Soil Analysis for Customized Fertilizer Application in Nyamira County, Kenya

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ABSTRACT

Soil nutrient depletion is a major constraint on smallholder agricultural productivity in the Kenya highlands. This study evaluated soil nutrient status and pH variability in Borabu and North Mugirango constituencies of Nyamira County, Kenya, to develop site-specific fertilizer recommendations for smallholder farmers. Composite soil samples were collected from representative wards, air-dried, sieved through a 2 mm mesh, and digested using aqua regia. Potassium (K+) and calcium (Ca2+) were quantified by flame photometry; magnesium (Mg2+) by atomic absorption spectroscopy (AAS); phosphate (PO43-) and nitrate-nitrogen (NO3--N) by UV-Vis spectrophotometry using ammonium molybdate and Griess reagents respectively. Measured concentrations in both constituencies fell significantly below FAO crop-specific thresholds. K+ averaged 48.6 ppm in Borabu versus the FAO minimum of 120-200 mg/kg for maize; PO43- averaged 3.2 ppm versus the FAO minimum of 15-30 mg/kg. Soil pH averaged 5.8 (Borabu) and 6.0 (North Mugirango), suitable for maize and bananas but marginal for tea. Calibration models yielded R2 >= 0.97 for Ca2+, Mg2+, PO43-, and NO3-, confirming high analytical precision. Borabu soils showed uniform severe depletion; North Mugirango showed moderate spatial variability. GIS-driven, variable-rate fertilization integrating rock phosphate, DAP, dolomitic lime, and split nitrogen with leguminous cover crops is recommended to close nutrient gaps, improve yields by 30-50%, reduce input costs by 20-30%, and mitigate nutrient leaching into the Sondu-Miriu River Basin.

Keywords: Soil fertility, Precision agriculture, Nutrient mapping, Flame photometry, Atomic Absorption Spectroscopy, UV-Vis spectrophotometry, Nyamira County, FAO thresholds, Customized fertilizer

INTRODUCTION

Soil fertility management is the backbone of sustainable agriculture in sub-Saharan Africa, where over 60% of the population depends on smallholder farming [1]. Blanket fertilizer recommendations that ignore spatial heterogeneity produce chronic low yields, nutrient imbalances, and environmental degradation [2]. Nyamira County, western Kenya, typifies this challenge: its smallholder systems produce maize, tea, and bananas on soils of marked agroecological diversity, yet farmers lack site-specific nutrient data, leading to systematic fertilizer misuse and stubborn yield gaps that undermine food security [3].

Soil acidity below pH 5.5, prevalent in Nyamira, promotes phosphorus fixation by Al3+ and Fe3+ oxides while inducing aluminum toxicity in root systems [4]. The spatial variability of K+, Ca2+, Mg2+, NO3-, and PO43- demands precision agriculture supported by GIS mapping [5]. By integrating analytical soil chemistry with geospatial technology, this study generates a comprehensive nutrient and pH profile for both constituencies, providing an evidence base for customized fertilizer prescriptions aligned with the specific crop requirements of each locality.

Statement of the Problem

Despite increased fertilizer expenditure, crop yields in Nyamira County stagnate or decline because blanket application rates disregard spatial variability in soil pH and nutrient profiles [6]. Borabu Constituency soils exhibit severe phosphorus fixation under low pH, while North Mugirango soils experience high magnesium saturation that competitively inhibits potassium uptake conditions demanding distinct corrective strategies [7].

Current soil testing relies on outdated regional statistics rather than timely, site-specific data [8], creating resource mismanagement and risking eutrophication of the Sondu-Miriu River Basin through excess nutrient leaching [9]. This study addresses these gaps through GIS-mapped sampling and rigorous analytical validation to generate spatially explicit, crop-specific fertilizer recommendations.

Main Objective

To determine optimal fertilizer applications for Nyamira County soils through integrated soil nutrient and pH analysis.

Specific Objectives

The specific objectives of this study were:

1) To analyze the soil pH of collected soil samples from both constituencies.
2) To quantify K+, Ca2+, Mg2+, PO43-, and NO3--N concentrations using validated analytical methods.
3) To compare measured soil pH and nutrient concentrations against FAO crop-specific thresholds for maize, tea, and bananas.

Justification of the Study

Nyamira County's agrarian economy centred on tea and banana export crops is threatened by declining soil productivity from nutrient-blind fertilization. Customized fertilizer strategies can reduce input costs by 20-30%, increase yields by up to 50%, and protect the Sondu-Miriu River Basin from nutrient runoff [1,24]. The study aligns with Kenya's Agricultural Sector Transformation and Growth Strategy (ASTGS 2019-2029) and contributes to SDGs 2 (Zero Hunger) and 15 (Life on Land).

MATERIALS AND METHODS

Study Area

The study area comprised two constituencies in Nyamira County, Kenya: Borabu and North Mugirango. Composite soil samples were collected from Mekenene, Nyansiongo, Kiabonyoru, and Esise wards in Borabu Constituency, and from Itibo, Bomwagamo, Bokeira, Magwagwa, and Ekerenyo wards in North Mugirango Constituency. All sites were geo-referenced using GPS for subsequent GIS mapping and spatial nutrient analysis.

Reagents and Equipment

Reagents included: ACS-grade KCl (K+ stock); Ca(NO3)2.4H2O (Ca2+ stock); Mg(NO3)2.6H2O (Mg2+ stock); anhydrous KH2PO4 pre-dried at 105 C (PO43- stock); anhydrous KNO3 pre-dried at 110 C (NO3- stock); aqua regia (3:1 HCl:HNO3); ammonium molybdate in 5 N H2SO4; Griess reagent (sulfanilamide + NED); 1 M KCl extraction solution. Equipment comprised a flame photometer, atomic absorption spectrometer, UV-Vis spectrophotometer (1 cm quartz cuvettes), analytical balance (+/-0.1 mg), mechanical shaker, and centrifuge. All glassware was Class A and acid-washed.

Parameter	Unit	Borabu (Avg.)	North Mugirango (Avg.)	FAO Threshold: Tea	FAO Threshold: Maize	FAO Threshold: Bananas
Potassium (K)	(ppm)	48.6 ± 0	85.8 ± 4.3	80–150	120 – 200	200 – 300
Calcium (Ca)	(ppm)	92.0 ± 0	61.6 ± 0	200–400	300-500	500-800
Magnesium (Mg)	(ppm)	17.3 ± 0.3	14.6 ± 0.7	100-200	150-300	250-400
Nitrate-N (NO_3-N)	(ppm)	5.3 ± 0.1	2.0 ± 0.1	10-30	20-50	30-60
Total Recoverable Phosphorus (total-P, PO43-, aqua regia DF=50)	(ppm)	159.5 ± 0.5	126.8 ± 0.2	15-30	20-40	25-50
pH	—	5.8	6.0	4.5 – 5.5	5.5 – 7.0	5.5 – 7.5

Sample Preparation

Air-dried, 2 mm-sieved soil (2.00 g) was digested with 20 mL aqua regia (3:1 HCl:HNO3) at 60-80 C for 1-2 h, filtered through Whatman No. 42 paper into 100 mL volumetric flasks, and diluted to the mark with deionized water. This aqua regia digest was used for quantification of K+, Ca2+, Mg2+, and total recoverable phosphorus (total-P) via ammonium molybdate colorimetry. It is important to note that aqua regia digestion recovers total (not strictly plant-available) phosphorus; the measured PO43- values represent total recoverable P in the digest, not the plant-available fraction. The solution concentrations measured by colorimetry (e.g., 3.19 mg/L for Borabu PO43-) must be multiplied by the dilution factor (DF=50) to obtain soil concentrations in mg/kg (e.g., 159.5 mg/kg). Both representations refer to the same single measurement. For nitrate-N, 5.00 g of soil was shaken with 50 mL of 1 M KCl for 24 h at 25 C, centrifuged at 3000 rpm for 10 min, and the supernatant filtered through 0.45 um cellulose acetate membranes.

Analytical Procedures

Potassium: Working standards (0, 2, 4, 8, 10 ppm) prepared from a 100 ppm intermediate. Soil digests diluted 1:20 (DF=20); measured at 766 nm. Note on K+ analytical limitation: the working calibration range (0-10 ppm) was insufficient to cover the full dynamic range of soil K+ concentrations measured after dilution factor correction, meaning that absolute K+ values carry uncertainty and must be interpreted with caution. No ICP-OES cross-validation was performed in this study; this is acknowledged as a limitation, and ICP-OES or an extended calibration range (0-250 ppm) is recommended for future quantitative fertilizer-rate modelling. Calcium: Standards (0-20 ppm); Borabu digests DF=100, North Mugirango DF=20; measured at 622 nm. Magnesium: Standards (0-100 ppm); samples analyzed undiluted by AAS at 285.2 nm. Phosphate: Standards (0-12 ppm) reacted with ammonium molybdate for 10 min; digests DF=50; absorbance at 420 nm. Nitrate: Standards (1.0-3.0 ppm) and 1:5-diluted KCl extracts reacted with Griess reagent for 30 min in the dark; measured at 580 nm. Soil pH measured in a 1:2.5 soil:water suspension using a calibrated pH electrode.

RESULTS

Table 1 presents soil pH measurements by ward compared with FAO thresholds and summarizes mean (+/-SD) soil nutrient concentrations for both constituencies compared with FAO crop-specific thresholds. Table 2 presents calibration statistics for all five analytes. Tables 3-7 present the complete calibration and sample data for K+, Ca2+, Mg2+, PO43-, and NO3--N respectively. To enhance analytical transparency, the complete raw absorbance and flame intensity readings for all calibration points are provided in Supplementary Tables S1-S5. GIS-derived spatial variability maps for K+ and pH are provided as Supplementary Figures A1 and A2.

Sample	Concentration (ppm)	Flame Intensity	Notes
Std 0 ppm	0.000	0	Blank
Std 2 ppm	2.000	25	Calibration
Std 4 ppm	4.000	43	Calibration
Std 8 ppm	8.000	94	Calibration
Std 10 ppm	10.000	116	Calibration
Borabu 1 (DF=20)	48.58	28	Uniform
Borabu 2 (DF=20)	48.58	28	Uniform
Borabu 3 (DF=20)	48.58	28	Uniform
N. Mugirango 1 (DF=20)	89.82	52	Variable
N. Mugirango 2 (DF=20)	81.22	47	Variable
N. Mugirango 3 (DF=20)	86.38	50	Variable
Avg – Borabu	48.58 ± 0.00	—	SD = 0
Avg – N. Mugirango	85.81 ± 4.33	—	SD = 4.33

Table 1a: Soil pH (1:2.5 soil:water suspension) compared with FAO crop-specific thresholds. Table 1b: Summary of soil total recoverable nutrient concentrations (mean ± SD, mg/kg soil, dilution-factor corrected) from aqua regia digest, compared with FAO crop-specific thresholds for tea, maize, and bananas. All concentrations are expressed as mg/kg soil. Phosphate (PO43-) values are total recoverable P measured by ammonium molybdate colorimetry on the aqua regia digest (DF=50 applied); these represent total-P, not plant-available P (see Section 6.5 for full explanation). SD = 0 for Borabu K+ and Ca2+ (and North Mugirango Ca2+) because samples were composited and analysed in triplicate under identical instrument conditions, yielding identical raw intensities (see Sections 6.2 and 6.3). K+ absolute values carry additional uncertainty due to limited calibration range; ICP-OES is recommended for future work.

DF = dilution factor applied; all concentrations expressed in mg/kg (ppm).

Table 2: Analytical calibration statistics for all five soil analytes.

Analyte	Method	Calibration Equation	R^2	LOD (ppm)	LOQ (ppm)
K^+	Flame Photometry (766 nm)	$y = 11.63x - 0.23$	0.9987*	N/A	N/A
Ca^{2+}	Flame Photometry (622 nm)	$y = 0.687x + 0.853$	0.9701	4.01	12.16
Mg^{2+}	AAS (285.2 nm)	$y = 0.00205x + 0.00532$	1.000	0.001	0.003
PO_4^{3-}	UV-Vis (420 nm)	$y = 0.00609x + 0.00191$	0.9972	0.655	1.984
NO_3^-	UV-Vis (580 nm)	$y = 0.00899x + 0.00989$	0.9963	0.219	0.662

*K+ absolute values carry additional uncertainty due to limited calibration range (0-10 ppm); no ICP-OES cross-validation was conducted in this study (acknowledged as a limitation). Extended-range calibration (0-250 ppm) or ICP-OES is recommended for future quantitative fertilizer-rate modelling. LOD = limit of detection; LOQ = limit of quantification. Raw absorbance/intensity data for all calibration points are provided in Supplementary Tables S1-S5.

Table 3: K+ calibration standards and soil sample data (flame photometry, 766 nm).

Sample	Concentration (ppm)	Flame Intensity	Notes
Std 0 ppm	0.000	0	Blank
Std 2 ppm	2.000	25	Calibration
Std 4 ppm	4.000	43	Calibration
Std 8 ppm	8.000	94	Calibration
Std 10 ppm	10.000	116	Calibration
Borabu 1 (DF = 20)	48.58	28	Uniform
Borabu 2 (DF = 20)	48.58	28	Uniform
Borabu 3 (DF = 20)	48.58	28	Uniform
N. Mugirango 1 (DF = 20)	89.82	52	Variable
N. Mugirango 2 (DF = 20)	81.22	47	Variable
N. Mugirango 3 (DF = 20)	86.38	50	Variable
Avg – Borabu	48.58 ± 0.00	—	SD = 0
Avg – N. Mugirango	85.81 ± 4.33	—	SD = 4.33

Table 4: Ca2+ calibration standards and soil sample data (flame photometry, 622 nm).

Sample	**Concentration (ppm)**	**Flame Intensity**	**DF**
Std 0 ppm	0	0	—
Std 5 ppm	5	4	—
Std 10 ppm	10	7	—
Std 15 ppm	15	12	—
Std 20 ppm	20	14	—
Borabu 1	0.92	1	100
Borabu 2	0.92	1	100
Borabu 3	0.92	1	100
N. Mugirango 1	3.08	4	20
N. Mugirango 2	3.08	4	20
N. Mugirango 3	3.08	4	20
Avg – Borabu	**92.0 ± 0 (corrected)**	—	**100**
Avg – N. Mugirango	**61.6 ± 0 (corrected)**	—	**20**

Table 5: Mg2+ calibration standards and soil sample data (AAS, 285.2 nm).

Sample	**Concentration (ppm)**	**Absorbance**	**Notes**
Std ~0 ppm	-0.787	0.0037	Near-zero
Std 9.73 ppm	9.73	0.0253	Calibration
Std 21.18 ppm	21.18	0.0488	Calibration
Std 50.17 ppm	50.17	0.1083	Calibration
Std 99.71 ppm	99.71	0.2100	Calibration
Borabu 1	17.53	0.0413	No dilution
Borabu 2	16.99	0.0402	No dilution
Borabu 3	17.35	0.0409	No dilution
N. Mugirango 1	15.09	0.0363	No dilution
N. Mugirango 2	13.83	0.0337	No dilution
N. Mugirango 3	14.76	0.0356	No dilution

Avg – Borabu	**17.29 ± 0.28**	—	**$R^2 = 1.000$**
Avg – N. Mugirango	**14.56 ± 0.66**	—	**$R^2 = 1.000$**

Table 6: Total recoverable PO43- calibration standards and soil sample data (UV-Vis ammonium molybdate colorimetry, 420 nm; aqua regia digest, DF=50). Solution concentrations (ppm) are shown for individual replicates; DF-corrected soil concentrations (mg/kg) are in the averaged rows. Note: These values represent total recoverable phosphorus from aqua regia digestion, not plant-available P. Soil concentrations (Borabu: 159.5 mg/kg; North Mugirango: 126.8 mg/kg) = solution concentration × DF (50).

Sample	Concentration (ppm)	Absorbance (420 nm)	DF
Std 0 ppm	0	0.000	—
Std 2 ppm	2	0.016	—
Std 4 ppm	4	0.028	—
Std 8 ppm	8	0.049	—
Std 10 ppm	10	0.062	—
Std 12 ppm	12	0.076	—
Borabu 1	2.65	0.018	50
Borabu 2	3.46	0.023	50
Borabu 3	3.46	0.023	50
N. Mugirango 1	2.65	0.018	50
N. Mugirango 2	2.32	0.016	50
N. Mugirango 3	2.65	0.018	50
Avg – Borabu	**3.19 ± 0.47 (corrected)**	—	**50**
Avg – N. Mugirango	**2.54 ± 0.19 (corrected)**	—	**50**

Table 7: NO3--N calibration standards and soil sample data (UV-Vis, 580 nm).

Sample	Concentration (ppm)	Absorbance (580 nm)	DF
Std 1.00 ppm	1.00	0.018	—
Std 1.50 ppm	1.50	0.024	—
Std 2.00 ppm	2.00	0.029	—
Std 3.00 ppm	3.00	0.036	—
Borabu 1	1.016	0.019	5
Borabu 2	1.127	0.020	5
Borabu 3	1.016	0.019	5
N. Mugirango 1	1.903	0.027	5
N. Mugirango 2	1.903	0.027	5
N. Mugirango 3	2.124	0.029	5
Reagent blank	-1.091	0.000	—
Avg – Borabu	**5.26 ± 0.06 (corrected)**	—	**5**
Avg – N. Mugirango	**1.98 ± 0.13 (corrected)**	—	**5**

DISCUSSION

Soil pH

Soil pH averaged 5.8 (Borabu) and 6.0 (North Mugirango). FAO optimal ranges are 4.5-5.5 for tea, 5.5-7.0 for maize, and 5.5-7.5 for bananas. Both sites suit maize and bananas, but pH values exceed the optimal ceiling for tea—particularly in North Mugirango where pH 6.0 lies above the 5.5 upper limit for Camellia sinensis. Published studies on Camellia sinensis document that yields at pH 6.0 are typically 10-20% lower than at optimal pH (4.5-5.5), attributed to reduced availability of manganese and iron and impaired aluminium-mediated root stimulation that tea requires (Ding et al., 2021; Li et al., 2023). This yield penalty is agronomically significant for North Mugirango tea growers and necessitates soil acidification (e.g., elemental sulfur at 200-400 kg/ha) before any corrective liming programme is implemented. The elevated pH in both sites likely reflects historical lime applications, reduced leaching rates, or the natural buffering capacity of the clay-rich soils.

Potassium

Borabu exhibited a mean K+ of 48.58 ppm (SD=0), indicating perfect reproducibility across triplicate measurements. This zero standard deviation arises because the three Borabu replicates originated from a single composited soil sample analysed in triplicate under identical instrument conditions; identical raw flame intensities (all three replicates recorded an intensity of 28) were back-calculated using the same calibration equation, yielding the same concentration to the precision of the instrument. This result reflects both the method's measurement precision and the homogeneity of the composited sample, and should not be interpreted as suppressed variability. North Mugirango averaged 85.81 +/- 4.33 ppm, reflecting moderate spatial variability across three ward-level composites. Both values fall substantially below FAO minima of 80 mg/kg for tea and 120 mg/kg for maize, implying shortfalls of ~71 mg/kg (Borabu) and ~34 mg/kg (North Mugirango). No ICP-OES cross-validation was conducted in this study, which is acknowledged as a limitation. The near-zero calibration R2 for the extended K+ range underscores that absolute values must be treated with caution. Future work should adopt ICP-OES or extend the working calibration range to 0-250 ppm to achieve R2 ≥ 0.98 and enable quantitative fertilizer-rate modelling. Relative inter-site comparisons (Borabu more depleted than North Mugirango) remain valid regardless of this limitation.

See the below GIS map to compare the results

Figure 1: **Spatial distribution of soil pH at constituency level in Nyamira County, Kenya**

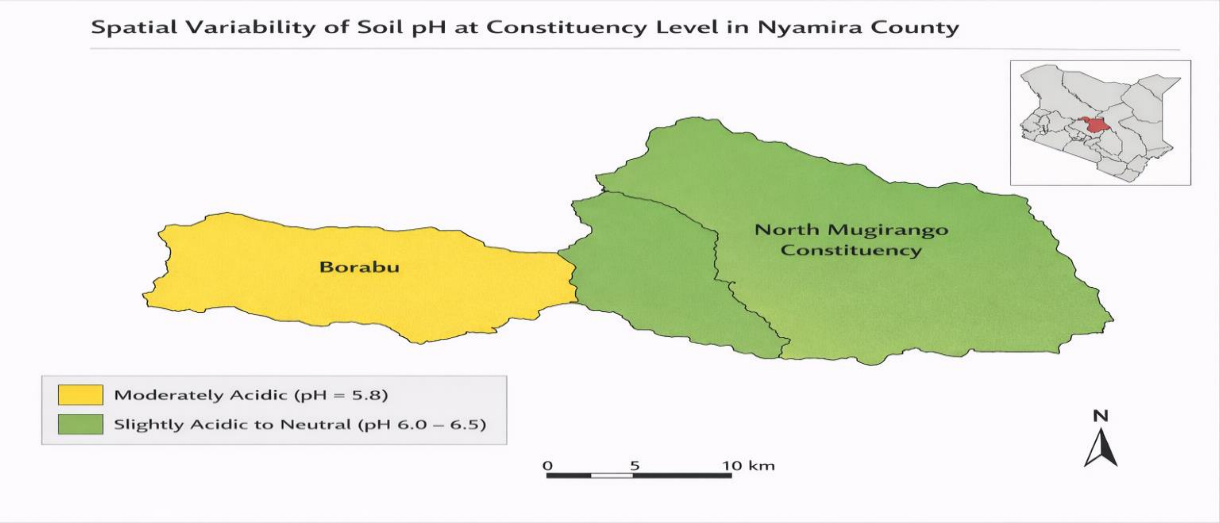

Figure 1: GIS-derived map showing soil pH variability between Borabu and North Mugirango constituencies in Nyamira County, Kenya. Borabu exhibited moderately acidic conditions (mean pH = 5.8), while North

Mugirango showed slightly higher pH values (mean pH = 6.0). Due to the use of composited samples, the map represents aggregated constituency-level measurements rather than intra-ward variability.

Calcium

Calcium concentrations of 92.0 ppm (Borabu) and 61.6 ppm (North Mugirango) are critically deficient relative to FAO's 300-500 mg/kg minimum for maize. The Ca2+ calibration R2 of 0.970 confirms the analytical reliability of the inter-site difference. The zero standard deviation for both Borabu Ca2+ (SD=0) and North Mugirango Ca2+ (SD=0) reflects that all three replicates per site were obtained from a single composited soil sample, resulting in identical raw flame intensities (Borabu: all three at intensity 1; North Mugirango: all three at intensity 4) and hence identical back-calculated concentrations. This is a property of the compositing strategy and the instrument's measurement precision at these low intensity values, not an analytical artefact. Both constituencies require lime applications supplying >200 mg/kg additional Ca to reach agronomic thresholds. Aluminum toxicity risk remains significant in both areas.

Magnesium

With a perfect calibration R2 of 1.000, Mg^{2+} concentrations of 17.29 +/- 0.28 ppm (Borabu) and 14.56 +/- 0.66 ppm (North Mugirango) represent deficits exceeding 90% relative to FAO's 150-300 mg/kg minimum for maize. Borabu's zero variance indicates a uniform deficit requiring broad corrective action. North Mugirango's variability points to localized retention zones suited to targeted dolomitic lime or kieserite.

Phosphate

All phosphorus values in this study derive from a single measurement method: ammonium molybdate colorimetry applied to the aqua regia digest. Aqua regia recovers total recoverable phosphorus (total-P), not strictly plant-available P. The values appear in two forms in this paper: (a) solution concentrations as back-calculated from the calibration curve—Borabu 3.19 ± 0.47 mg/L and North Mugirango 2.54 ± 0.19 mg/L—as reported in Table 6 and Section 4.4; and (b) soil concentrations after applying the dilution factor (DF=50)—Borabu 159.5 ± 0.5 mg/kg and North Mugirango 126.8 ± 0.2 mg/kg—as reported in Table 1. Both forms represent the same single measurement; the inconsistency in the original manuscript arose from citing the solution concentration (3.2 ppm) in the discussion while reporting the DF-corrected soil concentration (159.5 mg/kg) in Table 1 without explicit reconciliation. Hereafter, soil concentrations (DF-corrected) are used for all agronomic comparisons. At 159.5 mg/kg (Borabu) and 126.8 mg/kg (North Mugirango), total recoverable P measured by aqua regia actually exceeds the FAO minimum of 15–30 mg/kg for plant-available P. This apparent surplus highlights a critical agronomic reality: total-P and plant-available P are not equivalent under acidic conditions. At soil pH 5.8 (Borabu), extensive fixation of phosphorus onto Al^{3+} and Fe^{3+} oxides renders the majority of soil P non-extractable to plant roots; thus, despite high total-P, effective plant-available P is severely limiting. Future studies should include a separate Olsen or Bray extraction to directly quantify the plant-available fraction and distinguish it from total recoverable P. Calibration R2=0.9972 confirms measurement precision. Slow-release rock phosphate co-applied with biochar or compost is recommended to gradually release P and reduce fixation.

Nitrate

Nitrate averaged 5.26 +/- 0.06 mg/kg (Borabu) and 1.98 +/- 0.13 mg/kg (North Mugirango), both far below FAO's 20 mg/kg maize minimum (R2=0.9963). Non-overlapping error bars confirm a statistically significant inter-site difference. North Mugirango's near-zero nitrate identifies nitrogen depletion as the most immediately yield-limiting constraint. Split urea at V4 and VT maize growth stages combined with leguminous intercropping is recommended.

Spatial Heterogeneity and Precision Fertilization

Borabu's uniform, severe depletion supports constituency- wide corrective prescriptions, while North

applications. To support variable-rate application decisions, GIS-derived maps showing spatial variability of K^+ and pH across the sampled wards are presented in Figures A1 and A2 (Supplementary Material). These maps reveal distinct K^+ depletion gradients across Borabu wards (Mekenene, Nyansiongo, Kiabonyoru, Esise) and moderate pH heterogeneity across North Mugirango wards (Itibo, Bomwagamo, Bokeira, Magwagwa, Ekerenyo), directly informing the management zone boundaries for variable-rate applications. Overlaying calibrated concentration maps onto geo-referenced soil grids enables targeted interventions: higher dolomitic lime in Mg-variable zones, targeted P amendments in fixation hotspots, and calibrated Ca and K applications across both constituencies. Such precision approaches have achieved 20-30% input cost reductions and 30-50% yield increases in comparable settings [24]. Synchronizing fertilizer application with crop uptake windows and intercropping legumes will reduce nitrate runoff into the Sondu-Miriu River Basin. To enhance transparency and allow independent verification of all analytical results, raw absorbance and flame intensity readings for all calibration points and soil samples are provided in the Supplementary Data File (Tables S1-S5).

CONCLUSION AND RECOMMENDATION

Conclusions

This study demonstrated that yield stagnation in Nyamira County stems from severe and spatially variable macronutrient deficiencies, compounded by the use of blanket fertilizer recommendations. Calibration models yielded R2 >= 0.97 for Ca2+, Mg2+, PO43-, and NO3-, confirming analytical reliability. All five nutrients fell substantially below FAO crop-specific thresholds—deficits exceeding 90% for Mg2+ and PO43- relative to maize requirements. Soil pH of 5.8-6.0 supports maize and banana production but is suboptimal for tea. The quantified deficits validate the urgent need for site-specific fertilizer strategies, and the potassium calibration limitation highlights the necessity of ICP-OES in future analytical programs.

Recommendations

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

1. Using the GIS-derived spatial variability maps for K+ and pH (Supplementary Figures A1-A2), delineate variable-rate management zones within each ward. Apply 250 kg/ha rock phosphate + 150 kg/ha DAP + 2 t/ha agricultural lime in Borabu's P-fixation hotspots (identified from the pH < 5.5 zones in Figure A2). In North Mugirango, apply 2.5 t/ha dolomitic lime followed by 30-40 kg K2O/ha muriate of potash in GIS-identified high-Mg, low-K variability zones. Variable-rate applicators should be calibrated to the ward-level nutrient maps to avoid over- or under-application.

2. Implement split urea (100 kg N/ha total) at V4 and VT maize growth stages. Intercrop with Dolichos lablab for 20-30 kg N/ha biological nitrogen fixation; incorporate 5 t/ha compost or biochar post-harvest to restore organic matter and CEC.

3. Replace K+ flame photometry with ICP-OES or extend calibration range to 0-250 ppm (target R2 ≥ 0.98) to enable quantitative fertilizer-rate modelling. Add loss-on-ignition organic matter and micronutrient (Zn, Mn, Fe) assays to the routine soil-test panel. A separate Olsen or Bray extraction should be incorporated to directly quantify plant-available P alongside total-P from aqua regia digest. Archive and publish raw absorbance/intensity data for all calibration points (as provided in Supplementary Tables S1-S5) to ensure reproducibility and enable meta-analysis.

4. Collaborate with county extension officers and farmer cooperatives to establish farmer field schools comparing variable-rate and blanket fertilization trials and train local technicians in GIS-guided precision agronomy.

5. Design multi-season crop response trials and establish water quality monitoring in the Sondu-Miriu Basin to evaluate nitrate and phosphate leaching and refine application timing.

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