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**Soil Micronutrient Deficiencies and Hidden Hunger: Insights from Zagga District Soils, Kebbi State, Nigeria**

By

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**Abstract**

*Micronutrient deficiencies in soils not only constrain agricultural productivity but also contribute to hidden hunger through reduced nutritional quality of food crops. This study investigated the availability of zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn) in soils of Zagga District to assess their implications for soil fertility and food security. Results showed that Zn concentrations were generally low (0.44–2.23 mg/kg; mean = 0.81 mg/kg), indicating widespread deficiency, while Fe was abundant (1.47–13.04 mg/kg; mean = 9.30 mg/kg), Cu was borderline (0.28–0.76 mg/kg; mean = 0.47 mg/kg), and Mn was adequate (1.27–5.71 mg/kg; mean = 3.11 mg/kg). Correlation analysis confirmed that Zn availability was linked to clay content, Cu to organic matter, Fe to soil acidity, and Mn to pH stability. These findings suggest that Zn is the most critical limiting nutrient in the soils, with direct consequences for crop yield and nutritional quality. Addressing Zn deficiency through fertilizer enrichment, biofortification, and integrated soil–crop–nutrition management is essential to improve food security and reduce hidden hunger in soils of the study area.*

**Keywords:** Soil Micronutrients; Hidden Hunger; Zinc Deficiency; Soil Fertility; Zagga District

**INTRODUCTION**

Micronutrient malnutrition, often described as hidden hunger, affects more than two billion people globally, with the highest prevalence in Sub-Saharan Africa and South Asia (WHO, 2020; Cakmak, 2008). Unlike calorie deficiency, hidden hunger arises from insufficient intake of essential vitamins and minerals, impairing human growth, immunity, and productivity. Zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn) are among the critical micronutrients linking soil fertility to crop nutrition and ultimately to human health (Alloway, 2008; Fageria *et al.*, 2011).

Soils form the primary reservoir of these nutrients, but their availability to plants depends on complex interactions involving parent material, organic matter, pH, and pedogenic processes. Deficiencies at the soil level directly reduce crop yields and also lower the micronutrient density of harvested food crops, perpetuating cycles of malnutrition (Welch & Graham, 2004; Joy *et al.*, 2015). This soil–plant–human nutrition continuum has become a major focus of sustainable agriculture and global food security initiatives.

In Nigeria and much of the savannah zone of West Africa, Zinc deficiency has been identified as the most widespread

soil-related constraint to crop production (Oyinlola & Chude, 2010). Although Fe, Cu, and Mn are generally more abundant in soils of this region, their bioavailability to plants can still be limited by soil chemistry, texture, and management practices (Shehu *et al.*, 2015; Kolawole *et al.*, 2023). Thus, understanding the status of these micronutrients is critical not only for agricultural productivity but also for the nutritional quality of staple crops such as maize, sorghum, and millet that dominate local diets.

Despite the well-documented prevalence of soil fertility constraints in Northern Nigeria, there is still limited research connecting soil micronutrient availability to food security outcomes. Most studies have been agronomic or pedological, with fewer explicitly addressing nutritional implications. This creates a gap in linking soil science to broader development goals such as the UN Sustainable Development Goal 2 (“Zero Hunger”), which emphasizes both yield improvement and nutrition-sensitive agriculture.

The objective of this study was therefore to assess the availability of Zn, Fe, Cu, and Mn in soils of Zagga District of Kebbi State, Nigeria, and to evaluate their implications for crop nutrition and food security. By integrating soil chemical analysis with a nutritional perspective, this paper highlights

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how soil micronutrient deficiencies contribute to hidden hunger, and suggests strategies for improving soil fertility, crop quality, and human health.

## Materials and Methods

**Study Area:** The study was carried out in Zagga District, Bagudo Local Government Area of Kebbi State (Figure 1). The study site is located in the southwest of Zagga town along Dakingari-Koko Road in Bagudo LGA of Kebbi State (Figure 1). It has a longitudinal extent of  $4^{\circ} 00' - 4^{\circ} 11' 32''$  E and latitudinal stretch of  $11^{\circ} 27' 20''$  to  $11^{\circ} 35' 30''$  N, lying parallel to the main road. The study area encompasses 12,857ha. For this study, a portion measuring 170ha was allocated for the present study.

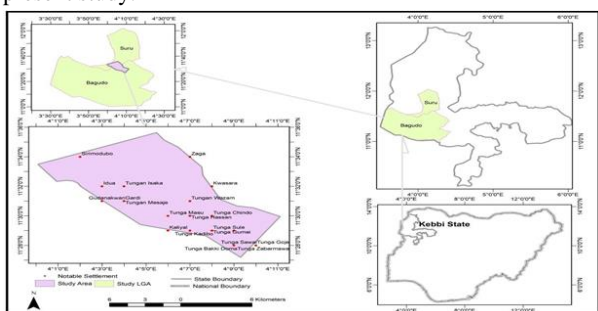


Figure 1: Map of Nigeria showing the study area

The climate of Kebbi state is hot, semi-arid tropical (AW) in Koppen's classification (Wali *et al.*, 2016), characterized by a long dry season lasting between the months of October and May with a short but intensive wet season between the months of May and October. Annual rainfall is variable and declining, being 600mm to 875mm and on average 650mm during the period 1997 to 2014 (Usman *et al.*, 2016). Mean maximum temperature is about 45°C (highest in April to June) while mean minimum temperature is about 16°C (lowest in December and January) (Gada, 2014). The natural vegetation of the state consists of Northern Guinea Savannah in the south and south-east and Sudan Savannah in the north (Olayide *et al.*, 2023).

### Fieldwork, pedon description and Soil Sampling

A semi-detailed soil survey was conducted at a scale of 1:25,000 following established procedures described by Kairis *et al.* (2020). The study area was systematically pegged using a fixed grid pattern, and representative soil profile pits were excavated within each identified mapping unit.

Eight representative soil pedons (ZG6–ZG13) were described, sampled, and classified. Horizon-wise soil samples were collected from both surface horizons (epipedons) and subsurface horizons (endopedons). Standard soil survey techniques were employed to record soil depth, color, texture, and structural characteristics in accordance with FAO (2006) guidelines.

Soil horizons were delineated based on observable variations in color, texture, structure, consistence, root distribution, and the presence of mottles or concretions. Soil color determinations were made using the Munsell Soil Color Chart. Morphological descriptions followed the criteria outlined by FAO (2006).

Samples from each identified horizon were collected primarily to confirm diagnostic features relevant to soil classification, including clay accumulation, base saturation status, and horizon boundary differentiation. All soil samples were air-dried, gently crushed, and sieved (<2 mm) prior to laboratory analyses.

### Laboratory Analysis

Soil samples were analyzed for Zn, Fe, Cu, and Mn availability:

- Micronutrient extraction was conducted using the DTPA method (USDA-NRCS, 2014).
- Concentrations were measured with Atomic Absorption Spectrophotometry (AAS).
- Soil pH was measured in a 1:2.5 soil–water suspension.
- Organic carbon was determined using the Walkley–Black method and converted to organic matter.
- Particle size distribution was determined by hydrometer method, with clay fraction recorded as an indicator of texture.

### Nutrient Classification and Food Security Implications

Micronutrient status was evaluated using critical limits relevant for crop production:

- **Zn:** deficient <0.5 mg/kg; adequate >1.0 mg/kg (FFD, 2012; Oyinlola & Chude, 2010).
- **Fe:** critical value 2.0 mg/kg (Havlin *et al.*, 2016).
- **Cu:** critical limit 0.5 mg/kg (Nathan & Stecker, 2020).
- **Mn:** critical limit 1.0 mg/kg (Havlin *et al.*, 2016).

Values below these thresholds were interpreted not only as constraints for crop productivity but also as potential risks for reduced micronutrient density in edible parts of crops, contributing to hidden hunger.

### Statistical Analysis

Descriptive statistics (mean, range, standard deviation, and coefficient of variation) were computed to evaluate overall micronutrient status. Pearson correlation analysis was used to assess relationships between micronutrient availability (Zn, Fe, Cu, and Mn) and selected soil properties (pH, organic matter, and clay content). Simple linear regression analysis was employed to identify key soil factors controlling micronutrient availability. Multivariate relationships among soil properties and micronutrients were further examined using principal component analysis (PCA). Statistical significance was evaluated at  $p < 0.05$ .

## Results and Discussion

### Micronutrient Status of ZG Soils

The availability of Zn, Fe, Cu, and Mn in ZG soils varied considerably across pedons and horizons (Table 1). Mean values were 0.81 mg/kg (Zn), 9.30 mg/kg (Fe), 0.47 mg/kg (Cu), and 3.11 mg/kg (Mn).

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**Table1. Descriptive statistics of micronutrient concentrations and some soil properties**

Variable	Mean	Std. Dev.	Min	Max	CV (%)
Zn (mg/kg)	0.81	0.58	0.44	2.23	72
Fe (mg/kg)	9.30	4.05	1.47	13.04	44
Cu (mg/kg)	0.47	0.17	0.28	0.76	36
Mn (mg/kg)	3.11	1.52	1.27	5.71	49
pH	5.54	0.26	5.3	6.0	5
Organic Matter (g/kg)	0.92	0.49	0.53	2.00	53
Clay (%)	12.6	10.6	3.0	26.2	84

### Zinc (Zn): The Critical Limiting Micronutrient

Zinc concentrations in Zagga soils ranged from 0.44 to 2.23 mg/kg, with a mean value (0.81 mg/kg) below the established adequacy threshold, confirming Zn as the most deficient micronutrient in the study area, consistent with earlier reports across Northern Nigeria (Oyinlola & Chude, 2010). This widespread deficiency reflects the inherently low Zn content of the parent material combined with prolonged intensive cultivation without micronutrient replenishment (Alloway, 2008).

Zinc availability showed a significant positive relationship with clay content ( $r = 0.46, p < 0.05$ ), indicating improved Zn retention in finer-textured soils. Multiple linear regression further identified clay content as the strongest predictor of Zn availability ( $\beta = 0.41, p < 0.05; R^2 = 0.52$ ), confirming texture as the dominant control on Zn dynamics. Agronomically, Zn deficiency constrains crop growth and yield in dominant cereals such as maize, sorghum, and millet. Nutritionally, Zn-deficient soils produce grain with low Zn density. Its deficiency disrupts critical plant functions, including:

**Auxin Synthesis:** Stunting plant growth and leading to shortened internodes ("rosetting") (Broadley *et al.*, 2007).

**Chlorophyll Formation:** Reducing photosynthetic efficiency and vigor (Chen *et al.*, 2020).

**Membrane Integrity:** Making plants more susceptible to disease and environmental stress (Cakmak, 2000).

From a food security perspective, Zn deficiency in soils leads to lower Zn concentrations in staple crops such as maize, sorghum, and millet (widely cultivated in the area), which already provide low dietary Zn. This creates a double burden:

yield reduction and poor nutritional quality, directly contributing to hidden hunger (Cakmak, 2008; Joy *et al.*, 2015).

**The Double Burden (Food and Nutritional Security):** This soil deficiency creates a perilous "double burden" with profound implications for human health. Staple crops such as maize, sorghum, and millet, which form the bedrock of the local diet, are inherently inefficient at accumulating zinc. When grown on zinc-deficient soils, their grain zinc concentrations become critically low (Cakmak, 2008). Consequently, the population, which relies heavily on these cereals, consumes a diet grossly inadequate in zinc. This creates a vicious cycle, the very crops cultivated to stave off hunger are themselves nutritionally impoverished. This phenomenon is a primary driver of hidden hunger—a form of malnutrition where the diet is sufficient in calories but deficient in essential vitamins and minerals (WHO, 2002). The work of Cakmak (2008) and Joy *et al.* (2015) has been instrumental in highlighting how soil micronutrient management is directly linked to human nutritional outcomes.

**The Human Health Crisis and Economic Implications:** The human body requires zinc for over 300 enzymatic reactions. Chronic dietary zinc deficiency has severe consequences, particularly for the most vulnerable:

**Impaired Immune Function:** Increased susceptibility to infectious diseases like pneumonia, malaria, and diarrhea (Prasad, 2013).

**Stunted Growth and Development:** In children, zinc is crucial for linear growth, cognitive development, and neurological function (Black *et al.*, 2013).

**Complications in Pregnancy:** Contributing to low birth weight and poor maternal health (Hess & King, 2009).

This silent crisis perpetuates a cycle of poverty, reducing individual potential, burdening healthcare systems, and diminishing national productivity (Horton, 2007). Addressing zinc deficiency in Zagga's soils is, therefore, not merely an agricultural challenge but a fundamental imperative for public health, economic development, and long-term food and nutrition security.

### Iron (Fe): Abundant but Bioavailability Limited

Total Fe was high (mean 9.3 mg/kg), but availability was strongly pH-dependent ( $r = -0.74, p < 0.05$ ; regression  $R^2 = 0.58$ ). Sorghum and millet are susceptible to Fe-induced chlorosis under localized alkaline conditions. In acidic environments (low pH), ferric iron ( $Fe^{3+}$ ) is more readily reduced to the more soluble ferrous ( $Fe^{2+}$ ) form, which is the primary state in which plant roots absorb it (Zandi *et al.*, 2023). Additionally, antagonism with Mn ( $r = -0.53, p < 0.05$ ) may reduce Fe uptake despite adequate soil Fe. This illustrates that soil Fe sufficiency does not guarantee human Fe nutrition due to crop uptake limitations and dietary inhibitors.

**Agronomic Implications:** The high total iron suggests that widespread visual deficiency symptoms (e.g., interveinal

chlorosis in young leaves) may not be common. However, in localized zones with higher pH, or in crops sensitive to iron deficiency (like sorghum), "latent deficiency" can occur. In this state, yields are sub-optimal even in the absence of clear visual symptoms, as iron's role in chlorophyll synthesis and electron transport is compromised (Briat *et al.*, 2015). Plants have developed two primary strategies to cope with low Fe bioavailability: Strategy I (employed by dicots and non-grass monocots) involves acidifying the rhizosphere and enhancing reduction mechanisms, while Strategy II (in grasses like sorghum and millet) involves secreting phytosiderophores to chelate and solubilize Fe<sup>3+</sup> (Kobayashi & Nishizawa, 2012).

**The Human Nutrition Challenge (Antinutrient Barrier):**

The central paradox is that even if crops accumulate sufficient iron, this does not translate to adequate iron nutrition for the human population. The local diet is dominated by cereal grains (sorghum, millet, maize), which are high in phytic acid (myo-inositol hexakisphosphate), the primary storage form of phosphorus in seeds. In the human digestive tract, phytic acid forms insoluble complexes with iron (as well as zinc), strongly inhibiting its absorption (Hurrell & Egli, 2010). This is a primary cause of **non-hemoglobin iron deficiency**, as the plant-based (non-heme) iron from cereals has a very low bioavailability, typically around 1-10%, compared to 15-35% from heme iron in animal products (Petry *et al.*, 2010). This creates a critical public health burden. Iron deficiency is the most common nutritional disorder globally and a leading cause of anemia (WHO, 2017). Its consequences are severe and multifaceted:

**Impaired Cognitive Development:** In children, iron is essential for neurogenesis, myelination, and neurotransmitter function. Deficiency leads to reduced learning capacity, poor memory, and delayed cognitive development (Lozoff & Georgieff, 2006).

**Reduced Work Capacity and Fatigue:** Iron is a core component of hemoglobin, which transports oxygen. Deficiency causes anemia, reducing physical stamina and economic productivity (Haas & Brownlie, 2001).

**Poor Pregnancy Outcomes:** Maternal iron deficiency anemia increases the risk of preterm birth, low birth weight, and perinatal mortality (Stoltzfus, 2001).

Therefore, the case of iron in Zaggā underscores a fundamental principle in nutrition-sensitive agriculture: **total soil concentration is a poor predictor of human nutritional status**. Effective interventions must target the entire pathway from soil chemistry to plant uptake and, ultimately, to human absorption.

**Copper (Cu): Organic Matter Dependent**

Cu levels (mean 0.47 mg/kg) are borderline, particularly for maize and legumes intercropped with cereals. Availability is strongly controlled by organic matter ( $r = 0.75$ ,  $p < 0.05$ ; regression  $R^2 = 0.61$ ). Low Cu impairs enzyme activity, nitrogen fixation in legumes, pollen viability, and lignin formation, reducing both crop yield and nutritional quality. Copper has a particularly high affinity for organic ligands,

forming stable complexes with humic and fulvic acids (Kaninga, 2022).

**Agronomic Risks (Impact on Legumes and Cereal Yield):**

While not as geographically widespread as zinc deficiency, copper's borderline status poses a significant and specific threat to agricultural productivity. Legumes, such as cowpea (*Vigna unguiculata*), which is a crucial protein source and a common crop in the district, are highly sensitive to copper deficiency (Gupta *et al.*, 2024). Copper is a vital cofactor for the enzyme **diamine oxidase**, which is involved in lignin synthesis. In copper-deficient legumes, nodule formation and function are impaired, leading to reduced nitrogen fixation. This results in poor plant vigor and lower grain yield, undermining a key natural source of soil nitrogen replenishment (Khalid *et al.*, 2020). In cereals, copper is essential for lignin formation in cell walls, pollen viability, and chlorophyll formation. Deficiency can lead to wilting ("stem wilt" in wheat), white tip dieback, and poorly filled, shriveled grain (Nadeem & Farooq, 2019).

**Consequences for Grain Quality and Human Nutrition:**

The impact of copper deficiency extends beyond yield loss to the nutritional quality of the harvested grain. Copper is a component of several metalloenzymes critical for plant metabolism, including **ascorbate oxidase** and **cytochrome c oxidase**. Its deficiency disrupts these pathways, leading to alterations in the protein and carbohydrate composition of the grain (Ravet & Pilon, 2013). For human consumers, this translates to food with a less optimal nutritional profile. More directly, copper is an essential micronutrient for human health, playing a key role in:

**Iron Metabolism:** Copper is required for the enzyme **ceruloplasmin**, which oxidizes iron and facilitates its transport. Marginal copper intake can therefore contribute to secondary iron deficiency anemia (Collins *et al.*, 2010).

**Antioxidant Defense:** As a cofactor for **superoxide dismutase** (Cu,Zn-SOD), copper is vital for protecting cells from oxidative damage (Uriu-Adams & Keen, 2005).

**Connective Tissue and Neurotransmitter Synthesis:** Copper is involved in cross-linking collagen and the production of neurotransmitters, underscoring its systemic importance.

A reduction in the copper content of staple grains, even if not the primary cause of human deficiency, contributes to the overall burden of "hidden hunger" by diminishing the dietary density of this essential mineral (White & Broadley, 2009). Therefore, addressing the borderline copper status in Zaggā soils is critical not only for safeguarding legume production and overall crop yields but also for protecting the nutritional integrity of the local food supply.

**Manganese (Mn): Generally Adequate with Complex Nutrient Interactions**

Mn concentrations were generally above the critical threshold (1.0 mg/kg). However, its negative correlation with Fe ( $r = -0.53$ ,  $p < 0.05$ ) highlights antagonistic uptake interactions. In cereals like maize and sorghum, excessive Mn in some soils may suppress Fe absorption, creating localized deficiencies

despite adequate soil Fe. Manganese exists in multiple oxidation states, primarily as soluble Mn<sup>2+</sup> (plant-available) and insoluble Mn<sup>4+</sup> (unavailable). In waterlogged or highly acidic soils, reducing conditions favor the conversion to Mn<sup>2+</sup>, which can sometimes lead to toxicity (Millaleo *et al.*, 2010).

PCA analysis confirmed that Zn and Cu availability are primarily controlled by clay content and organic matter, Fe availability is regulated mainly by soil pH, and Mn behavior reflects mineralogical and interaction-driven controls.

**Antagonistic Interaction with Iron (Competitive Uptake Dynamics):** The significant negative correlation between manganese and iron ( $r = -0.53$ ) is a critical finding, highlighting a well-documented antagonistic relationship in plant nutrition. Both Mn<sup>2+</sup> and Fe<sup>2+</sup> are divalent cations and are absorbed by plants through similar membrane transporters, such as the Iron-Regulated Transporter (IRT1) system in roots (Guerinot, 2000). Consequently, an excess of one can competitively inhibit the uptake of the other. This competition can induce latent deficiencies; for instance, high manganese availability in a soil with borderline iron can suppress iron uptake, leading to iron deficiency chlorosis in sensitive crops, even when total soil iron is high (Marschner, 2012). This dynamic is particularly important to manage in crops like soybean, but it can also affect cereals and legumes common to the region, potentially compromising yield and plant health.

**Table 2. Correlation matrix of DTPA-extractable micronutrients and selected soil properties**

Variable	Zn (mg/kg)	Fe (mg/kg)	Cu (mg/kg)	Mn (mg/kg)	pH (H <sub>2</sub> O)	OM (g/kg)	Clay (%)
Zn	1.00	-0.21	+0.38	-0.12	-0.32	+0.30	+0.46
Fe	-0.21	1.00	-0.18	-0.53	-0.74*	-0.22	-0.35
Cu	+0.38	-0.18	1.00	+0.20	-0.08	+0.75*	+0.47
Mn	-0.12	-0.53	+0.20	1.00	+0.64	+0.42	+0.29
pH	-0.32	-0.74*	-0.08	+0.64	1.00	+0.25	-0.41
OM	+0.30	-0.22	+0.75*	+0.42	+0.25	1.00	+0.38
Clay	+0.46	-0.35	+0.47	+0.29	-0.41	+0.38	1.00

Notes: n = 8 pedons,  $p < 0.05$  = statistically significant,  $*p < 0.01$  = highly significant

**Implications for Food Security and Hidden Hunger**

- **Zn deficiency** in soils is the most critical threat, directly translating into low crop yields and reduced Zn density in cereals, perpetuating hidden hunger.

- **Fe sufficiency in soils** does not guarantee human sufficiency, due to poor crop uptake efficiency and dietary inhibitors.
- **Cu borderline levels** may become limiting under continuous cultivation, affecting both crop quality and nutritional outcomes.
- **Mn sufficiency** provides stability but its role is more supportive than primary in food security.

Thus, the results confirm that soil micronutrient deficiencies, particularly Zn, form a hidden layer of food insecurity, affecting both agricultural productivity and human nutrition.

**Study Limitations**

This study was conducted as a semi-detailed soil survey at a scale of 1:25,000 and was based on eight representative soil pedons (ZG6–ZG13). While this scale is appropriate for identifying dominant soil types, micronutrient constraints, and pedogenic controls within the study area, it limits the resolution at which fine-scale spatial variability can be captured. The number of pedons, although sufficient for pedological characterization and statistical inference at the mapping-unit level, may not fully represent micro-variations in soil properties arising from localized management practices or landscape heterogeneity. Consequently, the statistical relationships identified reflect dominant trends rather than site-specific extremes. Furthermore, the findings are most directly applicable to soils with similar parent materials, land-use history, and agroecological conditions in the Zagga District and adjoining areas of northwestern Nigeria. Extrapolation to other regions should therefore be undertaken with caution, particularly where soil-forming factors and management systems differ substantially.

**Conclusion and Recommendations**

**Conclusion**

The evaluation of Zagga soils revealed significant variation in micronutrient availability, with zinc (Zn) identified as the most critical limiting nutrient. Mean Zn concentrations (0.81 mg/kg) were below adequacy thresholds, confirming widespread deficiency, while Fe was abundant but its nutritional benefit constrained by plant uptake and human dietary inhibitors. Copper (Cu) was borderline and highly dependent on organic matter, while manganese (Mn) was generally sufficient across horizons.

From a food security perspective, these results highlight that Zn deficiency in soils represents both an agronomic and nutritional challenge, as it reduces crop yields and lowers the micronutrient density of staple grains, thereby perpetuating hidden hunger. The paradox of abundant Fe in soils but limited human Fe sufficiency underscores the complexity of soil–plant–nutrition linkages.

This study therefore reinforces the importance of integrating soil fertility management with nutrition-sensitive agriculture, recognizing that soil health is directly tied to crop nutritional quality and human well-being.

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## Recommendations

1. **Zinc Fertilization:** Incorporation of Zn-enriched fertilizers into extension packages should be prioritized to address widespread Zn deficiency and improve both yield and grain quality.
2. **Biofortification:** Promotion of Zn-efficient crop varieties (through plant breeding or genetic biofortification) should complement soil interventions, ensuring nutritional gains at the household level.
3. **Integrated Soil Fertility Management (ISFM):** Practices that enhance soil organic matter (compost, crop residues, cover crops) will improve Cu and Zn availability and sustain long-term fertility.
4. **Nutrition-Sensitive Agriculture:** Fertility programs should explicitly link soil management with human nutrition outcomes, aligning with food security policies in Nigeria and the Sustainable Development Goal 2 (“Zero Hunger”).
5. **Policy and Research:** National fertilizer recommendations should incorporate micronutrients (especially Zn), while further research should quantify the transfer of soil nutrient deficiencies into crop grain nutrient profiles to better assess risks of hidden hunger.

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