indicating predominantly light-textured soils.

The status of DTPA-extractable micronutrients revealed widespread constraints (Table 1). The mean available zinc (Zn) concentration was 0.68 mg kg^{-1}, with 62.5% of sampled horizons falling below the critical deficiency limit of 0.5 mg kg^{-1} (FFD, 2012). Iron (Fe) levels were generally sufficient (mean: 18.24 mg kg^{-1}), though showed high variability. Copper (Cu) availability was marginal, with a mean of 0.98 mg kg^{-1}, and manganese (Mn) was adequate (mean: 5.11 mg kg^{-1}). The high coefficients of variation (CV > 30%) for all micronutrients underscore their substantial spatial variability across the pedons.

TABLE 1 Descriptive statistics of soil properties and DTPA-extractable micronutrients in Zagga district soils

Parameter	Mean	Min.	Max.	Std. Dev.	CV (%)	Critical Limit
pH (H$_2$O)	5.54	4.90	6.35	0.42	7.6	-
OM (g kg^{-1})	0.92	0.31	1.89	0.41	44.6	-
Clay (%)	12.6	5.2	23.8	5.7	45.2	-
Zn (mg kg^{-1})	0.68	0.20	1.85	0.45	66.2	0.5
Fe (mg kg^{-1})	18.24	3.12	42.75	11.87	65.1	2.0
Cu (mg kg^{-1})	0.98	0.15	2.21	0.52	53.1	0.5
Mn (mg kg^{-1})	5.11	1.05	12.80	3.02	59.1	1.0

CV: Coefficient of Variation; Critical limits from FFD (2012) and Esu (1991).

3.2. CORRELATIONS BETWEEN MICRONUTRIENTS AND SOIL PROPERTIES
Pearson correlation analysis revealed distinct and significant relationships between micronutrient availability and specific soil properties (Table 2).

TABLE 2 Pearson correlation coefficients (r) between DTPA-extractable micronutrients and selected soil properties

Micronutrient	pH	Organic Matter	Clay
Zinc (Zn)	-0.32	+0.30	**+0.46***
Iron (Fe)	**-0.74***	-0.22	-0.35
Copper (Cu)	-0.08	**+0.75***	+0.47
Manganese (Mn)	**+0.64***	**+0.42***	+0.29

Bold indicates strong correlation ($|r| \geq 0.6$); *Italic* indicates moderate correlation ($0.3 \leq |r| < 0.6$). * p < 0.05.
A moderate positive correlation was found between Zn availability and clay content (r = +0.46). Iron displayed a strong negative correlation with soil pH (r = -0.74). Copper availability was strongly and positively correlated with organic matter (r = +0.75). Manganese exhibited a strong positive correlation with pH (r = +0.64) and a moderate positive correlation with organic matter (r = +0.42).

4. DISCUSSION
4.1. TEXTURE-DEPENDENT RETENTION OF ZINC
The significant positive correlation between DTPA-Zn and clay content (r = +0.46) underscores texture as a primary regulator of Zn availability in these soils. Finer particles provide greater surface area and cation exchange capacity (CEC), enhancing the retention of Zn^{2+} ions against leaching losses (Alloway, 2008). This explains the lower Zn concentrations observed in sandy horizons, where low CEC and high permeability facilitate Zn mobility (Rengel, 2015). Consequently, sandy pedons in the Zagga District are intrinsic deficiency hotspots. Management must therefore be texture-specific: sandy areas require targeted Zn fertilization, preferably through split applications or banding to improve efficiency, coupled with organic amendments to boost retention capacity.

4.2. pH-MEDIATED SOLUBILITY OF IRON
The strong negative correlation between Fe and pH (r = -0.74) is a classic demonstration of solubility control. In well-aerated soils, Fe exists primarily as Fe^{3+}, whose solubility decreases by approximately 1000-fold for each unit increase in pH due to hydrolysis and precipitation as insoluble oxides (Lindsay, 1979). While total Fe in these acidic soils is high, this relationship signals a significant risk. Any management practice that raises soil pH (e.g., liming) could rapidly induce Fe deficiency

chlorosis in sensitive crops. Effective Fe management must focus on strategies to enhance availability in the rhizosphere (e.g., use of Fe-chelates or acidifying fertilizers) rather than increasing total Fe inputs.

4.3. ORGANIC MATTER COMPLEXATION OF COPPER

The dominant control of organic matter over Cu availability (r = +0.75) is striking and aligns with the unique chemistry of Cu, which forms exceptionally stable, specific chelates with humic and fulvic acids (Tan, 2014). This complexation protects Cu from fixation and leaching while maintaining it in organically-bound, plant-available forms. The chronically low OM status of the cultivated Zagga district soils is thus the fundamental cause of marginal Cu levels. This finding pivots Cu management from a purely fertilizer-based approach to a soil-building strategy. Long-term sustainability of Cu fertility is inextricably linked to practices that rebuild soil organic carbon, such as compost application, cover cropping, and residue retention.

4.4. REDOX-DRIVEN DYNAMICS OF MANGANESE

The dual positive correlations of Mn with both pH and OM reveal a control mechanism distinct from simple solubility. Manganese cycling is predominantly governed by redox reactions (Barman, 2018). The positive correlation with OM is direct: during decomposition, OM consumes oxygen, creating localized reducing conditions that convert insoluble Mn^{4+} oxides to plant-available Mn^{2+}. The counterintuitive positive link with pH is likely indirect. In these soils, higher pH is often associated with slightly finer texture and higher OM, conditions that promote better water retention. This can lead to transient reducing microsites, even in generally well-drained profiles, thereby increasing Mn solubility. This lability makes Mn status highly sensitive to soil moisture fluctuations, posing risks of both deficiency in coarse, dry soils and potential toxicity in finer-textured, temporarily waterlogged areas.

4.5. SYNTHESIS AND AGRONOMIC IMPLICATIONS

This study quantitatively identifies the principal soil property controlling the availability of each micronutrient in the soils of the study area: Zn (Texture), Fe (pH), Cu (Organic Matter), and Mn (Redox/OM). These relationships provide a diagnostic framework for predicting deficiencies. For instance, a sandy soil inherently risks Zn deficiency, while a low-OM soil is likely Cu-deficient. The findings advocate for a paradigm shift from blanket micronutrient recommendations to property-based management. Routine soil tests for pH, OM, and texture should be used to assess vulnerability and guide targeted interventions. Ultimately, integrated practices that build soil organic matter and tailor amendments to specific field conditions will be most effective in mitigating hidden hunger and enhancing crop productivity in these fragile savannah agroecosystems.

5. CONCLUSION

This study elucidates the key soil properties governing the availability of essential micronutrients in the Zagga District soils of Kebbi State, Nigeria. The findings demonstrate that variability in DTPA-extractable Zn, Fe, Cu, and Mn is not random but is systematically controlled by distinct edaphic factors. Zinc availability is primarily regulated by soil texture, showing a positive association with clay content. Iron solubility is dominantly pH-dependent, decreasing sharply with increasing soil alkalinity. Copper dynamics are overwhelmingly controlled by organic matter content through stable chelation complexes. Manganese availability presents a more complex, redox-sensitive pattern, influenced by both pH and organic matter. These statistically significant correlations provide a mechanistic framework for predicting micronutrient deficiencies. They move the management paradigm beyond blanket fertilizer applications towards a diagnostic, soil property-based strategy. For sustainable crop production, interventions must be tailored: enhancing clay and organic matter in sandy zones for Zn and Cu, employing pH-aware strategies for Fe, and managing organic matter and drainage for Mn. Ultimately, integrating these relationships into soil fertility management plans will be crucial for addressing hidden hunger, improving nutrient use efficiency, and safeguarding agricultural productivity in this vulnerable savannah ecosystem.

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