Geospatial Assessment of Soil Nutrient Limitations and Site-Specific Fertilizer Recommendations for Potato Farming Systems in Plateau State, Nigeria

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DOI: https://doi.org/10.51584/IJRIAS.2025.10100000168

Received: 30 October 2025; Accepted: 06 November 2025; Published: 20 November 2025

ABSTRACT

Precision agriculture approaches require detailed understanding of soil nutrient heterogeneity to develop costeffective fertilization strategies for sustainable food production. This study employed geospatial technologies to map soil nutrient limitations and formulate zone-specific fertilizer recommendations for potato production systems in Bokkos and Mangu Local Government Areas, Plateau State, Nigeria. Through systematic sampling of 240 georeferenced locations across 3,329.41 km², we analysed soil pH, organic carbon, nitrogen, phosphorus, and potassium using inverse distance weighting interpolation in ArcGIS. Results revealed severe nutrient stratification across the study landscape, with soil acidity affecting 77% of farmlands (pH 4.0-5.36), creating a primary constraint requiring approximately 2,050 km² of lime application. Nitrogen deficiency dominated 83.2% of the area (0.01-0.084% N), while phosphorus limitations encompassed 55.6% of farmlands (3.68-8.91 mg/kg). Conversely, potassium showed adequate levels across 51.5% of locations. Geographic clustering analysis identified three distinct soil management zones: Zone A (central volcanic belt, 45% coverage) exhibiting superior fertility with pH 5.68-7.0 and elevated N-P-K levels; Zone B (peripheral granitic areas, 35% coverage) showing moderate degradation; and Zone C (severely depleted regions, 20% coverage) requiring intensive rehabilitation. Economic analysis suggests prioritizing Zone B with balanced NPK fertilization could yield 300% return on investment, while Zone A requires only maintenance inputs. Zone C necessitates multi-year soil amendment programs combining lime (2-3 tons/ha), organic matter (5-10 tons/ha), and starter fertilizers. This research provides the first comprehensive nutrient prescription map for Plateau State potato systems, enabling farmers and extension services to implement precision fertilization strategies that could potentially increase yields by 40-60% while reducing input costs by 25-30% through targeted application.

Keywords: Precision agriculture, soil fertility mapping, nutrient management zones, fertilizer recommendations, spatial interpolation

INTRODUCTION

Declining soil fertility represents the most significant biological constraint to sustainable food production in subSaharan Africa, where continuous cultivation without adequate nutrient replenishment has depleted soil reserves across millions of hectares. Nigeria's agricultural intensification, particularly in highland regions, has accelerated soil degradation, with annual nutrient mining estimated at 40-80 kg N, 5-10 kg P, and 20-30 kg K per hectare. This nutrient depletion directly impacts high-value crops like Irish potato (*Solanum tuberosum* L.), which requires substantial mineral nutrition for optimal tuber production. Traditional blanket fertilizer recommendations, typically based on regional averages, fail to account for significant spatial variability in soil properties within farming landscapes. Recent advances in geospatial technologies and geostatistics now enable precision mapping of soil nutrient distributions, allowing development of site-specific management strategies that optimize input use efficiency while maximizing economic returns.

Irish potato is an annual herbaceous tuber crop representing the world's largest non-cereal crop and ranking fourth globally in importance after maize, wheat, and rice. Global production reached approximately 375 million tons in 2022, with significant production in Asia, Europe, and Africa. In Africa, potato production is estimated at 25 million metric tonnes with an average yield of 13,215.4 kg/ha. Nigeria ranks as the fourth largest producer in sub-Saharan Africa and seventh in Africa, with an output of 1,216,409 metric tons. The Jos Plateau represents Nigeria's primary potato production region, contributing over 90% of national output with approximately 1.2 million metric tons annually. However, yields averaging 3.1 tons/ha remain drastically below the genetic potential of 25-30 tons/ha achievable under optimal management conditions. Multiple production constraints contribute to this yield gap, including pest pressure, seed quality issues, and climatic factors, but soil fertility limitations consistently rank as the primary biophysical constraint across farmer surveys and agronomic trials.

Bokkos and Mangu Local Government Areas constitute critical production zones within the Plateau State potato belt, hosting thousands of smallholder farmers who depend on potato cultivation for household income and food security. These areas exhibit considerable landscape diversity, encompassing volcanic highlands, granitic plains, and dissected terrain with varying parent materials, soil types, and fertility status. Understanding this spatial heterogeneity is essential for designing effective soil management interventions that address location-specific constraints while optimizing scarce agricultural resources. This study aimed to: (1) characterize the spatial distribution and variability of key soil chemical properties limiting potato production across Bokkos and Mangu LGAs; (2) identify distinct soil nutrient management zones based on fertility characteristics and amendment requirements; (3) develop zone-specific fertilizer and soil amendment recommendations tailored to economic and agronomic conditions; and (4) estimate potential yield improvements and economic benefits from implementing precision nutrient management strategies. Unlike previous descriptive soil surveys, this research emphasizes actionable prescription mapping to facilitate immediate adoption by agricultural stakeholders.

STUDY AREA

2.1 Location and Administrative Context

The research area encompasses Bokkos and Mangu Local Government Areas in the central zone of Plateau State, Nigeria (Figure 1). The study area is located between latitudes 9°01'50.2"N and 9°44'6.5"N, and longitudes 8°41'27"E and 9°19'56"E, at elevations ranging from 600 to 1,800 meters above sea level. Bokkos covers approximately 1,472 km², while Mangu spans about 1,645 km², totalling 3,329.41 km² of predominantly agricultural landscape.

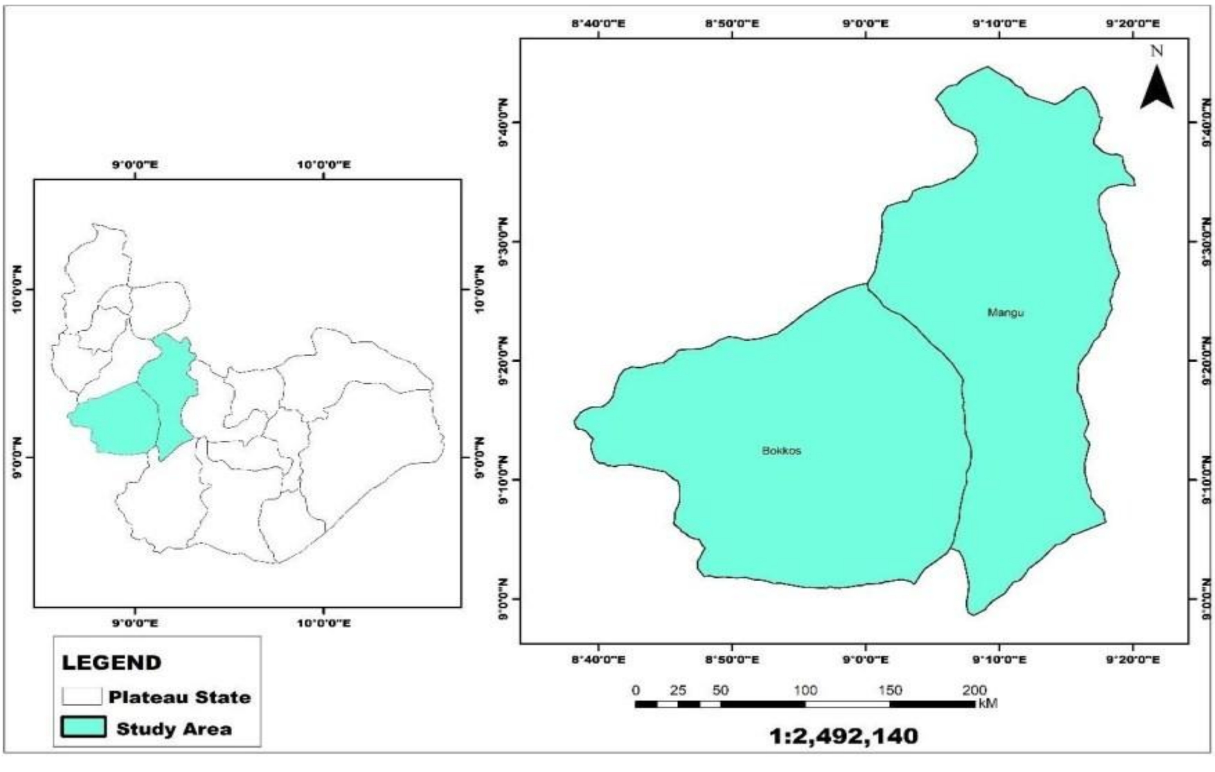

Figure 1: Location map of the study area showing Mangu and Bokkos Local Government Areas

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

2.2 Climate and Agro-ecological Setting

The region experiences a tropical highland climate with distinct bimodal characteristics. The rainy season extends from April to October, delivering 800-1,400 mm of precipitation annually, followed by a dry season (November-March) marked by cool Harmattan winds. Temperature regimes are moderated by altitude, with means ranging from 18-28°C, creating conditions highly conducive to potato cultivation. Average maximum temperatures reach approximately 34°C, while minimum temperatures drop to 27°C. The warmest months occur from March to May, while the coldest period coincides with the December-January Harmattan season. These climatic conditions are optimal for Irish potato production, which thrives at temperatures around 27°C for tuber formation and requires cool growing seasons with moderate, well-distributed rainfall of 800-1,200 mm.

2.3 Geology and Parent Materials

Geological diversity characterizes the study area, with Pre-Cambrian Basement Complex rocks dominating the landscape (Figure 2). Granitic formations, particularly migmatite-gneiss complexes, occur extensively across both LGAs, weathering to produce sandy-clay and loamy soils with moderate fertility. These granitic rocks contain substantial clay content generated from feldspar breakdown and other clay-forming minerals. Importantly, Tertiary volcanic activities centred around Kerang-Ampang zones deposited basaltic rocks and volcanic ash across approximately 1,200 km² of the central study area, creating distinct soil fertility patterns. Newer basaltic rocks are found mainly in Kerang and Ampang areas, while older basaltic boulders occur in parts of Bokkos and Mangu. These younger volcanic materials contribute basic cations and micronutrients, resulting in more productive agricultural soils compared to granitic-derived counterparts. Soils derived from basaltic rocks and volcanic ashes are particularly productive for food crops, especially at altitudes between 1,600-3,000 m around Kerang. Volcanic ash deposits from previous volcanic activities, including the notable Pidong crater lake near Kerang, have significantly enhanced soil physical and chemical properties in these zones.

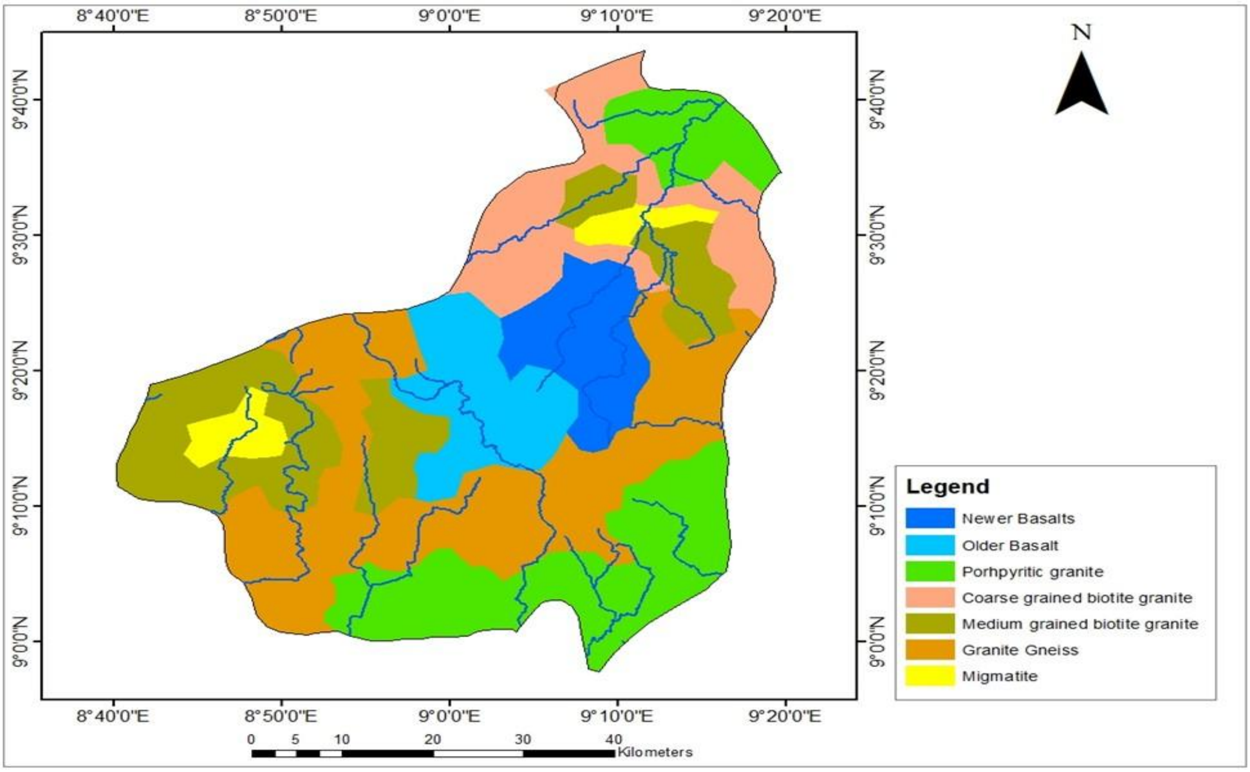

Figure 2: Geological map showing the distribution of rock types in Mangu and Bokkos LGAs

2.4 Vegetation and Land Use Patterns

The study area falls within the northern guinea savannah vegetation zone and is characterized by diverse land use patterns. Agricultural land use dominates approximately 65% of Mangu LGA and 60% of Bokkos LGA, with Irish potato serving as the primary cash crop in rotation with cereals (maize, sorghum), legumes (beans,

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

soybeans), and various vegetables. Farm sizes average 0.5-2.0 hectares, with cultivation intensity reaching 2-3 crop cycles annually in irrigated areas. Traditional farming practices predominate, with limited fertilizer use (averaging 50-100 kg NPK/ha when applied) and minimal organic inputs despite declining yields observed over the past two decades. The intensive cultivation practices without adequate nutrient replenishment have contributed to progressive soil degradation across much of the landscape.

MATERIALS AND METHODS

3.1 Sampling Design and Field Procedures

A stratified random sampling approach was implemented to ensure representative coverage across both LGAs while capturing landscape variability. Using satellite imagery (Sentinel – 2 and ASTER Digital Elevation Model, six preliminary sampling strata were delineated based on topography, land use intensity, and apparent vegetation vigour. Within each stratum, sampling locations were randomly selected from active potato farming areas identified through ground reconnaissance and farmer consultations across different farming communities in both LGAs.

Field equipment included GPS receiver (Garmin 78MAPCSx with ±3m accuracy), soil auger, plastic buckets, polythene bags, hand trowel, permanent markers, masking tape, hardcover notebooks, and pens. At each of 240 sampling locations, four sub-samples were collected within a 10-meter radius using a soil auger at 0-30 cm depth, representing the primary rooting zone for potato production. Sub-samples were thoroughly homogenized to create composite samples (approximately 1 kg each), which were placed in clean, labeled polyethylene bags with unique GPS coordinates recorded in situ. Sampling occurred during the dry season (January-February 2024) to ensure standardized soil moisture conditions and minimize seasonal variations in measured parameters.

3.2 Laboratory Analyses

All soil samples went standardized analyses. Particle size distribution was determined by hydrometer method after organic matter removal, classifying textures using USDA taxonomy. Soil pH was measured in 1:2.5 soil water suspension using a calibrated glass electrode pH meter after 30-minute equilibration. This was carried out at the Centre for Dryland Agriculture, Bayero University kano, Kano State.

Organic carbon was quantified via Walkley-Black wet oxidation method, with results expressed as percentage organic matter using the van Bemmelen conversion factor (1.724). Total nitrogen was determined by Kjeldahl digestion-distillation method following sulfuric acid digestion and boric acid trapping. Available phosphorus was extracted using Bray-1 solution (0.03N NH_4F + 0.025N HCl) appropriate for acidic soils, with colorimetric determination at 882nm wavelength. Exchangeable potassium was extracted with neutral 1N ammonium acetate and measured by flame photometry.

Quality control procedures included duplicate analyses of 10% of samples, method blanks, and certified reference materials. Analytical precision was maintained within ±5% for all parameters, meeting international soil testing standards.

3.3 Geospatial Analysis and Mapping

Spatial interpolation employed inverse distance weighting (IDW) in ArcGIS 10.8 software, selected for its robust performance with moderate sample sizes and ability to preserve local variations. IDW parameters were optimized through cross-validation, with power parameter set at 2 and search radius of 12 nearest neighbours providing minimum root mean square error. Continuous raster surfaces (30m resolution) were generated for each soil property across the 3,329.41 km² study extent.

Nutrient management zones were delineated through overlay analysis combining pH, organic matter, nitrogen, phosphorus, and potassium surfaces. Classification employed agronomic threshold values established from international standards for agricultural soil fertility assessment: pH < 5.5 (requiring lime), organic matter < 1.5% (critical deficiency), nitrogen < 0.08% (severe limitation), phosphorus < 10 mg/kg (insufficient), and potassium

INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN APPLIED SCIENCE (IJRIAS)
ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

< 0.28 cmol/kg (deficient). Zones were defined based on number and severity of limiting factors, producing a management prescription map for agricultural decision-making.

RESULTS

4.1 Soil Physical Properties and Texture Distribution

Textural analysis revealed nine distinct classes across the study area, with sandy clay loam predominating (68% of total area) (Figure 3). Mangu LGA exhibited higher clay content, with sandy clay loam covering 75% of the area, while Bokkos showed greater textural diversity with sandy loam occupying over 60% of the total area and scattered clay loam pockets. These medium-textured soils generally provide favourable physical conditions for potato cultivation, offering adequate drainage while maintaining sufficient water-holding capacity for tuber development. Silty clay loam represented the smallest proportion in both LGAs.

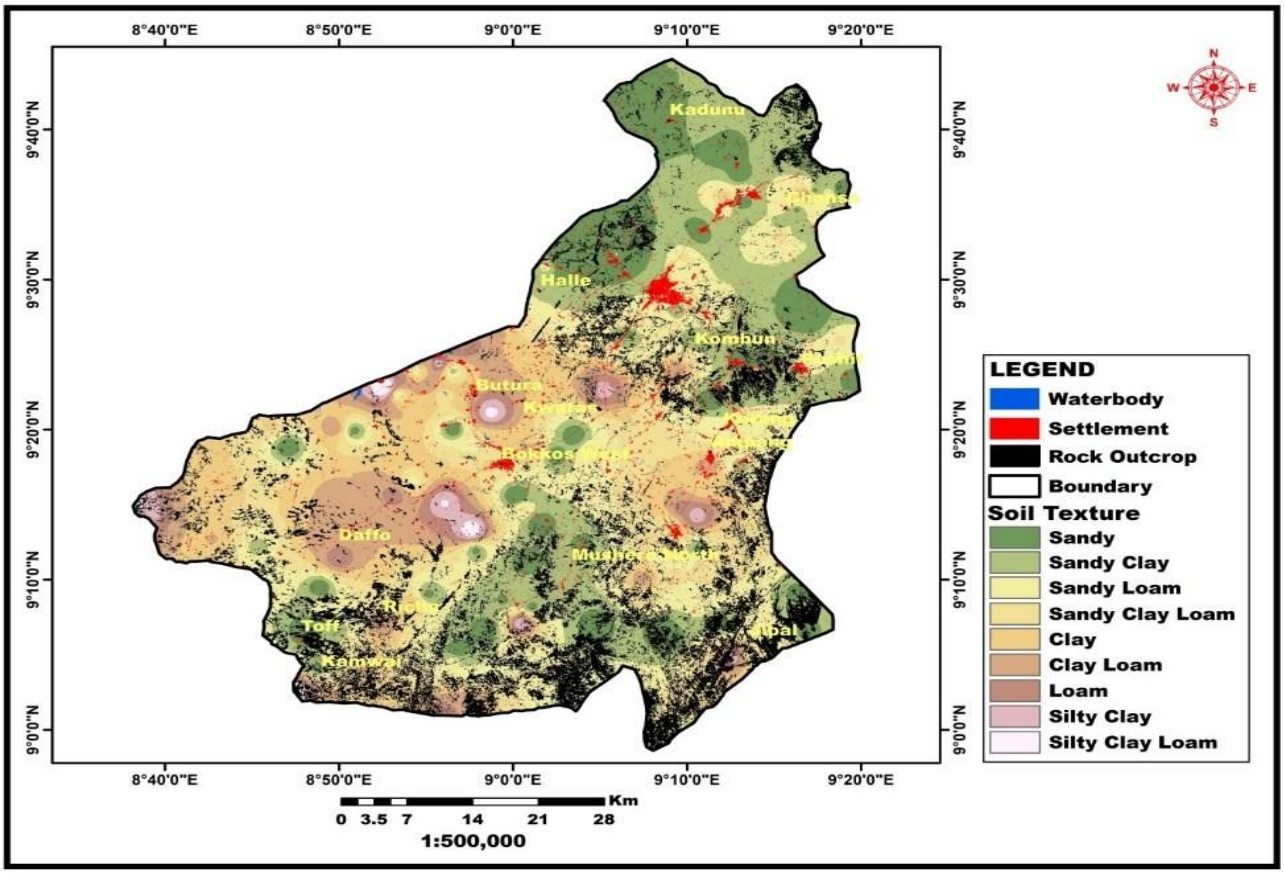

Figure 3: Soil Texture for Mangu and Bokkos LGAs

The textural distribution closely correlated with underlying geology. Granitic-derived soils showed higher sand fractions (60-75% sand), reflecting feldspar and quartz weathering products, while basaltic areas around KerangAmpang exhibited elevated clay content (25-40% clay) from weathering of ferro-magnesium minerals. Importantly, no purely sandy soils (>85% sand) were encountered, suggesting drainage limitations are unlikely to constrain production. Conversely, heavy clay soils occupied minimal area (<3%), avoiding waterlogging concerns that affect potato quality.

4.2 Soil pH Distribution and Acidity Constraints

Soil reaction exhibited pronounced spatial variability, ranging from strongly acidic (pH 4.0) to neutral (pH 7.0) across the study landscape (Figure 4, Table 1). Statistical analysis revealed mean pH of 5.12 ± 0.68, with 77% of samples falling below the critical threshold of pH 5.5 where aluminium toxicity and nutrient deficiencies typically constrain crop growth. The distribution revealed that 32%, 28.6%, 17.1%, 18%, and 4.4% of soils were classified as very strongly acidic, strongly acidic, moderately acidic, slightly acidic, and neutral, respectively.

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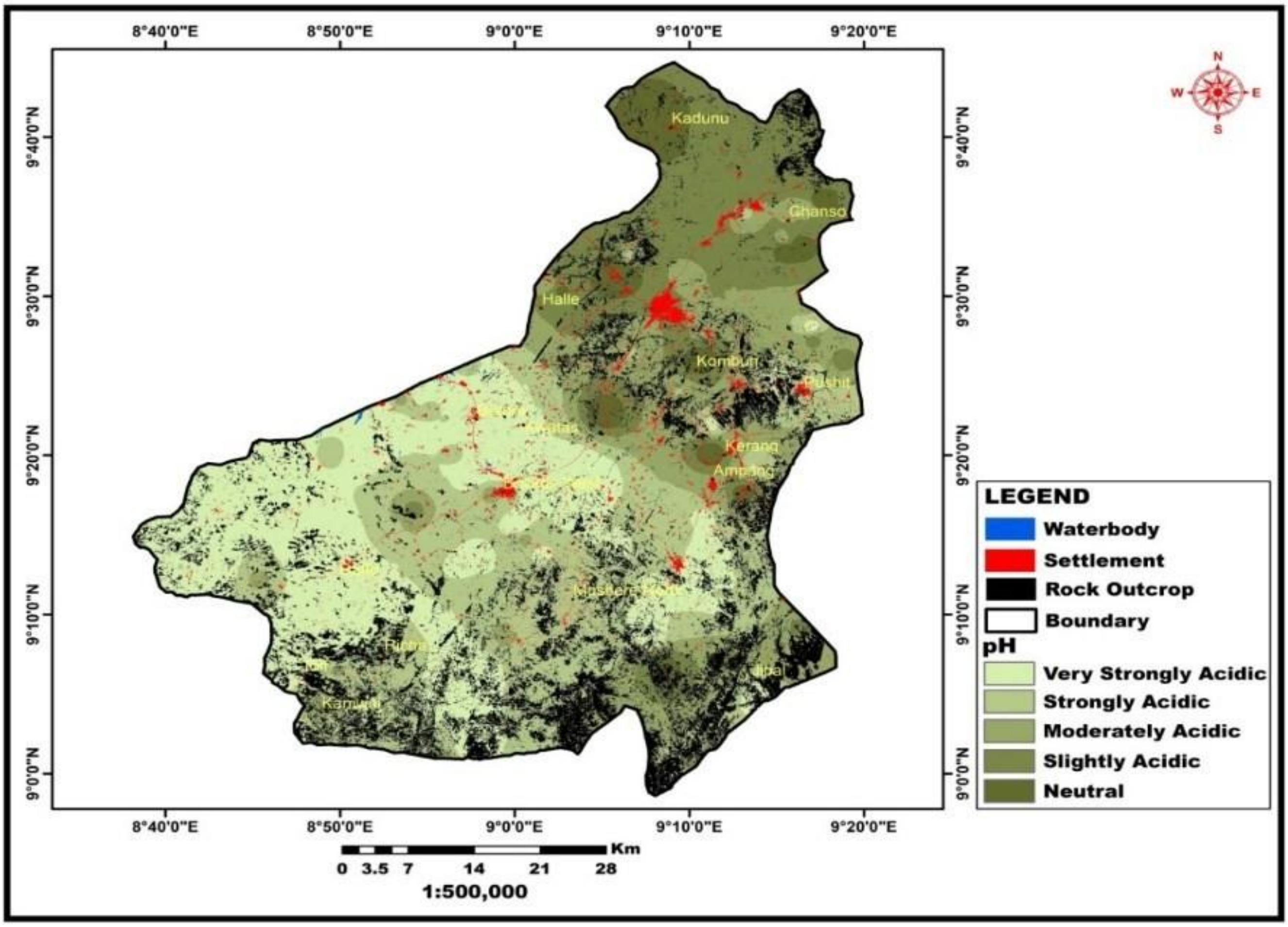

Figure 4: Spatial distributions of soil pH for Mangu and Bokkos LGAs

Table 1: Spatial distribution of soil pH classes and lime requirement estimates

pH Classification	pH Range	Area (km²)	Coverage (%)	Estimated Lime Required (tons/ha)*
Very Strongly Acidic	4.05-4.79	850.84	32.0	3.0-4.0
Strongly Acidic	4.79-5.07	758.58	28.6	2.0-3.0
Moderately Acidic	5.07-5.36	453.23	17.1	1.0-2.0
Slightly Acidic	5.36-5.68	477.20	18.0	0.5-1.0
Neutral	5.68-7.06	116.81	4.4	None required
Total		**2,656.65**	**100.0**	

*Lime requirements calculated for target pH 6.0 using buffer method estimates

Geographic patterns in pH distribution revealed distinct clustering. Bokkos LGA demonstrated more severe acidity, with 74.5% of area classified as strongly to very strongly acidic (pH < 5.1), compared to 60% in Mangu. The central volcanic belt spanning Kerang, Ampang, Kwatas, and Daffo exhibited significantly higher pH values (5.5-7.0), attributed to weathering of basic cations from basaltic parent materials and volcanic ash deposits. This "fertility corridor" covers approximately 1,100 km² and represents the most productive agricultural zone in both LGAs.

4.3 Organic Matter Status and Carbon Sequestration Potential

Soil organic matter concentrations ranged from 0.2% to 3.5%, with mean values of 1.09 ± 0.54% indicating generally depleted conditions across the study area (Figure 5, Table 2). Critical deficiency (< 1.5% organic matter) affected 67.6% of sampled locations, directly contributing to poor soil structure, low nutrient retention capacity, and reduced biological activity. Very low, low, and moderate levels covered 789.59 km² (29.7%), 1,008.15 km² (37.9%), and 542.07 km² (20.4%) respectively.

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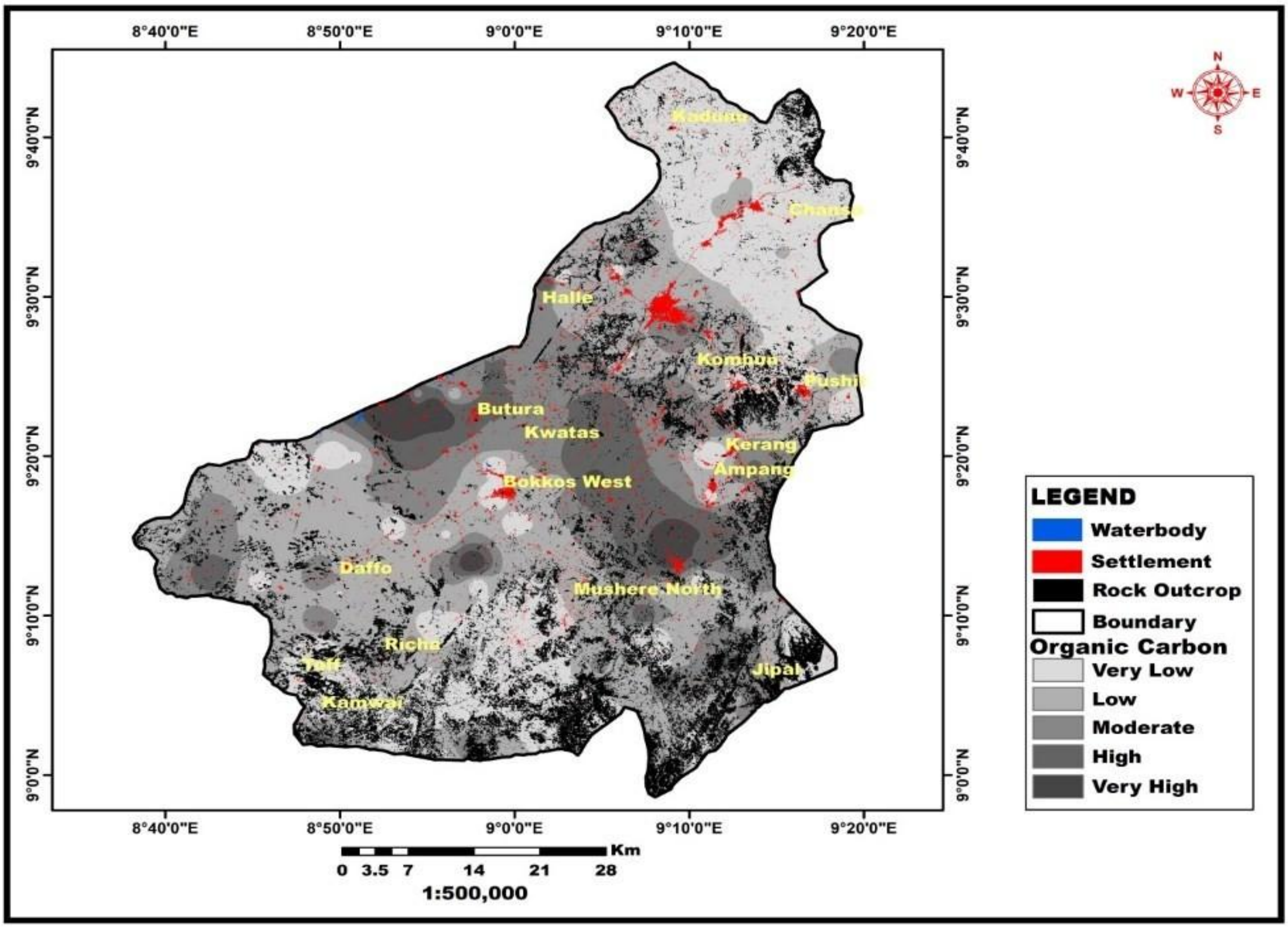

Figure 5: Spatial distributions of Organic Matter (%) for Mangu and Bokkos LGAs

Table 2: Organic matter distribution and carbon stock estimates

Organic Matter Class	OM Range (%)	Area (km²)	Coverage (%)	Estimated C Stock (tons C/ha)**
Very Low	0.20-0.89	789.59	29.7	8-12
Low	0.89-1.19	1,008.15	37.9	12-16
Moderate	1.19-1.52	542.08	20.4	16-22
High	1.52-2.06	251.98	9.5	22-30
Very High	2.06-3.47	64.86	2.4	30-45
Total		**2,656.65**	**100.0**	

**Based on soil bulk density 1.35 g/cm³ and 30cm depth

Spatial patterns mirrored pH distribution, with elevated organic matter concentrated in central volcanic zones, particularly around Kerang, Ampang, Kwatas, and Daffo. This correlation reflects both inherent soil properties (basaltic soils retain organic matter more effectively than sandy granitic soils) and historical land management (volcanic areas have traditionally received more crop residues and occasional manure applications). Notably, the most severely depleted areas (< 0.5% OM) occurred in intensively cultivated granitic zones of northern Bokkos and eastern Mangu, where continuous cropping without organic inputs has progressively degraded soil quality.

4.4 Nitrogen Deficiency Patterns

Total nitrogen distribution demonstrated critical deficiency across 83.2% of the study area, with concentrations ranging from 0.01% to 0.58% (mean 0.064 ± 0.038%) (Figure 6, Table 3). This severe nitrogen limitation represents the single most important nutrient constraint to potato production in the region. Very low and low nitrogen levels covered 1,132.49 km² (42.6%) and 1,078.12 km² (40.6%) respectively.

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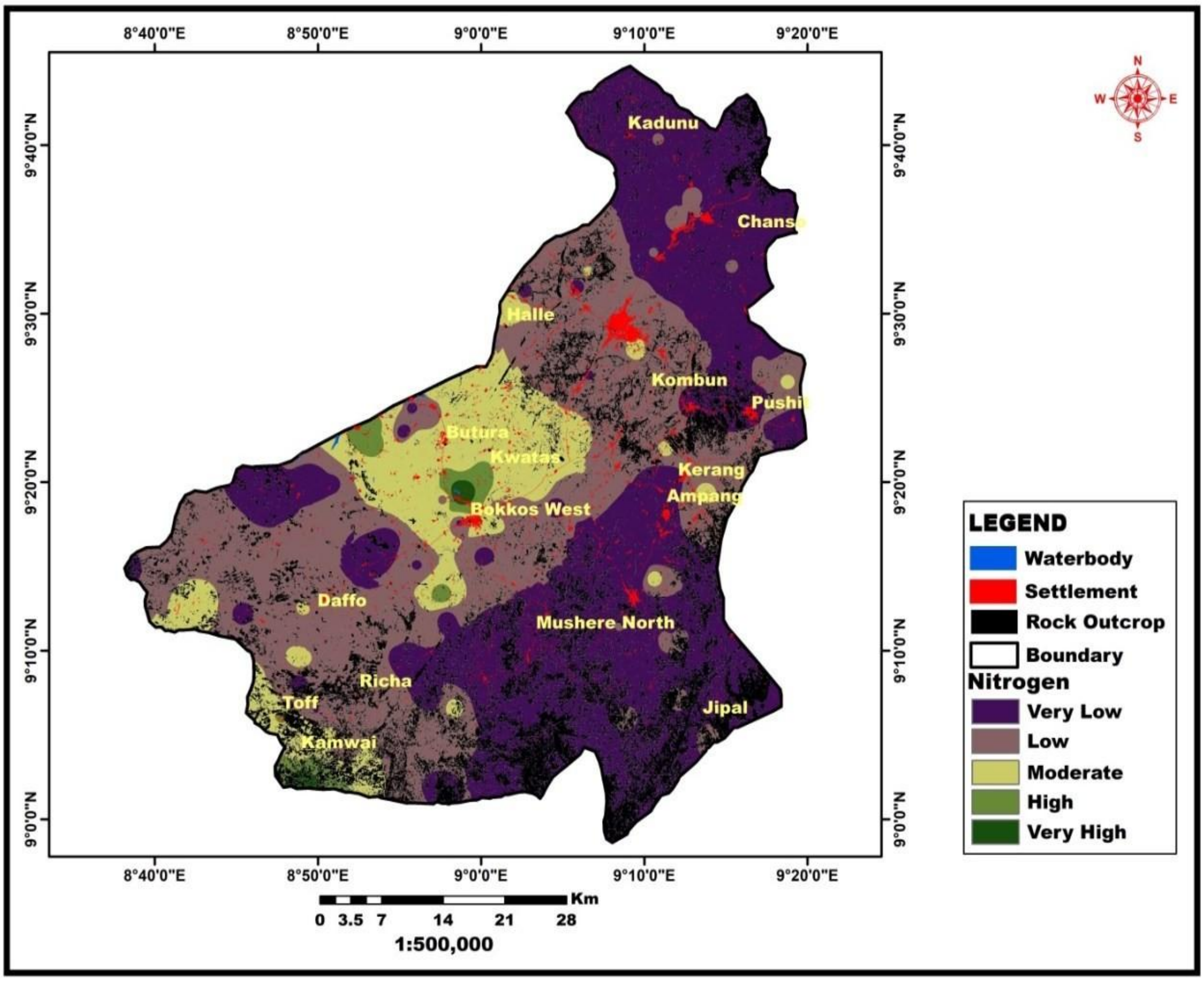

Figure 6: Spatial distributions of Total Nitrogen (%) for Mangu and Bokkos LGAs Table 3: Total nitrogen distribution and fertilizer nitrogen equivalents

Nitrogen Class	N Range (%)	Area (km²)	Coverage (%)	Supplemental N Required (kg/ha)***
Very Low	0.01-0.06	1,132.49	42.6	150-200
Low	0.06-0.08	1,078.12	40.6	100-150
Moderate	0.08-0.14	394.14	14.8	50-100
High	0.14-0.29	43.55	1.6	0-50
Very High	0.29-0.58	8.35	0.3	None required
Total		**2,656.65**	**100.0**	

***Estimated for potato production (target 20-25 tons/ha) after accounting for soil nitrogen mineralization

The strong positive correlation between organic matter and total nitrogen ($r^2 = 0.87$, $p < 0.001$) confirms that nitrogen depletion stems primarily from organic matter degradation under intensive cultivation. Areas with very low nitrogen (< 0.06%) corresponded almost entirely with severely depleted organic matter zones, suggesting that sustainable nitrogen management must address underlying organic matter deficits rather than relying solely on inorganic fertilizers. Higher nitrogen concentrations were concentrated in central portions of both LGAs, particularly in areas with basaltic parent materials and volcanic ash deposits.

4.5 Phosphorus Availability and Fixation Issues

Available phosphorus ranged from 3.68 to 23.24 mg/kg (mean 9.87 ± 4.23 mg/kg), with 55.6% of the study area exhibiting deficient to very deficient levels (< 10 mg/kg) according to Bray-1 extraction (Figure 7, Table 4). This widespread phosphorus limitation reflects both inherent low phosphorus in parent materials and severe fixation in acidic soils. Very low and low phosphorus levels were distributed across 734.25 km² (27.6%) and 744.39 km² (28.0%) respectively.

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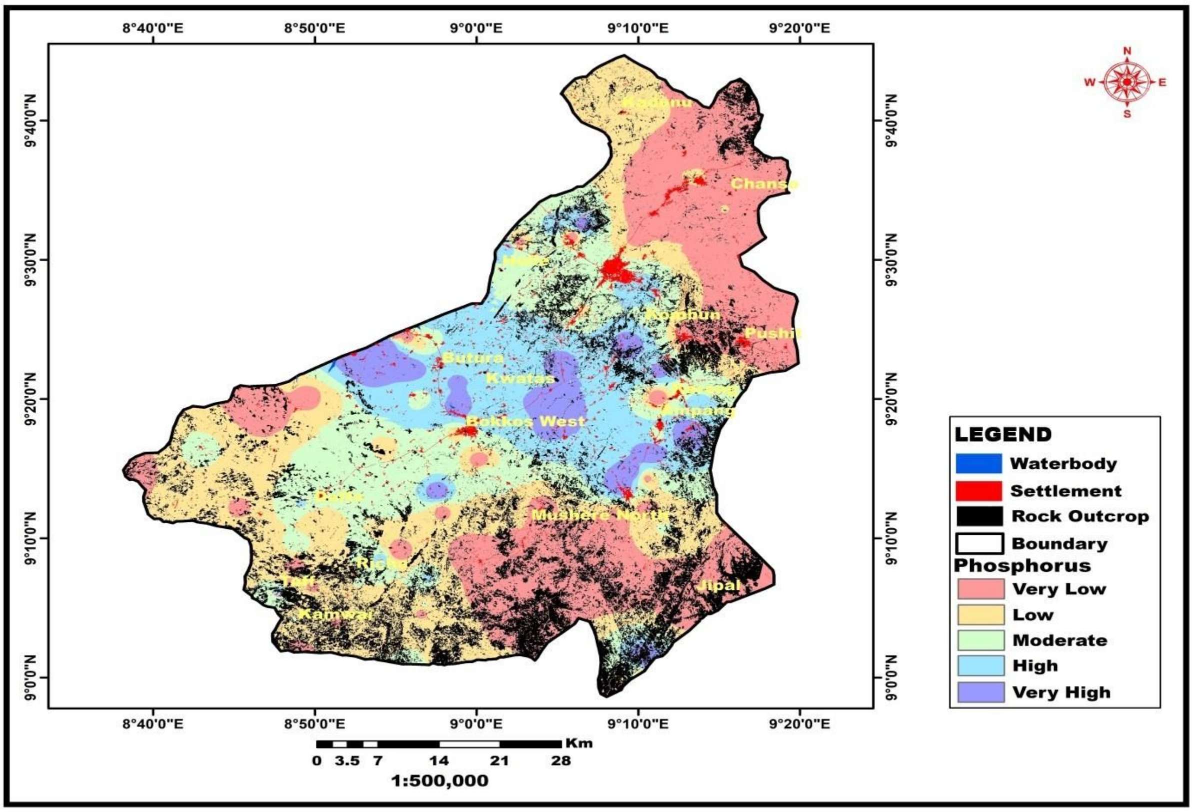

Figure 7: Spatial distributions of soil Phosphorus (mg/kg) for Mangu and Bokkos LGAs

Table 4: Available phosphorus distribution and fertilizer requirements

Phosphorus Class	**P Range (mg/kg)**	**Area (km²)**	**Coverage (%)**	**P_2O_5 Fertilizer Required (kg/ha)******
Very Low	3.69-6.83	734.25	27.6	80-120
Low	6.83-8.91	744.39	28.0	60-80
Moderate	8.91-11.28	578.40	21.8	40-60
High	11.28-14.05	443.82	16.7	20-40
Very High	14.05-23.25	155.78	5.9	0-20
Total		**2,656.65**	**100.0**	

****Recommendations account for expected fixation rates in acidic soils (50-70% of applied P)

The geographic distribution of phosphorus deficiency strongly correlated with soil acidity patterns ($r^2 = 0.72$, $p < 0.001$), confirming that low pH exacerbates phosphorus unavailability through fixation by iron and aluminium oxides. Statistical analysis revealed that soils with pH < 5.0 averaged only 6.2 mg/kg available phosphorus, compared to 13.8 mg/kg in soils with pH 5.5-7.0, despite similar total phosphorus contents. This finding emphasizes that lime application must precede or accompany phosphorus fertilization in acidic zones to achieve efficient phosphorus utilization. The central volcanic corridor again demonstrated superior phosphorus status, with 68% of this zone exhibiting moderate to high availability, particularly around Kerang, Ampang, Kwatas, and Daffo.

4.6 Potassium Status and Management Implications

Exchangeable potassium showed the most favourable nutrient status, ranging from 0.10 to 0.75 cmol/kg (mean 0.31 ± 0.12 cmol/kg), with 51.5% of the study area exhibiting moderate to very high levels (Figure 8, Table 5).

This relatively better potassium availability reflects abundant potassium-bearing minerals in both granitic (orthoclase feldspar, biotite) and basaltic (pyroxene, hornblende) parent materials. Moderate levels occupied 891.21 km² (33.5%), while low levels covered 868.09 km² (32.7%).

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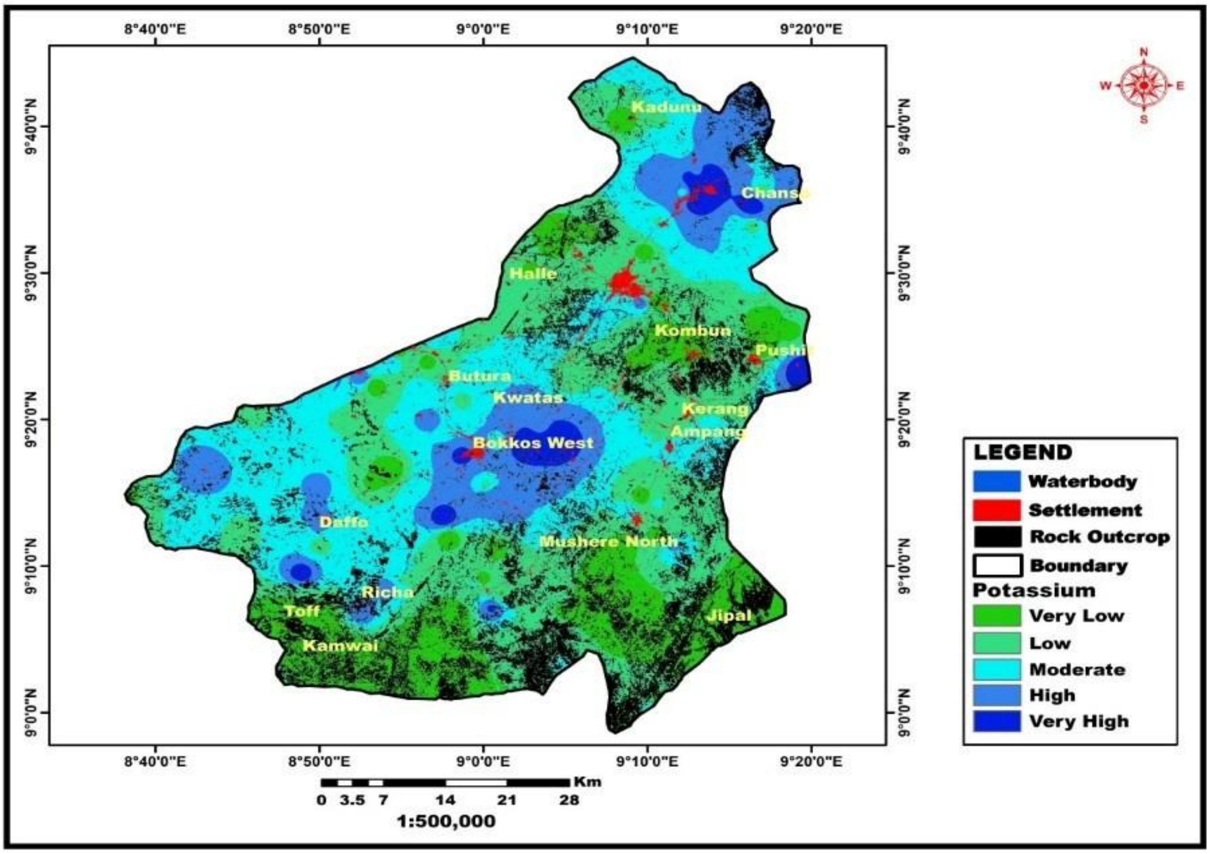

Figure 8: Spatial distributions of Potassium (cmol (+)/kg) for Mangu and Bokkos LGAs

Table 5: Exchangeable potassium distribution and supplementation needs

Potassium Class	**K Range (cmol/kg)**	**Area (km²)**	**Coverage (%)**	**K_2O Fertilizer Required (kg/ha)*******
Very Low	0.10-0.22	419.49	15.8	100-150
Low	0.22-0.28	868.09	32.7	60-100
Potassium Class	**K Range (cmol/kg)**	**Area (km²)**	**Coverage (%)**	**K_2O Fertilizer Required (kg/ha)*******
Moderate	0.28-0.33	891.21	33.5	30-60
High	0.33-0.43	395.81	14.9	0-30
Very High	0.43-0.75	82.05	3.1	None required
Total		**2,656.65**	**100.0**	

*****Potassium recommendations consider luxury consumption by potato (high K demand) and expected leaching in sandy soils

Despite generally adequate potassium levels, potato's exceptional potassium demand (160-200 kg K_2O/ha for high-yielding crops) necessitates supplementation across most production areas. Spatial patterns revealed lower potassium concentrations in intensively cropped areas, particularly in sandy loam soils where leaching losses compound crop removal. These zones (approximately 1,288 km² or 48.5% of total area) would benefit from annual potassium applications to maintain adequate availability and prevent progressive depletion under continuous potato cultivation.

4.7 Integrated Soil Fertility Management Zones

Overlay analysis integrating all measured soil parameters delineated three distinct nutrient management zones with contrasting fertility characteristics and amendment requirements (Table 6):

Zone A - High Fertility Volcanic Belt (1,197 km², 45.1%): Encompasses central areas of both LGAs, particularly around Kerang, Ampang, Kwatas, and Daffo. Characterized by pH 5.7-7.0, organic matter 1.5-3.5%, moderate to high N-P-K levels. Requires minimal soil amendments—maintenance fertilization (80-100 kg N,

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40-60 kg P_2O_5, 60-80 kg K_2O per hectare) sufficient for target yields. Represents priority zone for production intensification and technology adoption given favourable baseline conditions.

Zone B - Moderate Fertility Transition Areas (930 km², 35.0%): Surrounds volcanic core, predominantly on granitic-derived soils with sandy clay loam to sandy loam textures. pH 5.0-5.7, organic matter 0.9-1.5%, low to moderate nutrients. Requires moderate interventions: lime application (1-2 tons/ha), enhanced fertilization (120150 kg N, 60-80 kg P_2O_5, 80-100 kg K_2O per hectare), organic matter supplementation (3-5 tons compost/ha). Cost-benefit analysis indicates highest economic returns from targeted investments in this zone due to responsive soils and moderate input requirements.

Zone C - Severely Degraded Peripheral Areas (530 km², 20.0%): Distributed across northern Bokkos and eastern Mangu, primarily on intensively farmed granitic soils. pH < 5.0, organic matter < 0.9%, critically deficient N-P-K. Requires intensive rehabilitation: heavy lime application (2-4 tons/ha), substantial organic matter incorporation (5-10 tons/ha), high fertilizer rates (150-200 kg N, 80-120 kg P_2O_5, 100-150 kg K_2O per hectare). Multi-year investment needed; short-term economics unfavourable but long-term rehabilitation essential for sustainable production.

Table 6: Comparative characteristics and management prescriptions for soil fertility zones

Parameter	**Zone A (Volcanic)**	**Zone B (Transition)**	**Zone C (Degraded)**
Area (km²)	1,197	930	530
Mean pH	6.2	5.4	4.7
Mean OM (%)	2.1	1.2	0.7
Mean N (%)	0.121	0.073	0.038
Mean P (mg/kg)	14.8	9.2	5.6
Parameter	**Zone A (Volcanic)**	**Zone B (Transition)**	**Zone C (Degraded)**
Mean K (cmol/kg)	0.38	0.29	0.19
Lime requirement (t/ha)	0	1.5	3.0
N fertilizer (kg/ha)	90	135	175
P_2O_5 fertilizer (kg/ha)	50	70	100
K_2O fertilizer (kg/ha)	70	90	125
Organic matter (t/ha)	2	4	8
Total input cost (NGN/ha)	145,000	235,000	385,000
Expected yield (t/ha)	22-25	18-22	12-16
Net return (NGN/ha)******	485,000	395,000	185,000
Benefit-cost ratio	4.3	2.7	1.5

******Based on farm gate price NGN 350/kg and production costs excluding land/labour **5.**

DISCUSSION

5.1 Soil Nutrient Heterogeneity and Precision Management Implications

The pronounced spatial variability documented in this study demonstrates that conventional uniform fertilizer recommendations are agronomically suboptimal for potato production systems in Plateau State. Coefficient of variation values exceeding 40% for pH, organic matter, nitrogen, and phosphorus confirm high heterogeneity across relatively short distances (2-5 km), necessitating zone-specific rather than blanket management approaches. This heterogeneity stems from multiple interacting factors: geological parent material diversity (granitic versus basaltic origins), topographic influences on erosion and deposition patterns, historical land management intensity (years under cultivation, input levels), and proximity to volcanic activity zones. The delineation of three distinct management zones provides a practical framework for implementing precision agriculture concepts without requiring sophisticated variable-rate application technologies beyond the reach of smallholder farmers.

5.2 Geological Controls on Soil Fertility Patterns

The strong correlation between geological parent materials and soil fertility patterns provides predictive power for extrapolating findings beyond sampled locations (Buol et al., 2011; Jenny, 1941). Basaltic-derived soils consistently demonstrated 1.0-1.5 pH units higher values, 40-60% greater organic matter content, and 2-3 times higher available phosphorus compared to granitic counterparts within the same climatic zone. These differences reflect fundamental mineralogical contrasts: basalts rich in calcium-bearing plagioclase and ferro-magnesium minerals weather to release basic cations and nutrients, while granites dominated by quartz and potassium feldspar produce acidic, nutrient-poor soils (Certini et al., 2004; Opfergelt et al., 2012). The volcanic fertility corridor spanning Kerang-Ampang-Kwatas-Daffo (approximately 1,200 km²) represents a strategic agricultural asset that should receive priority infrastructure investments to maximize economic returns from naturally superior production potential.

5.3 Addressing Soil Acidity Through Strategic Liming Programs

The predominance of acidic soils (77% of study area) represents the foundational constraint that must be addressed before other nutrient interventions can achieve full effectiveness. Aluminium toxicity in very strongly acidic soils (pH < 4.8, covering 850 km²) directly damages potato root systems, reducing nutrient uptake capacity regardless of fertilizer applications. Additionally, phosphorus fixation intensifies below pH 5.5, rendering expensive phosphorus fertilizers largely unavailable to crops. Strategic liming offers multiple benefits beyond pH adjustment: enhanced nitrogen mineralization from organic matter, improved phosphorus availability, increased cation exchange capacity, reduced aluminium and manganese toxicity, and enhanced beneficial microbial populations. Implementation challenges include lime availability, application logistics, and farmer awareness, requiring policy interventions focused on subsidizing lime costs, establishing regional distribution hubs, and conducting demonstration trials.

5.4 Integrated Organic-Inorganic Nutrient Management

The severe organic matter depletion (67.6% of area < 1.5% OM) and its strong correlation with nitrogen deficiency ($r^2 = 0.87$) indicate that sustainable fertility improvement requires integrated organic-inorganic approaches rather than relying solely on mineral fertilizers. Organic matter provides multiple functions that synthetic fertilizers cannot replicate gradual nutrient release synchronized with crop demand, improved soil structure and water retention, enhanced cation exchange capacity, buffering against pH extremes, and fostering beneficial soil biological communities. Practical organic matter sources for smallholder systems include composted crop residues, livestock manure, green manures in rotation, and biochar from crop waste pyrolysis. Economic analysis suggests that compost application (5 tons/ha at NGN 5,000/ton) combined with reduced inorganic nitrogen rates (30% reduction) can maintain yields while improving long-term soil quality.

5.5 Economic Prioritization and Policy Recommendations

Cost-benefit analysis reveals stark differences in investment returns across fertility zones, providing clear guidance for prioritizing soil improvement efforts. Zone B (moderate fertility transition areas) offers the highest benefit-cost ratio of 2.7:1, suggesting that extension resources and policy incentives should prioritize these 930 km² where moderate investments can generate substantial yield improvements. Key policy recommendations include: transitioning input subsidies toward zone-specific packages, establishing district-level soil testing laboratories with mobile units, training extension agents in precision agriculture concepts, promoting community-based composting enterprises, and establishing market systems rewarding high-quality potato production through price premiums.

CONCLUSIONS

This comprehensive geospatial assessment reveals pronounced spatial heterogeneity in soil fertility across Plateau State's primary potato production zone, with critical implications for agricultural productivity and sustainability. Soil acidity affects 77% of farmlands, nitrogen deficiency encompasses 83.2%, phosphorus limitations span 55.6%, while potassium shows relatively favourable status across 51.5% of the study area. This multi-nutrient constraint pattern reflects complex interactions between parent geology, intensive cultivation history, and inadequate nutrient replenishment practices.

Delineation of three distinct management zones—high fertility volcanic belt (45%), moderate fertility transition areas (35%), and severely degraded peripheral regions (20%)—provides an actionable framework for implementing precision nutrient management. Zone-specific recommendations optimize input use efficiency while maximizing economic returns, with benefit-cost ratios ranging from 4.3:1 in high fertility zones to 1.5:1 in degraded areas requiring intensive rehabilitation.

Strategic interventions must prioritize: (1) widespread liming programs addressing foundational acidity constraints; (2) integrated organic-inorganic nutrient management building soil organic matter while supplying crop nutrients; (3) efficient phosphorus management combining liming, appropriate sources, and precision placement; (4) adequate potassium supply matching potato's exceptional demand; and (5) soil conservation practices preventing further degradation.

Implementation of zone-specific precision management strategies documented in this study could potentially increase potato yields by 40-60% while reducing input costs by 25-30% through targeted application. These improvements would significantly enhance farmer profitability, strengthen food security, and promote environmental sustainability through optimized resource use. However, realizing this potential requires supportive policy frameworks addressing input availability, farmer capacity building, market linkages, and research investments. This research establishes baseline soil fertility conditions and provides prescription maps enabling immediate action by agricultural stakeholders, with approaches readily transferable to other crop systems and regions across sub-Saharan Africa.

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ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

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