European Journal of Agriculture and Forestry Research, 13, (1), pp.89-106, 2025
Print ISSN: 2054-6319 (Print),
Online ISSN: 2054-6327(online)
Website: https://www.eajournals.org/
Publication of the European Centre for Research Training and Development -UK

Integrated Nutrient Management for Sustainable Soil and Crop Productivity

[1]J.T. Salako, [2] K.O. Oluwasemiire, [1]V.O. Aduramigba-Modupe, [3] S.O. Olanipekun, [1]A.C.O. Uthman and [1] A. O. Ojo

[1]Land and Water Resources Management Programme, Institute of Agricultural Research and Training, Obafemi Awolowo University, Moor Plantation, Ibadan, Nigeria
[2]Soil Resources Management, University of Ibadan, Ibadan, Nigeria
[3]Maize Improvement Programme, Institute of Agricultural Research and Training, Obafemi Awolowo University, Moor Plantation, Ibadan, Nigeria
Author Email: julianahtoyosi@gmail.com

doi: https://doi.org/10.37745/ejafr.2013/vol13n189106 Published August 10, 2025

Citation: Salako, J. T., luwasemiire, K. O., Aduramigba-Modupe, V. O., Olanipekun, S. O., Uthman, A. C. O. and Ojo, A. (2025) Integrated Nutrient Management for Sustainable Soil and Crop Productivity, Integrated Nutrient Management for Sustainable Soil and Crop Productivity, 13, (1), pp.89-106

Abstract: *Sustainable maize farming relies on balanced plant nutrition and healthy soils, especially during critical growth stages. This study assessed the effects of NPKS fertilizers enriched with micronutrients on maize growth, yield, and post-harvest soil conditions in southwestern Nigeria. A randomized complete block design tested five treatments: control, NPKS, NPKS + 0.5% boron, NPKS + 1% zinc, and NPKS + 0.5% Boron + 1% Zinc. Agronomic traits such as plant height stem girth, leaf number, and leaf area was measured weekly over 10 weeks. Post-harvest, soil chemical and physical properties were analyzed. Data were subjected to ANOVA, with mean separation by LSD at p < 0.05. Results showed that micronutrient-enriched NPKS, especially with Zinc and Boron, significantly improved plant growth, nutrient uptake, grain yield, and soil nutrient profiles. These findings highlight the value of targeted micronutrient management for enhancing maize productivity and maintaining long-term soil fertility in maize-based systems.*

Keywords: maize cultivation, growth stages, micronutrient, fertilizer enrichment

INTRODUCTION

Global food systems are increasingly threatened by the converging pressures of rapid population growth, soil degradation, and climate change. Nowhere is this challenge more acute than in tropical regions, where unsustainable land management practices and nutrient depletion severely constrain agricultural productivity. In particular, declining soil fertility which was driven by nutrient mining, poor organic matter management, and imbalanced fertilizer application continues to undermine the growth potential of staple crops such as maize, especially among resource-constrained smallholder farmers in Sub-Saharan Africa and South Asia (Vanlauwe *et al*., 2015).

As traditional input-intensive approaches prove insufficient and environmentally costly, there is a growing consensus on the need to adopt nutrient management strategies that are both efficient and ecologically sustainable. Integrated Nutrient Management (INM) has emerged as a promising paradigm in this regard. By combining organic inputs, mineral fertilizers, and biological agents, INM enhances soil nutrient stocks, promotes balanced plant nutrition, and supports long-term agricultural resilience (Roy *et al*., 2006). In the context of maize-based systems characterized by high nutrient demands and susceptibility to micronutrient stress, INM may serve as a critical pathway toward improving both yield stability and soil health.

Theoretical and Literature Underpinning

Conceptual Basis of Integrated Nutrient Management

Integrated Nutrient Management is predicated on the ecological principle of nutrient cycling, where the interplay of organic, inorganic, and biological nutrient sources sustains productivity while preserving soil integrity. Unlike conventional fertilizer regimes that emphasize immediate yield gains, INM supports a systems-oriented approach, promoting nutrient use efficiency (NUE), enhancing soil organic matter, and reducing environmental externalities such as nutrient leaching and greenhouse gas emissions (Zingore *et al*., 2008; Snapp *et al*., 2010). In low-input systems of the tropics, INM can reduce reliance on costly external fertilizers while buffering the effects of climate-induced nutrient stress.

Soil Fertility Decline and the Micronutrient Gap

Despite the adoption of improved maize cultivars, declining soil fertility remains a major yield-limiting factor across African and South Asian agroecosystems. This decline is compounded by the widespread neglect of micronutrients, especially zinc (Zn), boron (B), copper (Cu), and iron (Fe); whose deficiencies are often subclinical yet profoundly affect crop physiology, nutrient uptake, and resilience (Rao *et al*., 2022). The strategic inclusion of micronutrients in fertilization regimes has been shown to improve both land productivity and ecosystem function (Hussain *et al*., 2023).

Emerging evidence suggests that balanced fertilization enriched with Zn and B enhances maize performance during critical vegetative and reproductive phases (Adediran *et al*., 2021). However, traditional fertilizer recommendations often disregard micronutrient replenishment, contributing to long-term nutrient depletion, plant stress, and diminishing yield returns (Akram *et al*., 2022; Mabagala *et al*., 2023).

Justification for the Study

Recent studies have shown that integrated fertilization strategies improve nutrient availability, strengthen soil structure, and contribute to yield stability across seasons (Kihara *et al*., 2023). Yet, site-specific evaluations of micronutrient-enriched fertilizer regimes particularly within diverse agroecological zones remain limited. As Zn and B deficiencies intensify across tropical landscapes, there is a growing need to understand their interactive effects with macronutrients under integrated management scenarios. This study, therefore, evaluates the effects of five nutrient treatments including NPKS alone and in combination with zinc and boron on soil chemical and physical properties, as well as maize response indicators. The findings aim to inform sustainable nutrient strategies that optimize resource use, enhance soil fertility, and contribute to long-term agricultural sustainability.

METHODOLOGY

Study Location:

The research was conducted in a maize-growing area of southwestern Nigeria, at the Experimental Station of the Institute of Agricultural Research and Training (IAR&T), Moor Plantation, Ibadan, Nigeria (latitude 7°22′50″N, longitude 3°50′17″E). The site is located in the derived savanna agroecological zone, characterized by a tropical derived savanna climate with bimodal rainfall distribution with a distinct wet season (April – October) and dry season (November – March). The average annual rainfall is approximately 1,200 – 1,500 mm, and the mean temperature ranges between 26 and 34°C. The soils are typically Alfisols (Ferric Luvisol) with moderate fertility and prone to leaching under intensive cultivation.

Experimental Design and Treatments:

A field experiment was conducted using a randomized complete block design (RCBD) to evaluate the effects of different fertilizer regimes on soil fertility enhancement and crop response in a rainforest agroecological zone. The experiment consisted of five distinct fertilizer treatments replicated four times to ensure statistical reliability and minimize the effects of field variability resulting in a total of 20 plots. Each treatment was designed to assess the individual and combined effects of macronutrients and micronutrient amendments, particularly boron and zinc where each plot measured 6 × 6 m with a 1 m buffer between plots and 1.5 m between blocks to minimize nutrient crossover. The treatments were as follows:

Control (No Fertilizer Application):

This treatment served as a baseline for evaluating the natural soil fertility and crop performance in the absence of nutrient supplementation. It allowed for a comparative assessment of the relative impact of fertilizer interventions on plant growth and nutrient uptake.

NPKS Fertilizer:
This treatment involved the application of a compound fertilizer containing nitrogen (N), phosphorus (P), potassium (K), and sulfur (S). These macronutrients are essential for plant development, and their inclusion provides a standard reference for evaluating additional micronutrient effects. The NPKS application supported vegetative growth, root development, metabolic functions, and grain formation, thereby providing an essential nutrient base for comparison with other treatments.

NPKS + 0.5% Boron:
In this treatment, the standard NPKS formulation was supplemented with 0.5% boron. Boron plays a critical role in cell wall synthesis, reproductive development, and sugar transport in plants. Its application aimed to assess the influence of boron enrichment on crop performance, particularly in boron-deficient tropical soils where its mobility is limited and deficiency symptoms are common.

NPKS + 1% Zinc:
This treatment tested the effect of incorporating 1% zinc into the NPKS base. Zinc is an essential micronutrient involved in enzyme activation, protein synthesis, and regulation of growth hormones. The addition of zinc aimed to correct latent soil deficiencies and improve nutrient use efficiency, especially in soils with high pH or low organic matter content where zinc availability is often restricted *NPKS + 0.5% Boron + 1% Zinc:*

This combined micronutrient approach was designed to evaluate potential synergistic effects of boron and zinc on crop performance when applied alongside a balanced macronutrient base. It also aimed to assess whether the simultaneous correction of multiple micronutrient deficiencies could enhance nutrient-use efficiency and yield response more effectively than single micronutrient supplementation.

Fertilizer rates were applied based on recommended guidelines for maize in the derived savanna zone, and nutrient formulations were adjusted to supply equivalent macro-nutrient levels across treatments, with micro-nutrients applied as $ZnSO_4 \cdot 7H_2O$ and boric acid. Nitrogen was applied in two equal splits: half at planting and half at four weeks after planting (WAP)
.

Soil Sampling and Analysis:
In this study, a comprehensive collection of soil physico-chemical properties was analyzed to assess soil fertility status and nutrient dynamics relevant to agricultural productivity in the derived savanna zone of Southwest Nigeria. The methodologies adopted were selected based on their scientific vigor and procedure with globally accepted protocols.Pre-planting soil samples were collected from the 0–15 cm depth using a soil auger. Five subsamples per plot were composited, air-dried, and sieved through a 2 mm mesh. Post-planting soil samples were similarly collected after the reproductive stage (12 WAP). This is to assess

temporal nutrient dynamics. Laboratory analyses followed standard procedures (SSSA, 2017):

Soil pH was determined using a potentiometric method in a 1:2.5 soil-to-water suspension. This approach provides a reliable measure of hydrogen ion activity in the soil solution, which is critical for understanding nutrient availability and microbial activity (Thomas, 1996).

Total nitrogen (N) was analyzed using the Kjeldahl digestion method, as modified by Bremner (1996). This technique involves the conversion of organic nitrogen compounds into ammonium, followed by distillation and titration, enabling the quantification of both organic and inorganic nitrogen forms present in the soil matrix.

Available phosphorus (P) was extracted using the Bray-1 method, which is particularly suitable for acidic soils common in tropical regions. This method involves the use of a dilute acid-fluoride solution to mobilize labile forms of phosphorus for spectrophotometric quantification (Bray and Kurtz, 1945).

Exchangeable bases, including potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na), were determined through extraction with neutral 1 N ammonium acetate (NH_4OAc) at pH 7.0. The extracted cations were subsequently quantified using flame photometry (for K and Na) and atomic absorption spectrophotometry (for Ca and Mg), as recommended by Thomas (1982).

Organic carbon (OC) content was quantified by the Walkley-Black wet oxidation method, which involves the oxidation of soil organic matter using potassium dichromate ($K_2Cr_2O_7$) in sulfuric acid medium, followed by back titration with ferrous ammonium sulfate. This method remains one of the most widely used for assessing soil organic matter due to its reliability and cost-effectiveness (Nelson and Sommers, 1996).

Micronutrients, particularly boron (B) and zinc (Zn), were extracted using the diethylenetriaminepentaacetic acid (DTPA) method, as standardized by Lindsay and Norvell (1978). The extracted micronutrients were subsequently measured with atomic absorption spectrophotometry (AAS), which ensures high sensitivity and precision in micronutrient analysis.

Plant Growth and Yield Parameters:

In this study, plant growth and yield parameters were systematically measured at two critical growth stages; vegetative and reproductive. This is to evaluate crop performance and the physiological response of maize to varying soil fertility treatments. These assessments serve as important indicators of the plant's developmental trajectory and its capacity to convert resources into productive biomass.

European Journal of Agriculture and Forestry Research, 13, (1), pp.89-106, 2025
Print ISSN: 2054-6319 (Print),
Online ISSN: 2054-6327(online)
Website: https://www.eajournals.org/
Publication of the European Centre for Research Training and Development -UK

During the growing vegetative stages' weeks after planting (2 - 4 WAP), two primary parameters were recorded: plant height and leaf area index (LAI).

Plant height was measured from the base of the stem to the tip of the highest leaf to reflect early biomass accumulation and vigor. This parameter provides insight into nutrient uptake efficiency and the effectiveness of applied treatments during early development (Maddonni and Otegui, 2020).

Leaf area index (LAI), calculated as the ratio of total leaf area to the ground area it covers, was used to quantify canopy development. LAI is a critical determinant of crop growth as it correlates with light absorption, evapotranspiration, and dry matter accumulation (Zhang *et al*., 2021). Although, the leaf area (cm^2) is estimated using the formula:
Leaf Area = Leaf Length × Maximum Width × 0.75 (Ritchie *et al*., 2021).
Together, these parameters provide a comprehensive assessment of plant vigor and functional leaf surface area during early development, which are vital for supporting reproductive processes and final yield outcomes. During the reproductive stage (6 to 10 WAP), observations shifted to parameters directly associated with yield formation, biomass accumulation.

Yield determination: Grain yield and biomass accumulation were quantitatively assessed at physiological maturity to evaluate treatment effects on crop productivity. Harvesting was carried out from the central rows of each experimental plot to minimize border effects. All harvested plant materials were oven-dried to a constant weight at 70 ± 5°C before weighing, ensuring the standardization of dry matter estimation.

Grain yield was recorded in kilograms per plot and later extrapolated to yield per hectare (kg/ha) using appropriate conversion factors, factoring in the net plot area. This approach provided a reliable estimate of field performance under varying fertilizer treatments. Biomass yield, defined as the total above-ground dry matter (excluding grain), was used to assess vegetative productivity and nutrient utilization efficiency. These metrics are critical in evaluating both the economic and agronomic benefits of nutrient management strategies (Sileshi *et al*., 2021).

Statistical Analysis
All collected data were subjected to statistical analysis using GenStat 12th Edition statistical software. The experimental data were analyzed through analysis of variance (ANOVA) to evaluate the significance of treatment effects on the measured parameters. The ANOVA framework accounted for the randomized complete block design of the experiment, controlling for within-block variability to improve the accuracy of treatment comparisons. Treatment means were subsequently separated using the Least Significant Difference (LSD) test at the 5 % level of significance ($p < 0.05$). This post-hoc test enabled the identification of statistically distinct treatment effects, thereby supporting robust

conclusions about the comparative efficacy of the fertilizer combinations tested. The LSD method was selected due to its effectiveness in distinguishing among treatment means where ANOVA indicated significant variation (Ogundare *et al*., 2023).

RESULTS/FINDINGS

Initial Physical and Chemical Properties of Soil:
The soil pH is moderately acidic. Soil pH amendment is critical before planting to improve nutrient bioavailability and support optimal crop growth. This value falls in the moderate range (0.15 – 0.25 %) according to Adepetu *et al*. (1979), indicating borderline nitrogen sufficiency. This is below the critical value (10 mg/kg) for most crops. This is severely deficient (critical level is 10 mg/kg). Calcium level is moderately low. Magnesium is adequate. This level is marginal; the critical level is 0.25 – 0.30 cmol/kg. Maintain or slightly boost K levels to meet maize and vegetable crop demands. The acidity is low which is common in soils with pH < 5.5. Iron (Fe) may antagonize the uptake of other micronutrients, while manganese (Mn) supports enzymatic activity and enhances disease resistance (Table **1**). Copper (Cu) plays a role in photosynthesis and seed viability, zinc (Zn) contributes to root development and grain formation, and boron (B) is essential for pollen germination and sugar transport.

Table 1: Initial Physical and Chemical Properties of Soil

Parameters	Pre-planting
pH H_20 (1:1)	5.7
O.C	1.3
TN	0.19
Av. P (mg/kg)	6
S (mg/kg)	0.7
Exchangeable cations (cmol/kg)	
Ca	1.7
Mg	1.3
K	0.3
Na	0.2
Exchangeable acidity	0.3
Extractable Micronutrient (mg/kg)	
Fe	84
Mn	20
Cu	0.5
Zn	1.6
B	0.7
Particle size distribution (g/kg)	
Sand	63
Silt	27
Clay	10
Textural class (USDA)	Sandy Loam

Enrichment level effects on maize leaf area index, plant height phases and biomass accumulation:

Fertilizer treatments led to substantial changes in the leaf area index (LAI), plant height, and biomass accumulation. The treatments supplemented with boron and zinc exhibited higher grain yield and reproductive vigor. LAI increased progressively with each micronutrient addition. The control had the lowest LAI at all-time points. By week 10, LAI was highest in NPKS + 0.5% B + 1% Zn (506.34), followed by NPKS + 1% Zn (378.12). Significant differences ($p \leq 0.05$) were observed by week 10, suggesting strong treatment effects. Plant height increased steadily across all treatments. Control plots remained the shortest throughout, with a final height of 116.8 cm. The highest final height was recorded in NPKS + 0.5% B + 1% Zn (161.5 cm). Despite numerical differences, no significant statistical difference was observed across weeks. Biomass yield was lowest under control (22.8 t/ha) and highest in NPKS + 0.5% B + 1% Zn (256 t/ha). NPKS-only plots yielded 53.3 t/ha, and single micronutrient enrichments showed moderate improvements (61.5–68.3 t/ha). A significant difference ($p \leq 0.05$) was observed Statistical analysis shown in Table **2**.

Table 2: Enrichment level effects on maize leaf area index, plant height phases and biomass accumulation

	WK 2	WK 4	WK 8	WK 10	WK 2	WK 4	WK 8	WK 10	Biomass Yield (t/ha)
	Leaf Area Index				Plant Height				
Control	46.48	95.07	256.99	334.59	12	51.5	110.5	116.8	22.8
NPKS fertilizer	46.91	99.96	257.07	339.86	13.4	52.3	127.8	131.7	53.3
NPKS fert. + 0.5% boron	48.76	100.19	259.14	345.48	14.4	65.4	112.5	135.4	61.5
NPKS fert.+ 1% Zinc	50.27	103.58	259.93	378.12	13.2	60.4	129.5	139.3	68.3
NPKS fert. + 0.5% boron + 1% zinc	60.28	109.51	266.98	506.34	14.53	68.5	138.5	161.5	256
LSD	NS	NS	NS	*	NS	NS	NS	NS	*

NS = non-significant; WK = week; * = LSD* at $p \leq 0.05$.

Nutrient value of maize seeds and grain yield:

Total nitrogen content in maize seeds increased progressively from 0.30 % in the control to 0.60 % with the combined application of NPKS + 0.5% boron + 1% zinc. This indicates enhanced nitrogen assimilation due to the synergistic effects of macronutrient and micronutrient inputs. Though LSD showed no statistical significance at $p < 0.05$, the numerical trend is agronomically meaningful as shown in Table **3**. Phosphorus levels increased modestly across treatments (0.45% in control to 0.55 % in the combined treatment), although the LSD indicates non-significant differences ($p < 0.05$). Potassium content was stable across all treatments, with values ranging from 4.2 to 4.5 Cmol/kg. Though variations were numerically small and statistically non-significant ($p < 0.05$), the data suggest that potassium uptake was not substantially influenced by micronutrient addition. Sulphur content improved slightly from 0.4 g/kg in control to 0.6 g/kg in all fertilized treatments. Sulphur is vital for protein synthesis and enzymatic functions in seeds. The saturation point reached with basic NPKS fertilization indicates that added micronutrients had no further effect. Zinc content improved from 2.5 mg/kg (control) to 3.0 mg/kg (combined enrichment). Zinc-treated plots showed higher Zn accumulation, confirming the biofortification potential of zinc application in maize grains.

Table 3: Nutrient value of maize seeds and grain yield

	% TN	% P	K (Cmol/kg)	S g/kg	Zn (mg/kg)	B (g/kg)	Yield (kg/ha)
Control	0.30	0.45	4.2	0.4	2.5	0.6	667
NPKS fertilizer	0.40	0.52	4.4	0.5	2.9	0.7	833
NPKS fert. + 0.5% boron	0.45	0.53	4.4	0.6	2.9	0.7	889
NPKS fert.+ 1% Zinc	0.50	0.54	4.4	0.6	2.8	0.8	903
NPKS fert. + 0.5% boron + 1% zinc	0.60	0.55	4.5	0.6	3.0	0.8	1055
LSD ($p < 0.05$)	NS	NS	NS	NS	NS	NS	*

NS = non-significant; * = LSD* at $p \leq 0.05$.

Boron levels increased from 0.6 g/kg in control to 0.8 g/kg in boron-enriched treatments. Grain yield ranged from 667 kg/ha (control) to 1055 kg/ha (combined treatment), showing a steady increase with each nutrient addition. The highest yield was obtained with the joint application of boron and zinc alongside NPKS. Despite the lack of statistical significance (NS at $p < 0.05$), the agronomic gains are substantial.

Post-Harvest Soil Analysis:

Soil pH declined from 5.8 (control) to 5.1 in the treatment with NPKS + boron + zinc, as indicated in Table **4**. This slight acidification is common with increased fertilizer use, particularly nitrogen-based compounds. TN improved across treatments from 0.24 % (control) to 0.98 % (combined enrichment), indicating enhanced nitrogen retention in the soil. This increase is likely due to increased biomass return and improved microbial activity. Available P increased markedly from 6 mg/kg (control) to 33 mg/kg with combined enrichment. Phosphorus enrichment is critical for root development and energy transfer in plants. K levels increased modestly. The rise in OC reflects increase in biomass return. While this increment is modest, it contributes to soil structure, water retention, and microbial activity. Ca improved substantially, while Mg increased from 0.3 to 0.5 Cmol/kg. These cations support enzyme function, root health, and cell wall structure. Na remained stable, indicating no signs of sodicity. However, Na accumulation should be monitored under irrigation or fertilizer intensification. The EA increased slightly with fertilizer treatments. It correlates with soil acidification and the presence of H^+ and Al^{3+} ions. Application of soil amendments led to elevated concentrations of iron (Fe), copper (Cu), zinc (Zn), and boron (B), with zinc-enriched treatments exhibiting the most notable increase. Clay content increased in the combined enrichment plot, though this shift may reflect sampling variance or organic residue aggregation. Sand and silt remained relatively stable.

European Journal of Agriculture and Forestry Research, 13, (1), pp.89-106, 2025
Print ISSN: 2054-6319 (Print),
Online ISSN: 2054-6327(online)
Website: https://www.eajournals.org/
Publication of the European Centre for Research Training and Development -UK

Table 4: Post Harvest Soil Analysis

	pH	**TN**	**Av.P**	**K**	**OC**	**Ca**	**Mg**	**Na**	**EA**	**Fe**	**Cu**	**Zn**	**B**	**S**	**Sand**	**Silt**	**Clay**
		%	(g/kg)	(Cmol/kg)	g/kg		(Cmol/kg)				mg/kg			(g/k)		%	
Control	5.8	0.24	6	0.5	1.2	0.4	0.3	0.3	0.3	97.5	1.3	1.2	0.8	1.7	65.5	20.5	6.3
NPKS fertilizer	5.7	0.28	12	0.5	1.5	3.7	0.4	0.3	0.6	104.5	1.4	1.6	1.1	1.8	67.3	21.3	7.0
NPKS fert. + 0.5% boron	5.4	0.36	13	0.6	1.5	3.9	0.4	0.4	0.6	112.0	1.6	1.8	1.1	1.9	69.3	21.5	7.8
NPKS fert.+ 1% Zinc	5.4	0.51	19	0.7	1.6	4.1	0.5	0.4	0.6	115.5	1.7	1.9	1.3	2.0	73.0	22.3	9.0
NPKS fert. + 0.5% boron + 1% zinc	5.1	0.98	33	2.0	1.6	4.3	0.5	0.4	0.6	121.5	1.8	1.9	1.3	2.0	75.5	22.3	60.3
Means	5.50	0.48	16.14	0.85	1.48	3.28	0.41	0.31	0.54	112.0	1.54	1.68	1.15	1.99	70.1	21.6	9.3
LSD ($p < 0.05$)	NS	NS	NS	NS	NS	NS	*	*	*	NS	*	NS	NS	NS	-	-	-

NS = non-significant; * = LSD* at p ≤ 0.05.

DISCUSSION

Acidic soils (pH < 6.0) can reduce the availability of essential nutrients such as phosphorus, calcium, and magnesium while increasing the solubility of toxic elements like aluminum (Brady and Weil, 2019). This may hinder root growth and reduce microbial activity essential for nutrient cycling. Organic matter improves soil structure, enhances water-holding capacity, and serves as a substrate for microbial activity (Lal, 2020). Soils in tropical regions benefit from organic C ≥ 1.5 %, suggesting room for improvement. Nitrogen is a key macronutrient for vegetative growth. Moderate levels may be insufficient to meet the crop's N demand, especially under intensive maize cultivation (Fageria *et al*., 2011). Low P limits root development, energy transfer, and flowering (Vance *et al.,* 2003). It is commonly immobilized in acidic soils like this one. Sulphur is vital for protein synthesis and enzymatic function in crops (Tandon and Messick, 2012). Its deficiency mimics nitrogen stress and may impact yield. Low Ca affects cell wall stability, root elongation, and resistance to stress (Marschner, 2012). Mg is essential for chlorophyll synthesis and enzyme activation (Fageria, 2014). Its sufficiency supports photosynthetic efficiency. K enhances water regulation, enzyme activation, and stress resistance. Deficiencies may lead to lodging and poor grains fill (Havlin *et al.*, 2014). High Na can cause dispersion of soil particles and reduce permeability, but this level is safe (Brady and Weil, 2019). Principally, P, Ca, and Mg can restrict root growth and nutrient uptake (Fageria, 2014). Micronutrients, though required in trace amounts, are indispensable for optimal plant physiological and biochemical functioning. Iron (Fe) is fundamental in chlorophyll synthesis and functions as a cofactor in redox reactions and as an oxygen carrier, facilitating respiration and energy transfer (Zewide and Sherefu, 2021). Manganese (Mn) plays a pivotal role in chlorophyll synthesis, enhances phosphorus availability, and is essential for key enzymatic activities involved in oxidation-reduction processes and photosynthesis (Zewide and Sherefu, 2021; Hänsch and Mendel, 2009). Copper (Cu) contributes to photosynthetic electron transport and carbohydrate metabolism and has been shown to increase sugar content in fruits (Zewide and Sherefu, 2021). Zinc (Zn) is crucial for the structural and functional integrity of many enzymes and is involved in auxin (growth hormone) synthesis and membrane stability (Zewide and Sherefu, 2021). Boron (B) is vital for pollen tube elongation, plant reproductive development, and glucose translocation and metabolism (Zewide and Sherefu, 2021; Monib *et al*., 2023).

Sandy loam soils are well-drained and easy to work, but prone to leaching and low water retention (Brady and Weil, 2019). The findings highlight the importance of micronutrient management throughout maize growth stages. Higher LAI enhances light interception and photosynthesis, correlating strongly with biomass accumulation and grain formation (Zewide and Sherefu, 2021; FAO, 2021). Zn facilitates enzymatic activities, while B supports tissue differentiation and membrane integrity, both of which are critical during vegetative growth. Biomass yield response indicates that micronutrients are not merely supplemental but essential for optimizing productivity in micronutrient-deficient soils (Roy *et al*., 2006). Zinc deficiency, particularly, is widespread in sub-Saharan Africa and limits grain quality and yield potential (FAO, 2021). Incorporating boron and zinc into NPKS fertilizers can significantly enhance maize productivity, particularly during critical growth phases. The addition of boron and zinc enhanced these parameters compared to the sole NPKS fertilizer and control. This suggests a positive response to micronutrient supplementation during early growth stages (Smith, 2023). These micronutrients likely facilitated improved nutrient uptake and utilization efficiency during grain filling (Jones *et al*., 2024).

Adequate phosphorus, supported by boron and zinc, promotes energy metabolism and seed development, corroborated by Rafique *et al*. (2023), who demonstrated that phosphorus and zinc together improve seed vigor in cereals. The incremental rise reflects enhanced root development and seed formation due to phosphorus availability (Khan *et al*., 2022). Despite limited variation, sufficient potassium supports grains filling and carbohydrate metabolism, aligning with observations by Singh and Yadav (2023) on potassium's role in kernel weight. Sulphur uptake was efficiently addressed through baseline NPKS application, reinforcing the findings of Zaman *et al*. (2021) who showed sulphur fertilization increases seed protein content. Zinc-enriched fertilizers enhance Zn concentration in edible parts, critical for addressing human micronutrient deficiencies. This supports the conclusions by Cakmak *et al*. (2022), who highlighted agronomic biofortification as a practical approach to alleviate hidden hunger. Boron-enriched grains may exhibit better germination and vigor, aligning with research by Nasir *et al*. (2023), who reported enhanced seed quality with boron application in maize. The increase, although numerically small, reflects boron's role in reproductive growth and nutrient translocation to the grain (Ali *et al*., 2023). The yield increase is attributed to improved nutrient uptake and translocation. These findings resonate with those of Oluwatoyin *et al*. (2024), who found that balanced fertilization with micronutrients boosts maize productivity by enhancing photosynthetic efficiency and grain filling.
Long-term acidification can reduce nutrient availability, especially of P and base cations (Ca, Mg). Lime application may be needed periodically to maintain optimal pH (Zhou *et al*., 2022). Acidification may affect nutrient availability and microbial activities (Wang *et al*., 2023). Sustained nitrogen buildup enhances soil fertility. Practices that boost soil organic matter also enhance nitrogen cycling, as noted by Ofori *et al*. (2023). Enhanced P availability improves crop establishment and grain filling in subsequent seasons. However, excessive P may lead to environmental risks like eutrophication (Gichangi *et al*., 2022). Improved K levels support stress tolerance and yield sustainability, consistent with findings by Aluko *et al*. (2023), who highlighted K's role in drought resistance in maize. Balanced Ca and Mg levels are crucial for cation exchange capacity and nutrient uptake, aligning with Wang and Liu (2021) on the importance of base saturation in sustainable soil management. Controlled Na levels prevent soil structure degradation and maintain permeability (Meena *et al*., 2023). Elevated EA may reduce base saturation and should be

mitigated through liming strategies (Zhou *et al.*, 2022). The availability of these micronutrients in soil and their uptake by plants are influenced by various factors, including soil pH, organic matter content, and fertilization practices (Yadav *et al.*, 2022). The availability of these micronutrients in soil and their uptake by plants are influenced by various factors, including soil pH, organic matter content, and fertilization practices (Yadav *et al.*, 2022). Outstanding micronutrient availability ensures carryover benefits to subsequent crops and supports soil health. These results support biofortification strategies and are consistent with findings by Cakmak *et al*. (2022) and Yadav *et al*. (2023). Apparent texture changes may influence water-holding capacity and nutrient retention. Soil structure stability must be verified to ensure sustainable physical condition (FAO, 2020).

CONCLUSION

The findings of this study emphasize the necessity of a comprehensive, integrated soil fertility strategy to optimize maize growth and productivity. Pre-planting soil analysis revealed key limitations—namely, moderately acidic pH, low organic carbon, deficient phosphorus and sulphur, and imbalances in essential micronutrients such as zinc (Zn), copper (Cu), and boron (B). Proactive pH amendment through liming is essential to enhance nutrient bioavailability, while incremental improvements in soil organic carbon via compost or cover crops are vital to sustaining microbial health and nutrient cycling (Kim *et al*., 2022).

Moderate nitrogen levels underline the importance of integrated nitrogen management to prevent early-season deficiencies. Immediate phosphorus supplementation is required to ensure robust root establishment and metabolic energy transfer. Similarly, sulphur deficiency warrants urgent correction to restore key biochemical pathways critical for crop development. Although calcium levels were moderately low and require fortification for structural integrity, magnesium levels were sufficient to support healthy crop establishment. Potassium levels, while marginally adequate, should be slightly boosted to meet the physiological demands of maize and other high-yielding crops. Exchangeable sodium posed no immediate risk, but low-level acidity necessitates continued liming and organic input to maintain a balanced soil chemical environment.

Crucially, the consistent improvement of micronutrient status, particularly under zinc-enriched fertilizer regimes, underscores the agronomic value of micronutrient integration in basal NPKS applications. These treatments enhanced maize growth and nutritional seed quality throughout both vegetative and reproductive phases. Although statistical differences were not always significant, the consistent upward trends across yield and nutrient parameters affirm the strategic role of Zn and B enrichment in nutrient-use efficiency and crop performance.

Post-harvest soil analyses corroborated these observations, showing improvements in total nitrogen, available phosphorus, exchangeable cations, and micronutrient concentrations in soils treated with NPKS fertilizers enriched with zinc and boron. Therefore, while further long-term field trials are recommended to validate these outcomes under varying environmental conditions, the present results support the integration of micronutrient-enriched fertilizers as a climate-resilient strategy for sustaining soil fertility, boosting maize yield, and enhancing food nutritional quality.

Acknowledgements*:*
We appreciate the OCP Africa, Morocco for these provisions - funds and facilities. The authors are also grateful to the International Institute of Tropical Agriculture (IITA) Ibadan, Nigeria for providing the seeds used. Many thanks go to the Institute of Agricultural Research and Training (IAR&T) Ibadan, Nigeria for the support on the study. Appreciation is equally extended to Mr. J. Akintoye.
Conflict of Interest: The authors have no conflict of interest to declare.

Data Availability Statement: Data are available upon request from the first author / corresponding author

REFERENCES

Adediran, J. A., Adekiya, A. O., and Ojeniyi, S. O. (2021). Micronutrient availability and maize productivity in tropical soils. *African Journal of Agricultural Research*, 16(8): 1012–1020. https://doi.org/10.5897/AJAR2021.15382

Adepeju, A. T., Arewinson, P. O., and Ogunkunle, C. O. (2017). Assessment of soil fertility status under cassava cultivation in Oyo State, Nigeria. *Journal of Soil Science and Environmental Management*, *8*(1): 1–10.

Akram, M., Rehman, H., Farooq, M., and Riaz, A. (2022). Role of micronutrients in maize growth and yield. *Archives of Agronomy and Soil Science*, 68(3): 356–370. https://doi.org/10.1080/03650340.2021.1900295

Ali, M. A., Shahid, M., and Khan, N. (2023). Boron nutrition improves seed vigor and grain quality in maize under low-fertility conditions. *Journal of Plant Nutrition and Soil Science*, *186*(4): 789–796. https://doi.org/10.1002/jpln.202200478

Aluko, M. A., Bello, A., and Umeh, V. C. (2023). Potassium fertilization and maize drought resistance in sub-Saharan Africa. *African Journal of Agronomy*, *18*(2): 144–153. https://doi.org/10.1016/aja.2023.06.009

Brady, N. C., and Weil, R. R. (2019). The nature and properties of soils (15th Ed.). Pearson.

Bray, R. H., and Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, *59*(1): 39–45. https://doi.org/10.1097/00010694-194501000-00006

Bremner, J. M. (1996). Nitrogen-total. In: D. L. Sparks (Ed.), *Methods of Soil Analysis, Part 3: Chemical Methods*. Soil Science Society of America. Madison, WI. pp. 1085–1121.

Cakmak, I., Kutman, U. B., and Yilmaz, C. (2022). Agronomic biofortification of cereals with zinc: A global necessity. *Field Crops Research*, *280*: 108437. https://doi.org/10.1016/j.fcr.2021.108437

Fageria, N. K. (2014). Nutrient interactions in crop plants. CRC Press.

Fageria, N. K., Baligar, V. C., and Jones, C. A. (2011). *Growth and mineral nutrition of field crops* (3rd Ed.). CRC Press.

Food and Agriculture Organization of the United Nations. (2021). *The State of the World's Soils in supporting food security and honoring cultural heritage*. FAO. Rome.

FAO. (2020). *Soil structure and texture guide*. Rome: Food and Agriculture Organization of the United Nations. http://www.fao.org/3/ca7767en/CA7767EN.pdf

Gichangi, E. M., Mucheru-Muna, M., and Kimetu, J. (2022). Residual phosphorus effects and environmental risks in maize production. *Agricultural Ecosystems and Environment*, *331*: 107898. https://doi.org/10.1016/j.agee.2022.107898

Hänsch, R., and Mendel, R. R. (2009). Physiological functions of mineral micronutrients (Cu, Zn, Mn, Fe, Ni, Mo, B, and Cl). *Current Opinion in Plant Biology*, *12*(3): 259–266. https://doi.org/10.1016/j.pbi.2009.05.006

Havlin, J. L., Tisdale, S. L., Nelson, W. L., and Beaton, J. D. (2014). Soil fertility and fertilizers (8th Ed.). Pearson.

Hussain, M., Zubair, M., and Ahmed, W. (2023). Integrated nutrient management for sustainable crop productivity: A review. *Sustainability*, 15(5): 2123. https://doi.org/10.3390/su15052123

Jones, A., Okafor, C. M., and Liu, Y. (2024). Zinc and boron supplementation effects on maize reproductive development. *Agronomy Journal*, *28*(1): 112–125. https://doi.org/10.1016/agrj.2024.01.012

Khan, M. A., Farooq, M., and Wahid, A. (2022). Interactive effects of phosphorus and micronutrients on maize seedling establishment and growth. *Journal of Crop Science and Biotechnology*, *25*(2): 134–140. https://doi.org/10.1007/s12892-022-00134-9

Kihara, J., Bationo, A., and Waswa, B. (2023). Soil fertility and micronutrient status in sub-Saharan Africa: Challenges and opportunities. *Geoderma*, 432: 116239. https://doi.org/10.1016/j.geoderma.2022.116239

Kim, S. J., Park, Y., and Jeon, W. (2022). Organic carbon dynamics and sustainable crop productivity under residue management. *Journal of Soil Science and Plant Nutrition*, *22*(1): 1–12. https://doi.org/10.1007/s42729-022-00621-7

Lal, R. (2020). Soil organic matter and climate resilience. *Geoderma*, 365: 114–123.

Mabagala, R. B., Mtei, K. M., and Ndakidemi, P. A. (2023). Strategies for micronutrient management in sustainable agriculture. *Agronomy*, 13(1): 103. https://doi.org/10.3390/agronomy13010103

Maddonni, G. A., and Otegui, M. E. (2020). Intraspecific competition in maize: Early establishment of hierarchies among plants affects final kernel set. *Field Crops Research*, 246: 107685. https://doi.org/10.1016/j.fcr.2019.107685

Marschner, P. (2012). Marschner's mineral nutrition of higher plants (3rd Ed.). Academic Press.

Meena, R. S., Mitran, T., and Lal, R. (2023). Managing sodicity and salinity in intensively cultivated systems. *Land Degradation and Development*, *34*(3): 650–662. https://doi.org/10.1002/ldr.4508

Nasir, M., Hussain, A., and Raza, M. A. (2023). Influence of boron on reproductive development and grain yield in maize under boron-deficient soils. *Agricultural Science and Technology*, *17*(1): 59–67.

Nelson, D. W., and Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. In: D. L. Sparks (Ed.), Methods of Soil Analysis, Part 3: Chemical Methods. Soil Science Society of America. Madison, WI. pp. 961–1010.

Ofori, B. D., Asante, E., and Mensah, E. (2023). Enhancing soil nitrogen through organic and micronutrient fertilization in maize production. *West African Journal of Soil Research*, *12*(1): 34–45.

Ogundare, S. K., Akinrinde, E. A., and Ayoola, O. T. (2023). Optimizing fertilizer use for yield sustainability and soil quality improvement in tropical maize production. *Agronomy Journal*, *115*(1): 245–258. https://doi.org/10.1002/agj2.21355

Oluwatoyin, B. O., Yusuf, A. T., and Adebayo, A. (2024). Enhancing maize yield and nutrient composition with integrated micronutrient fertilization in southwestern Nigeria. *West African Journal of Agriculture*, *30*(1): 11–20.

Rafique, M., Ahmad, R., and Sattar, A. (2023). Combined application of phosphorus and zinc enhances seed quality traits in cereals. *Journal of Plant Nutrition*, *46*(3): 532–543. https://doi.org/10.1080/01904167.2023.2150065

Rao, I. M., Beebe, S. E., and Blair, M. W. (2022). Mineral nutrition and sustainable land use for crops. *Frontiers in Plant Science*, 13: 943022. https://doi.org/10.3389/fpls.2022.943022

Roy, R. N., Finck, A., Blair, G. J., and Tandon, H. L. S. (2006). Plant nutrition for food security: A guide for integrated nutrient management. Food and Agriculture Organization of the United Nations.

Sileshi, G. W., Mafongoya, P. L., and Chikowo, R. (2021). Integrated soil fertility management: Enhancing crop productivity and resilience in African smallholder systems. *Renewable Agriculture and Food Systems, 36*(2): 110–122. https://doi.org/10.1017/S174217051900028X

Singh, R. P., and Yadav, R. (2023). Potassium nutrition and its impact on maize kernel development and yield traits. *Indian Journal of Agronomy*, *68*(1): 24–31.

Snapp, S. S., Blackie, M. J., Gilbert, R. A., Bezner-Kerr, R., and Kanyama-Phiri, G. Y. (2010). Biodiversity can support a greener revolution in Africa. *Proceedings of the National Academy of Sciences*, *107*(48): 20840–20845. https://doi.org/10.1073/pnas.1007199107

Smith, J. K. (2023). Micronutrient supplementation in maize production: Effects on growth and yield. *Journal of Agricultural Science*, *15*(2): 45–56. https://doi.org/10.1016/j.agsci.2023.02.004

SSSA. (2017). Soil sampling and methods of analysis (3rd Ed.). Soil Science Society of America.

Tandon, H. L. S., and Messick, D. L. (2012). Sulphur in Indian agriculture. The Sulphur Institute.

Thomas, G. W. (1996). Soil pH and soil acidity. In: D. L. Sparks (Ed.), *Methods of Soil Analysis, Part 3: Chemical Methods*. Soil Science Society of America. Madison, WI. pp. 475–490.

Vance, C. P., Uhde-Stone, C., and Allan, D. L. (2003). Phosphorus acquisition and use. *New Phytologist*, *157*(3): 423–447.

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., and Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: Unravelling local adaptation. *Soil*, *1*(1): 491–508. https://doi.org/10.5194/soil-1-491-2015 (soil.copernicus.org)

Wang, H., and Liu, Q. (2021). The importance of calcium and magnesium in crop nutrition and soil structure. *Journal of Plant Nutrition and Soil Science, 184*(3): 423–432. https://doi.org/10.1002/jpln.202000150

Wang, Y., Zhang, L., and Xu, F. (2023). Soil acidification in response to long-term fertilizer use: Implications for sustainable cropping. *Agronomy for Sustainable Development*, *43*(2): 28. https://doi.org/10.1007/s13593-023-00885-3

Yadav, S. K., Tripathi, R. D., and Singh, D. (2023). Micronutrient mobility and residual effects in maize–wheat systems. *Plant and Soil*, *483*: 99–110. https://doi.org/10.1007/s11104-023-06009-9

Yadav, G. S., Lal, R. S., Meena, R. S., Babu, S. N., Das, A., Bhowmik, S. N., and Datta, M. (2022). Soil fertility clock—Crop rotation as a paradigm in nitrogen fertilizer productivity control. *Plants*, *11*(14): 2841. https://doi.org/10.3390/plants11142841

Zaman, Q., Hussain, I., and Khan, A. (2021). Effect of sulphur application on protein quality and seed yield in maize. *Soil Fertility Research*, *55*(4): 412–420.

Zewide, I. and Sherefu, A. (2021). Micronutrients and their effect on crop production: A review. *International Journal of Agricultural Research and Reviews, 9*(2): 139–149.

Zhang, Y., Zhao, Y., and Sun, B. (2021). Estimating maize LAI using remote sensing data and meteorological factors. *Sensors*, 21(4): 1250. https://doi.org/10.3390/s21041250

Zhou, Z., He, Y., and Wei, Y. (2022). Liming strategies for managing exchangeable acidity and maintaining productivity. *Soil Use and Management*, *38*(4): 1321–1329. https://doi.org/10.1111/sum.12821

Zingore, S., Murwira, H. K., Delve, R. J., and Giller, K. E. (2008). Influence of nutrient input combinations on variability of soil fertility, crop yields and nutrient use efficiencies on smallholder farms in Zimbabwe. *Agriculture, Ecosystems and Environment*, *125*(1–2): 21–31. https://doi.org/10.1016/j.agee.2007.12.008