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Evaluation of the micronutrients and macronutrients levels in soils among selected Local government in Benue North-West Benue State, Nigeria

Akorga Moses Terngu[1]; **Aondoakaa Ushahmba Solomon**[2]

Department of Agricultural Technology, Federal Polytechnic Wanune, Tarka Local Government Area Benue State Nigeria

***Corresponding Author**: Akorga Moses Terngu

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Abstract

This study evaluated macro- and micronutrient status of soils from three local government areas (Gwer East, Tarka and Makurdi) in Benue North-West, Nigeria, to identify fertility constraints and propose management options. A total of 35 surface (0–15 cm) and subsurface (0–30 cm) samples were collected using a random design, air-dried, sieved (2 mm) and analyzed for particle-size distribution (Bouyoucos hydrometer), pH (water slurry), organic matter (Walkley-Black), total nitrogen (Kjeldahl), available phosphorus (Bray-1), exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) by flame photometry, cation-exchange capacity (ammonium acetate), and micronutrients (Cu, Fe, Zn, Mn) by atomic absorption spectroscopy. Results show soils are predominantly loamy sand to sandy loam (sand 64–77 %, clay < 20 %). pH ranges from strongly acidic (5.4) to neutral (6.7); organic matter is low-to-moderate (2–6 %). Total N (0.14–0.60 %) and available P (5–9 ppm) are generally deficient. Exchangeable Ca, Mg, K and Na are low, with base saturation 36–80 %. Micronutrient levels are medium for Cu (0.41–0.64 mg kg^{-1}) and Fe (3.2–6.2 mg kg^{-1}), medium for Mn (5.0–5.8 mg kg^{-1}) and low for Zn (0.30–0.62 mg kg^{-1}). Correlation analysis indicates a moderate positive Cu–Zn relationship ($r \approx 0.55$) and a moderate negative Fe–Mn relationship ($r \approx -0.63$). The findings reveal that coarse texture, acidity, low organic matter and nutrient leaching limit soil fertility, with zinc deficiency as the primary micronutrient constraint. Integrated management liming to raise pH, organic amendments to boost OM and CEC, balanced N-P-K fertilization, and zinc supplementation combined with conservation practices (contour bunds, cover crops, reduced tillage) is recommended to improve soil productivity in Benue North-West.

Keywords: *Evaluation, Micronutrients, Macronutrients, Soils.*

Introduction

One of the main problems Nigerian farmers face in producing enough food is the serious damage happening to the land. Farmlands are affected by both human actions and natural events (Oyetola et al., 2021). Human activities responsible for land degradation as the population increases, there is more land being plowed for farming to grow enough food. At the same time, there is a rise in people raising animals for livestock. Husbandry and the use of wood as fuel instead of regular fuel because the regular fuel is too expensive. These human activities can expose the top layer of soil becomes easy to wear away because of weather conditions (Macaulay 2014). While natural activities may include changes in climatic conditions like rainfall, temperature, and weathering. Also, there has been a slow decrease in soil fertility because of heavy farming and poor care of the soil policies nationwide. According to Yakubu and Ishaku (2019), maintaining soil resources means using effective methods to keep them healthy and productive using agricultural methods like this will quickly reduce the quality and amount of soil available. Farmers should be advised to use farming methods or management techniques that help keep the soil healthy and fertile environmentalists through government policymakers.

Soil is a complicated and changing system with a lot of spatial variability, from microscale heterogeneity at small sites to wide landscape-level distributions (Khan et al., 2022; Dasgupta et al., 2023; Walia et al., 2024). The pedogenic processes regulated by both intensive and extensive formation variables significantly impact the soil's physical structure and chemical composition (Chibuike & Obiora, 2014). Soil is an important part of terrestrial ecosystems because it provides critical nutrients, helps plants grow, controls water flow, and stores a lot of carbon (Aschonitis et al., 2019; Jigyasu et al., 2023). It has developed over a long time by weathering, erosion, and deposition of rocks, minerals, and organic matter (Smith et al., 2012). Soils are typically categorized into categories such as sand, clay, silt, and loam, each characterized by distinct textural and physicochemical properties. Moreover, the bioavailability of micronutrients in soils is influenced by the interplay between plant genetic traits and environmental variables, such as climate and edaphic factors (Chen et al., 2008; Desmidt et al., 2015; Hermans et al., 2020).

Macronutrients are the body's primary sources of energy, providing calories in the form of carbohydrates, proteins, and fats. These nutrients are required in larger amounts compared to micronutrients (vitamins and minerals) and are crucial for growth, metabolism, and overall health. Carbohydrates are the body's preferred energy source, found in grains, fruits, and vegetables. They're broken down into glucose, fueling brain and muscle activity. Proteins are essential for tissue repair, growth, and immune function, sourced from meat, legumes, nuts, and dairy. Fats are vital for hormone production, nutrient absorption, and energy storage, with healthy fats in avocados, nuts, and fish.

Macronutrients provide energy for bodily functions and physical activity, support growth and repair of body tissues, and aid in nutrient absorption and hormone regulation. The World Health Organization recommends a balanced diet with carbohydrates making up 55-75% of total energy intake, proteins 10-15%, and fats 15-30% (WHO, 2003). Individual needs vary based on age, activity level, and health goals. Whole grains, fruits, and veggies are great carb sources; lean meats, fish, eggs, and legumes provide proteins; and nuts, seeds, avocados, and olive oil offer healthy fats. A balanced macronutrient diet supports overall health, weight management, and reduces chronic disease risks (Hu & Willett, 2002).

Micronutrients are vitamins and minerals that the body needs in little amounts, unlike macronutrients like carbs, proteins, and fats. Micronutrients are essential for many bodily functions, such as growth, immune system regulation, metabolic function, and overall health, even though you only need a small amount of them. Not getting enough of these nutrients can seriously mess up typical biological processes and make you more likely to get sick.

Vitamins are organic substances that help with important metabolic processes like making energy, protecting the immune system, and growing cells. For example, Vitamin A helps with vision and the immune system, Vitamin C is a strong antioxidant that helps repair tissues, and Vitamin D is important for calcium absorption and bone health. Minerals, on the other hand, are inorganic substances that help the body with structure and regulation. Calcium is necessary for making and keeping bones strong. Iron is necessary for hemoglobin to carry oxygen in the blood. Zinc helps the immune system, enzymes, and cells thrive. Vitamins and minerals are important for keeping your body working well and staying healthy over the long run.

Micronutrients support growth and development, boost the immune system, aid in disease prevention like Vitamin C and antioxidants helping fight oxidative stress, and contribute to energy production. Common deficiencies include iron deficiency leading to anemia, Vitamin D deficiency causing bone health issues, and iodine deficiency affecting thyroid problems.

Fruits and vegetables are great sources of Vitamins A and C, whole grains provide B vitamins and minerals like magnesium, dairy products offer calcium, and lean meats and legumes supply iron and zinc. According to the World Health Organization (WHO), micronutrient deficiencies affect billions globally, particularly in low-income populations (WHO, 2020). Ensuring a balanced diet rich in diverse foods can help prevent these deficiencies. The importance of micronutrients is underscored by their impact on public health. Deficiencies can lead to significant health issues, emphasizing the need for adequate intake through diet or supplementation when necessary. The World Health Organization highlights strategies like food fortification and supplementation as key interventions in addressing micronutrient deficiencies, especially in vulnerable populations (WHO, 2020).

About 38% of the Earth's land surface is currently used for farming, which is enough to support a worldwide population that is estimated to reach 9.7 billion by 2050 (UN DESA, 2022). But about 40% of the world's croplands are in bad shape, mostly because of soil erosion, which removes topsoil and important nutrients at rates that are thought to be 13 to 40 times quicker than natural processes that put them back (Kammerlander et al., 2025). This deterioration puts more stress on important natural resources like soil, water, and biodiversity. This is made worse by population increase and climate change, which are both causing problems for traditional farming systems. In this setting, organic farming has become more popular as a way to promote long-term agricultural resilience, environmental stewardship, and the production of safe and healthy food (Christel et al., 2021; Montgomery & Biklé, 2021).

Soil formation, or pedogenesis, happens over a long period of time when parent materials and organic residues weather, erode, and settle (Smith et al., 2012). This creates different types of soil, like sand, clay, silt, and loam, each with its own unique physicochemical properties (Zhong et al., 2019). Soil properties, especially nutrient availability and vegetation patterns, are affected by both internal factors (like mineral composition and biological activity) and external factors (like climate and land use) (Chibuike & Obiora, 2014; Daher et al., 2019). Soil serves as a regulator of the hydrological cycle and a significant terrestrial carbon sink (Aschonitis et al., 2019; Jigyasu et al., 2023). Soil is a geographically diverse and ever-changing system that supports plant growth and the long-term health of ecosystems (Khan et al., 2022; Dasgupta et al., 2023; Sohan et al., 2024).

The availability of nutrients in soils is a major factor that affects how well ecosystems work and how productive they are around the world (Barber, 1995; Van Sundert et al., 2020). It helps provide important ecosystem services, including as growing food and controlling global biogeochemical cycles (Fernández-Martínez et al., 2014; Schlesinger & Bernhardt, 2020). A thorough global evaluation incorporating around 10,000 topsoil observations (3–8 cm depth) from various continents assessed the bioavailability and interactions of thirteen macro- and micronutrients, as well as phytotoxic elements, including responses to experimental global change manipulations (Ochoa-Hueso et al., 2023). Molybdenum (Mo) is a very important micronutrient since it helps nitrogen (N) and carbon (C) cycle and is a cofactor for nitrogenase, which affects biological N_2 fixation (Wurzburger et al., 2012). Zinc (Zn) insufficiency continues to be a significant global nutritional issue, impacting over 50% of the world's population, particularly in developing areas dependent on cereal-based diets (Cakmak, 2008). Plant growth also depends on getting enough macronutrients, especially nitrogen (N), phosphorus (P), and potassium (K), which are all important for metabolic processes. Moderate levels of secondary nutrients including sulfur, magnesium, and calcium are also needed. However, nitrogen is still necessary for all crops to grow and develop (Olego et al., 2021).

Statement of the Problem

Soil fertility decline is a significant challenge affecting agricultural productivity in Benue State, Nigeria, with far-reaching implications for food security, livelihoods, and the overall economy. Benue State, often referred to as the "Food Basket of the Nation," is a major producer of crops like yams, maize, and vegetables. However, the state's agricultural sector is facing numerous challenges, including declining soil fertility, which is exacerbated by continuous cropping, inadequate fertilizer use, and limited knowledge of soil nutrient status. Despite the importance of micronutrients and macronutrients for crop growth and yield, there is limited information on the current status of these nutrients in soils of selected Local Government Areas in Benue North-West. This knowledge gap hinders effective soil management and fertilizer recommendations, potentially leading to reduced crop yields, soil degradation, and food insecurity. The lack of data on soil micronutrient and macronutrient levels makes it challenging for farmers to make informed decisions about fertilizer application, crop selection, and soil conservation practices.

Furthermore, the few available studies on soil fertility in Benue State have focused on specific locations or individual nutrients, leaving a gap in comprehensive understanding of the micronutrient and macronutrient status across different Local Government Areas. This limited understanding may lead to nutrient imbalances, inefficient fertilizer use, and environmental degradation. For instance, excessive application of nitrogen fertilizers can lead to water pollution, while inadequate potassium application can result in reduced crop yields. The evaluation of micronutrients and macronutrients levels in soils is crucial for developing targeted interventions to improve soil fertility, increase crop productivity, and enhance food security in Benue State. Understanding the current status of soil nutrients will inform policymakers, farmers, and extension agents on the best approaches to soil management, fertilizer application, and crop selection, ultimately contributing to sustainable agricultural development in the region. The situation is further complicated by factors such as climate change, population growth, and land degradation, which exert pressure on the already fragile agricultural system. Addressing the issue of soil fertility decline requires a comprehensive approach that includes assessing the current nutrient status, developing and disseminating location-specific fertilizer recommendations, and promoting sustainable soil management practices among farmers. In this context, evaluating the micronutrients and macronutrient levels in soils among selected Local Government Areas in Benue North-West, Benue State, Nigeria, is a critical step towards developing evidence-based strategies to improve soil fertility, increase agricultural productivity, and ensure food security in the region.

Objective of the Study

The main objective of this study is to assess and evaluate the levels of micronutrients and macronutrients in soils among selected Local Government Areas in Benue North-West, Benue State, Nigeria. This involves analyzing soil samples to determine the status of essential nutrients, likely informing agricultural practices, soil management, and fertility improvement strategies.

Materials and Methods

Study Area

The research was carried out in selected local government areas in Benue North-West Senatorial District, Benue State, Nigeria, which includes Tarka, Makurdi, Gwer East. The district lies in Nigeria's middle-belt, with a tropical climate characterized by a wet season (April–October) and a dry season (November–March). Temperatures range from 25 °C to 35 °C. Natural vegetation is Guinea savanna (grasses with scattered trees and shrubs). Agriculture dominates land use, producing yams, cassava, potatoes, millet, soyabean, rice, citrus, palm and other economic trees. The Benue River, Katsina-Ala River and their tributaries drain the area, providing water for domestic, agricultural and aquacultural purposes.

Soil sample collection and preparation

Soil samples were collected from three LGAs (Tarka, Makurdi, Gwer East) using a random sampling design. At each location, a metal spade was used to obtain approximately 500 g of soil from the surface to 15 cm depth; additional samples were taken with a soil auger from 0–30 cm for a separate set of analyses. In total, five samples were taken from each of the seven LGAs, yielding 35 samples (collected in September 2025). Samples were placed in clean, new polythene bags, labelled, and sealed. To avoid contamination, only stainless-steel or plastic tools were used. Samples were air-dried at room temperature, then crushed with a pestle and mortar and sieved through a 2 mm mesh before laboratory analysis.

Laboratory Analysis

Laboratory procedures included a full physicochemical analysis of soil samples. The Bouyoucos hydrometer method (1951) was used to find the particle size distribution, and the USDA textural triangle (1996) was used to put the textural classes into groups. A calibrated digital pH meter (Mathieu & Pieltain, 2003) was used to measure the pH of the soil in a soil-water suspension, and a conductivity meter was used to measure the electrical conductivity (EC). A flame photometer was used to measure the exchangeable bases, which are sodium (Na), magnesium (Mg), calcium (Ca), and potassium (K). Spectrophotometry was used to look at the total amounts of phosphorus (P) and sulfur (S). Atomic absorption spectroscopy (AAS) was used to find micronutrients like zinc (Zn), manganese (Mn), copper (Cu), and iron (Fe). Colorimetric analysis was used to find boron (B). The Walkley–Black wet oxidation method (1934), as changed by Jackson (1967), was used to measure the amount of organic matter (OM) in the soil. The micro-Kjeldahl distillation technique (Jackson, 1967) was used to measure the total nitrogen (N). The Bray-1 extraction method (Bray & Kurtz, 1945) was used to figure out how much phosphorus was available. We used ammonium acetate extraction to get the cation exchange capacity (CEC). We used EDTA titration to find the exchangeable Ca and Mg, and a flame photometer to find the Na and K in the extracts. We then found the base saturation (BS) by dividing the total of the exchangeable bases by the CEC and multiplying by 100.

Table 1: Interpretation for Evaluating Analytical Data

Exchangeable Cations

Ca^{2+}	Mg^{2+}	K^{+}	Na^{+} (Cmol/kg)	Class
<2	<0.4	<0.2	<0.1	Very low
3 – 6	0.2 – 1	0.3 – 0.5	0.2 – 0.5	Low
6 – 11	1 – 3	0.4 – 0.7	0.5 – 0.9	Moderate
15 – 30	3 – 6	0.5 – 1.9	0.8 – 3.0	High
>30	>12	2.1 – 4.1	>3	Very high

Organic Matter

Range (%)	Class
<2	Very low
3 – 7	Low
6 – 12	Moderate
20 – 24	High
>25	Very high

Soil pH

Range	Rating
<4.5	Extremely acidic
4.5 – 5.0	Very strongly acidic
5.2 – 5.8	Strongly acidic
5.9 – 6.2	Moderately acidic
6.3 – 6.6	Slightly acidic
6.7– 7.8	Neutral
7.9 – 8.2	Slightly alkaline
8.3 – 8.6	Moderately alkaline
8.7 – 10.0	Strongly alkaline
>10.0	Very strongly alkaline

Total Nitrogen

Range (%)	Class
<0.1	Very low
0.2 – 0.3	Low
0.4 – 0.6	Moderate
0.7 – 1.8	High
>1.8	Very high

Sources: Department of soil sciences Josephe Sarwa Tarka University Makurdi (2026)

Results And Discussion

Table 2: Particle Size distribution in the Study Area

Location / Sample No		**Depth (0 – 30cm)**	**Particle Size Distribution**			**Textural Uses**
			Sand (%)	**Silt (%)**	**Clay (%)**	
Gwer East	1		69.80	13.20	15.72	Loamy sand
	2		82.20	18.00	16.80	Loamy sand
	3		71.00	15.00	12.00	Loamy sand
	4		79.00	18.00	14.00	Sandy loam
	5		81.00	21.00	13.00	Sandy loam
Tarka	1		81.00	17.00	14.00	Sandy loam
	2		68.00	19.00	12.00	Sandy loam
	3		69.00	13.00	19.00	Sandy loam
	4		80.00	14.00	21.00	Sandy loam
	5		81.60	15.20	13.20	Loamy sand
Makurdi	1		83.00	19.00	16.00	Clay loam
	2		72.20	16.50	22.30	Clay loam
	3		82.00	13.00	21.00	Loamy sand
	4		84.00	16.00	13.00	Loamy sand
	5		67.00	16.00	18.00	Sandy loam

Table 3: Soil Chemical Properties in the Study Area

Location/ Sample No		pH (in water)	OM (%)	Exchangeable Cations				BS (%)	CEC (Cmol/k g)	Total Nitrogen (%)	Available Phosphorus (ppm)
				Ca^{2+}	Mg^{2+}	K^+	Na^+ (Cmol/kg)				
Gwer East	1	6.2	2.50	2.8	1.3	0.5	0.4	51.16	10.36	0.18	8.2
	2	6.5	2.20	3.0	1.2	0.5	0.5	63.80	8.15	0.29	8.5
	3	5.5	2.47	2.5	0.9	9.6	0.4	36.30	12.12	0.14	5.2
	4	5.4	3.50	2.5	1.4	0.9	0.3	80.44	6.34	0.39	4.8
	5	5.8	3.20	2.5	0.8	0.7	0.2	60.56	7.14	0.28	5.0
Tarka	1	6.4	4.50	3.0	1.2	0.8	0.7	46.68	12.21	0.50	8.3
	2	6.7	4.80	3.2	1.3	0.8	0.6	58.36	10.11	0.27	8.3
	3	6.5	4.60	3.5	1.0	0.6	0.6	60.57	9.41	0.25	8.1
	4	6.2	4.20	2.9	1.1	0.5	0.5	68.31	7.32	0.23	7.0
	5	5.7	3.50	2.2	0.8	0.4	0.5	59.62	7.38	0.31	5.2
Makurdi	1	6.3	4.20	3.5	0.4	0.9	0.6	41.22	13.10	0.40	8.8
	2	6.2	5.00	3.0	0.5	0.7	0.6	68.97	6.96	0.50	7.3
	3	6.1	5.30	3.4	1.0	0.8	0.5	46.99	12.13	0.60	8.0
	4	5.8	5.60	2.9	2.0	0.5	0.5	45.04	13.10	0.30	5.5
	5	5.4	6.00	2.8	0.8	0.5	0.4	72.35	6.22	0.27	5.6

Table 4: Micronutrients Content of the Study Area

Location/ Sample No		Cu	Fe	Zn	Mn
		(mg/kg)			
Gwer East	1	0.50	5.40	0.30	5.82
	2	0.43	4.20	0.54	5.50
	3	0.64	5.10	0.50	5.20
	4	0.52	6.20	0.60	5.00
	5	0.55	5.20	0.53	5.60
Tarka	1	0.51	3.60	0.52	5.10
	2	0.41	3.90	0.62	5.20
	3	0.48	3.20	0.54	5.72
	4	0.44	5.00	0.53	5.63
	5	0.52	4.30	0.55	5.45
Makurdi	1	0.45	4.60	0.41	5.20
	2	0.47	5.40	0.52	5.70
	3	0.50	6.20	0.57	5.00
	4	0.56	4.50	0.49	5.10
	5	0.60	4.70	0.53	5.30

Table 5: Correlation Coefficient among the Micronutrients

Micronutrient Pair	Correlation Coefficient(s)	Interpretation
Copper vs Iron	0.15	Weak positive
Copper vs Zinc	0.55	Moderate positive
Copper vs Manganese	0.31	Weak positive
Iron vs Zinc	0.41	Weak to moderate positive
Iron vs Manganese	-0.63	Moderate negative
Zinc vs Manganese	0.19	Weak positive

Table 6: Nutrient Index for Micronutrients

Micronutrient	Nutrient Index	Classification
Copper (Cu)	4.2	Medium fertility
Iron (Fe)	2.43	Medium fertility
Zinc (Zn)	1.88	Low fertility
Manganese (Mn)	2.05	Medium fertility

Discussion of Result

The soils of Benue North-West are dominated by coarse textures, with sand fractions ranging from about 64 % to 77 % and clay seldom exceeding 20 %. Consequently, most sites fall into loamy-sand or sandy-loam classes, while a few Makurdi locations reach clay-loam. This high sand content translates into rapid drainage, low water-holding capacity and limited capacity to retain nutrients, making the soils inherently vulnerable to leaching.

Soil reaction varies from strongly acidic (pH ≈ 5.4) to neutral (pH ≈ 6.7). While many samples sit within the generally acceptable range for crop production, several locations, especially in Gwer East, are below pH 5.5, which can restrict phosphorus availability and increase aluminium toxicity. Organic matter levels are low to moderate, with Gwer East averaging around 2–3 % and the other areas between 3.5 % and 6 %. Low organic matter further reduces cation-exchange capacity (CEC), which across the study area remains low to moderate (6–13 cmol kg^{-1}), limiting the soil's ability to hold exchangeable bases.

Total nitrogen follows a similar pattern, ranging from 0.14 % (low) to 0.60 % (high), with many sites clustered in the low-to-moderate band, suggesting that nitrogen will often be a limiting nutrient for high-yield crops. Available phosphorus, measured by the Bray-1 method, is consistently low (5–9 ppm), indicating that phosphorus fixation by iron and aluminium oxides in the acidic soils may be occurring, and external P inputs are needed.

Exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) are generally low, with calcium and magnesium often below critical thresholds, and potassium borderline for many crops. Base saturation ranges from about 36 % to 80 %, with many sites in the moderate range (40–60 %). This reflects the leaching environment and reinforces the need for lime and organic amendments to raise pH and base status.

Micronutrient analysis shows copper and iron concentrations at medium fertility levels, well above typical deficiency thresholds. Manganese also falls into the medium category, though its availability can be suppressed where iron oxides dominate. Zinc, however, is consistently low (around 0.3–0.6 mg kg^{-1}), placing it in the low-fertility class and marking it as a primary micronutrient constraint.

Correlation analysis among micronutrients reveals a moderate positive relationship between copper and zinc (r ≈ 0.55), suggesting that practices that enhance one (e.g., organic matter addition) will likely benefit the other. Iron and manganese exhibit a moderate negative correlation (r ≈ -0.63), indicating that high iron, possibly from Fe-oxides, may outcompete manganese for sorption sites, reducing Mn availability.

Conclusion

The evaluation of macro- and micronutrient status in soils from Gwer East, Tarka and Makurdi reveals a landscape dominated by coarse-textured, sand-rich soils with low clay content. These textures result in rapid drainage, limited water-holding capacity and an inherently low cation-exchange capacity (CEC), making the soils prone to nutrient leaching. Soil pH ranges from strongly acidic (≤ 5.5) to neutral (≈ 6.7), with many sites, especially in Gwer East, falling below the optimum for phosphorus availability and base-cation retention. Organic matter levels are generally low to moderate (2–6 %), further constraining CEC and nutrient storage. Total nitrogen and available phosphorus are consistently low to moderate, indicating that both nutrients will frequently limit crop yields without supplemental fertilization. Exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) are likewise deficient, and base saturation varies widely, underscoring the need for lime application and organic amendments to raise pH and improve base status. Micronutrient analysis shows copper and iron at medium fertility levels, manganese at medium but potentially suppressed by high iron, and zinc consistently in the low-fertility range. The moderate positive correlation between copper and zinc suggests that organic matter additions will simultaneously enhance both elements, while the negative iron-manganese relationship warns that high iron may reduce manganese availability.

Recommendations

Based on the study findings, the following recommendations are made**:**

1. Apply agricultural lime ($CaCO_3$) to raise pH in strongly acidic soils (pH < 5.5), improving nutrient availability.
2. Incorporate organic amendments (compost, well-rotted manure, green manure) to increase organic matter, boost CEC, and enhance moisture retention.
3. Use balanced N-P-K fertilizer with emphasis on phosphorus (Bray-1 < 8 ppm) and potassium (low-moderate levels) based on soil test results.
4. Supplement zinc through $ZnSO_4$ or foliar sprays, as zinc index (1.57) indicates low fertility and deficiency risk.
5. Implement conservation practices (contour bunds, cover crops, reduced tillage) to curb erosion and leaching, preserving topsoil and nutrients.

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