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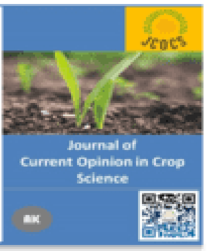

RESEARCH ARTICLE

Effect of triple superphosphate (TSP) fertilizer rates on cowpea growth and yield under irrigation: a case of lowland area, Sokoto state, Nigeria

Abdulrasheed Aliyu[1,3*], Donald Kelechi Madukwe[1], Ifunanya Ngozika Meka[1], Kehinde Afeez Ojeniyi[1,2*]

[1]OCP Africa, Agronomy Department, Abuja, Nigeria.
[2]Southern Illinois University, Department of Forestry, Carbondale-Illinois, USA.
[3]Muhammed VI Polytechnic University, Department of Agribusiness Innovation, Morocco.

Edited by:

Dr M. Murugan, PhD., Kerala Agricultural University, Keralam, India.

Reviewed by:

Dr Shimirwa, University of Technology and Arts of Byumba, Byumba, Rwanda; Dr Stevenson Pelegy Noah, Sokoine University of Agriculture, Morogoro, Tanzania.

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*Corresponding author e-mail address: abdulrasheed.aliyu@um6p.ma (Abdulrasheed Aliyu); kehindeafeez.ojeniyi@siu.edu (Kehinde Afeez Ojeniyi)

ABSTRACT

Generic fertilizer recommendations often fail to reflect the spatial heterogeneity of soils and the varietal specificity of crop nutrient requirements, thereby limiting yield potential and nutrient-use efficiency. This study evaluated the response of two improved cowpea varieties to different rates of triple superphosphate (TSP) fertilizer under irrigated lowland conditions in order to develop site- and variety-specific phosphorus management recommendations. Field experiments were conducted during the 2025 dry season across three lowland environments using a split-plot arrangement within a randomized complete block design with three replications. Treatments consisted of different TSP Fertilizer rates (0, 20, 40, 60, and 80 kg ha^{-1}) applied as triple superphosphate. While uniform basal applications of nitrogen and potassium were supplied to isolate phosphorus effects at 20 kg N ha^{-1} and 25 kg K_2O ha^{-1} respectively. Data on crop growth, yield components, grain yield, and soil properties were collected and analyzed. Results showed that varietal performance and yield response to phosphorus varied across locations. One variety (SAMPEA -18) consistently exhibited stronger vegetative growth and higher grain yield than the other (SAMPEA 20-T). Moderate phosphorus application (20–40 kg P ha^{-1}) generally produced the best yield performance, while both phosphorus deficiency and excessive application reduced productivity. SAMPEA 18 is the recommended variety for irrigated cowpea production at all P levels in this region, and a sustainable P management framework for this agroecological zone must integrate pre-season soil testing, in-season P budgeting calibrated to residual soil P, and multi-season evaluation of legacy P effects to maximize crop yield and economic return.

Keywords: cowpea, lowland irrigation, phosphorus use efficiency, SAMPEA varieties, TSP rates, yield.

INTRODUCTION

Cowpea (*Vigna unguiculata*) is an essential leguminous crop widely cultivated in sub-Saharan Africa, particularly in Nigeria, where it serves as a major source of protein for humans and livestock. In 2014, cowpea was cultivated on an estimated 12.3 million hectares in Africa, with approximately 10.6 million hectares in West Africa, particularly in Niger, Nigeria, Burkina Faso, Mali, and Senegal (FAOSTAT, 2016). The world's estimated annual cowpea production is put at 5.4 million tons, with Africa producing 5.2 million. Nigeria is the largest producer, accounting for approximately 3.6 million metric tons annually, yet national demand is estimated at 5 million metric tons, leaving a shortfall of over 1.4 million metric tons (IITA, 2021). In Nigeria, cowpea plays an important role in food and nutritional security, specifically in the semi-arid Sudan and Guinea savanna regions where production is concentrated. Beyond its nutritional value, cowpea is known for its ability to fix atmospheric nitrogen, enhance soil fertility, and support sustainable agricultural practices. Despite its agronomic and nutritional importance, cowpea productivity in Nigeria remains relatively low due to several constraints, among which soil nutrient deficiencies, particularly phosphorus (P) (Alhassan, 2021). Phosphorus is essential for nodulation, root development, energy transfer in plants, and its deficiency can significantly reduce cowpea productivity.

Nwoke et al. (2004) reported P levels as low as 2 mg kg^{-1} in Nigerian savannah soils, while Kamara et al. (2017) found that P concentrations fell below the critical threshold of 7 mg kg^{-1} (Mehlich-3 extractable P) in 93% and 92% of surveyed fields in the Sudan and northern Guinea savannahs, respectively. Intensive land use and insufficient fertilizer inputs have further exacerbated this nutrient depletion, making phosphorus management a central concern for optimizing cowpea productivity in these environments (Olusegun et al., 2020). Prior studies have investigated various phosphorus sources and integrated nutrient management strategies for cowpea in savanna environments. Research by Tanko et al. (2021) demonstrated that phosphorus application significantly influenced cowpea yield components under different agroecological conditions and emphasized the need for site-specific fertilizer recommendations tailored to soil types and crop requirements. Triple Superphosphate (TSP), a concentrated phosphorus fertilizer containing approximately 46% P_2O_5, has been recognized for its potential to correct P deficiencies and enhance legume performance. However, the optimum rate of TSP application that balances crop productivity with economic returns remains insufficiently resolved. Empirical evidence suggests that indiscriminate or excessive TSP application may not translate to proportional yield gains and can negatively affect input cost efficiency and environmental sustainability (Grace et al., 2016).

Even though the importance of P in enhancing legume productivity has been established, information on the optimum rates of TSP for different cowpea varieties under the specific soil and environmental conditions of the Sudan savanna, particularly under irrigated lowland production systems remains limited. This lack of location-specific recommendations often leaves smallholder farmers uncertain about the most efficient fertilizer investment, contributing to either under-application or excessive use of phosphorus fertilizers. Consequently, cowpea production remains largely seasonal and below its potential in many parts of northern Nigeria. Therefore, this study was conducted to evaluate the effect of different rates of TSP on the growth and yield of selected cowpea varieties cultivated on lowland soils in Sokoto State, Nigeria. The findings are expected to provide location-specific recommendations for optimal phosphorus fertilizer management that can enhance cowpea productivity, improve fertilizer use efficiency, and support sustainable crop production in the Sudan savanna zone.

MATERIALS AND METHODS

Study site description

The experiment was conducted during the 2025 dry season at three lowland irrigation sites in Sokoto State, Nigeria. These were: (i) the UDUS Fadama Teaching and Research Farm (lat. 13.107°N, long. 5.208°E); (ii) the Sokoto-Rima Floodplain Farm, Wamakko (lat. 13.041°N, long. 5.101°E); and (iii) Colony-Goronyo (lat. 13.497°N, long. 5.675°E). These sites represent major cowpea-producing lowland environments in the state. They were selected based on the prevalence of cowpea cultivation, measurable soil phosphorus deficiency, availability of water for dry-season irrigation, and logistical accessibility. All three sites lie within the Sudan savanna agroecological zone of Nigeria, characterized by a unimodal rainfall pattern with a wet season from June to September and a dry season from November to March. Mean annual rainfall is approximately 600 mm and mean annual temperature is approximately 38°C (www.weatherspark.com).

Pre-planting soil samples were collected from each site at a 0–20 cm depth using an auger. Samples were composited (two composite samples per site), air-dried, and analyzed at the OCP Africa Soil Testing Laboratory, Kaduna, Nigeria. The parameters determined included soil pH (1:2.5 soil–water suspension), organic matter (OM) by Walkley–Black wet oxidation, and total nitrogen (N) by Kjeldahl digestion. Available P was determined by Bray-1 extraction with colorimetric determination. Exchangeable potassium (K), calcium (Ca), and magnesium (Mg) were measured by ammonium acetate extraction with atomic absorption spectrophotometry. Cation exchange capacity (CEC) was determined by ammonium acetate at pH 7.0. Soil texture was determined using the hydrometer method (Bouyoucos). The resulting baseline soil characterization is summarized and discussed in the Results section.

Experimental design and treatments

The field experiment was a 6 × 2 factorial arranged in a split-plot design within a randomized complete block design (RCBD), replicated three times at each of the three locations. The study consisted of six distinct treatments: five incremental rates of TSP and one representative Farmer's Practice (FP). To ensure the internal validity of the P rate response, N and K were balanced across all five TSP treatments to meet the recommended nutrient requirements of cowpea, isolating P as the primary limiting variable. The main plot factor was TSP phosphorus rate (five levels), and Farmer's practice, and the sub-plot factor was cowpea variety (two levels), giving 12 treatment combinations per block and 36 experimental units per location (108 units total across all three sites). Each sub-plot measured 4 m × 3 m. The two cowpea varieties evaluated were SAMPEA 18 and SAMPEA 20-T, both improved varieties sourced from the Institute for Agricultural Research (IAR), Zaria, Nigeria. In addition to the variable TSP rates, a uniform basal application of 20 kg ha^{-1} N (as urea) and 25 kg ha^{-1} K_2O (as muriate of potash) was applied to all plots except for $F1_1$ (control), ensuring that phosphorus remained the principal differentiating nutrient across fertilized treatments and F_6. The farmer's practice (F6) treatment involved the application of decomposed cow dung at a rate of 10 t/ha, reflecting the local agronomic standard practice of 85 percent of the farmers within the study sites. Before application, the cow dung was analyzed for total N, P, and K content.

Treatment description

All treatments that received mineral fertilizer were given the same amount of nitrogen and potassium 20 kg N ha^{-1} and 25 kg K ha^{-1} *(in K_2O form)*, so that any differences observed between them could be attributed to phosphorus alone. The only treatment that did not follow this uniform pattern was F6, which represented what a typical farmer in the area would ordinarily do.

F_1 served as the control and received no phosphorus at all. F_2, F_3, F_4, and F_5 were each given increasing amounts of mineral phosphorus, at 20, 40, 60, and 80 kg P ha^{-1}, representing low, moderate, recommended, and high application rates, respectively. F_6, the farmer's practice treatment, used cowdung instead of mineral fertilizer as the nutrient source. Because cowdung is an organic material, its nitrogen, phosphorus, and potassium content was not fixed at a predetermined rate but was instead determined through laboratory analysis, which returned an N-P-K equivalent of 44-19-68 kg ha^{-1} in available nutrient forms

Crop Management Practices

In the cropping season before the experiment was established, rice was cultivated at the first site, whereas Tomatoes and wheat were grown at the second and third sites, respectively. Fields were hand-cleared, thoroughly levelled, and ensured to be debris-free before planting to provide uniform soil conditions. Irrigation was provided using a surface furrow/basin method, applied at a rate of 350 litres per plot every 7 days at approximately 75% field capacity, with guidance by tensiometer readings. Water applications were metered to ensure each plot received the same volume. Seeds from two improved cowpea varieties (SAMPEA 18 and SAMPEA 20-T) sourced from the Institute for Agricultural Research, Zaria, were planted at a spacing of 70 × 30 cm, with two seeds sown per hole at a depth of 5 cm. Planting operations were synchronized with scheduled irrigation to facilitate optimal seedling emergence and establishment. Manual weeding was conducted at 2, 4, and 6 weeks after sowing (WAS) to manage weed pressure throughout the critical stages of crop development. Pesticides were applied at both flowering and pod-filling stages to prevent pest infestations and minimize potential yield losses. Weekly scouting was performed throughout the trial to monitor pest and disease occurrence, with no diseases recorded or observed in any treatment during the study period. TSP fertilizer was band-applied at sowing according to the designated treatment rate, in addition to a uniform basal application of nitrogen and potassium fertilizers across all plots except for those following the local farmer practice, where it was applied during land preparation

Measured Observations

Growth performance was evaluated using several parameters: plant height (cm, measured from soil surface to the apical bud), number of branches per plant, number of leaves per plant, leaf area, leaf area index, number of nodules, and days to reach 50% flowering. These growth metrics were recorded at 2, 4, and 6 weeks after sowing to assess the effects of treatment on crop development. Five randomly selected and tagged plants within the net plot area of each sub-plot.

Leaf area (LA, cm^2) was estimated using the non-destructive formula proposed by Adeyemi et al. (2020): $LA = L \times W \times 0.75$ where L is the maximum leaf length (cm) and W is the maximum leaf width (cm), measured on the third fully expanded leaf from the apex of each tagged plant, and 0.75 is a correction factor for cowpea leaf shape. The leaf area index (LAI) was calculated as: $LAI = \text{Total leaf area per plant } (cm^2) \times \text{Plant population density } (\text{plants } m^{-2})$

Nodule count was determined at 6 WAS by carefully uprooting the five tagged plants per sub-plot, gently washing the roots under running water to avoid nodule detachment, and counting all intact, visible nodules on the entire root system. The mean nodule count per plant was calculated from the five sampled plants. Days to 50% flowering was recorded as the number of days from planting to the date on which at least 50% of plants in the net plot area had produced at least one open flower, observed by daily inspection of each sub-plot. Yield-related evaluations focused on the number of pods per plant, number of seeds per pod, 100-seed weight, total grain yield, and haulm yield. These components were determined at harvest to quantify productivity improvements due to experimental treatments. The total grain yield at less than 15% moisture content was measured from each plot using a weighing balance, while the 100-grain weight was measured using a scale. The number of pods/plants was taken from five tagged plants within the net plots.

Number of Pods per Plant:

$$\text{Average pods per plant} = \frac{\sum \text{Pods counted from sampled plants}}{\text{Number of sampled plants}}$$

$$\text{Average seeds per pod} \frac{\sum \text{Seeds counted in sampled pods}}{\text{Number of sampled pods}}$$

Grain Yield (t/ha):

$$\text{Grain yield} = \frac{\text{Weight of grains from sampled plants (kg)} \times 10{,}000}{\text{Area sampled } (m^2)} * 1000$$

Haulm Yield (t/ha):

$$\text{Haulm yield} = \frac{\text{Weight of above-ground biomass excluding grains (kg)} \times 10{,}000}{\text{Area sampled } (m^2)} * 1000$$

Soil Analysis

Soil samples collected before and after treatment application were analyzed at the OCP Africa Fertilizers Nigeria Limited laboratory (Kaduna Bulk Blending Plant) using internationally standardized methods to determine key physical and chemical characteristics such as pH, OM content, available P, N, K, and texture. Six composite soil samples (two per site) were collected at a depth of 0-20 cm using an auger. Samples were placed in transparent Ziplock bags and air-dried for one week. The pH-H_2O was determined according to ISO 10390:2021 by suspending the samples in distilled water at a 1:5 (m/v) soil-to-water or manure-to-water ratio, shaking for 1 h, equilibrating, and measuring potentiometrically using a calibrated pH meter equipped with a glass electrode and a temperature-compensated reference electrode. Electrical conductivity (EC) was measured according to ISO 11265:1994 on the same 1:5 (m/v) water extract used for pH, with conductivity recorded at 25 °C (temperature-corrected) using a calibrated conductivity meter with a conductivity cell. Total N in soil samples was determined according to ISO 13878:1998 (dry combustion/Dumas method), where finely ground samples were combusted at >900 °C in pure oxygen in the presence of a catalyst; nitrogen oxides were reduced to N_2 and detected by thermal conductivity. Available P in soil was extracted using the Bray II method (0.03 M NH_4F + 0.1 M HCl) at a 1:10 (m/v) ratio with 5 min shaking, followed by filtration. The extract was reacted with ammonium molybdate and ascorbic acid to form the molybdenum-blue complex, and absorbance was measured at 880 nm using a UV–Vis spectrophotometer or automated flow analyzer. Exchangeable K in soil was extracted according to ISO/TS 22171:2023 using 1 M neutral ammonium acetate (pH 7) at a 1:10 (m/v) ratio, followed by filtration/centrifugation. P concentration in the extract was quantified by flame emission spectroscopy or inductively coupled plasma optical emission spectrometry (ICP-OES). Organic matter was calculated according to ISO 10694:1995 from organic carbon content determined by dry combustion using an elemental analyser. Organic carbon values were multiplied by the van Bemmelen factor (1.724). The Soil texture was determined according to ISO 11277:2020. Samples were dispersed with sodium hexametaphosphate; the sand fraction was separated by wet sieving, and silt plus clay fractions were quantified by sedimentation (pipette or hydrometer method) in a settling column. Particle-size percentages were calculated from the mass fractions after oven-drying.

Manure Analysis

Dry samples of farmyard manure commonly used by farmers in the sites were collected in plastic bags. Representative composite samples were obtained from several points within the manure heap to ensure uniformity, labelled, and were analyzed at the OCP Africa Fertilizers Nigeria Limited laboratory (Kaduna Bulk Blending Plant) using an internationally standardized method. Manure samples were first digested using a mixture of perchloric acid and hydrochloric acid in a ratio of 1:3 ($HClO_4$: HCl) at 200 °C until near dryness. The digest was then diluted with distilled water and used for the determination of chemical properties. Soil reaction ($pH–H_2O$) was measured in a manure water suspension using a pH meter. Total N in the digested cow-dung manure was determined according to AOAC 993.13 using an automated combustion nitrogen analyzer with thermal conductivity detection. Total P in the acid-digested cow-dung manure was determined according to AOAC 978.01 by automated spectrophotometry after colour development with molybdate-ascorbic acid. Total K in the acid-digested cow-dung manure was measured according to AOAC 983.02 by flame emission spectroscopy. Organic matter was calculated according to ISO 10694:1995 from organic carbon content determined by dry combustion (simultaneous with total N analysis). Organic carbon values were multiplied by the van Bemmelen factor (1.724).

Statistical Analysis

The data were subjected to analysis of variance (ANOVA) for a split-plot design arranged in a Randomized Complete Block Design. Phosphorus rate was assigned to the main plots, while variety was assigned to the sub-plots. Locations were treated as random effects. The statistical model used was:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_k + (\alpha\gamma)_{ik} + \varepsilon_{ijk}$$

where Y_{ijk} is the observed response; μ is the overall mean; α_i is the effect of P rate i; β_j is the effect of block (replication) j; $(\alpha\beta)_{ij}$ is the main-plot error; γ_k is the effect of variety k; $(\alpha\gamma)_{ik}$ is the P rate × variety interaction; and ε_{ijk} is the residual (sub-plot) error. Analyses were performed separately for each location and then combined across locations using a combined ANOVA with location as a random factor. Before ANOVA analysis, the normality of residuals was assessed using the Shapiro–Wilk test, while the homogeneity of variances was tested using Levene's test, and independence of observations was ensured through randomization. Where ANOVA indicated significant treatment effects ($P \leq 0.05$), means were separated using Fisher's Least Significant Difference (LSD) at the 5% significance level (Steel et al., 1997). All analyses were conducted in R (version 4.2; R Core Team, 2022) using the 'agricolae' package.

RESULTS

Nutrient Composition of Cow Dung Applied

The farmyard manure (cow dung) used in this study, based on analysis, showed it to be characteristically alkaline with a pH of 9.52, and total nitrogen content (14,420 mg/kg) was relatively high, suggesting a strong potential for nitrogen mineralization upon soil incorporation. Similarly, the phosphorus (3,798.57 mg/kg) and potassium (8,445.62 mg/kg) concentrations indicate that the manure was nutrient-rich, capable of supplying appreciable amounts of these macronutrients to the soil. The organic matter content of 34.57% further underscores the quality of the manure as a soil amendment, as high organic matter levels are associated with improved soil structure, water retention, and microbial activity.

Table 1. Physicochemical properties of the soil before treatment application and after harvest.

Sl No.	Sample Identification	pH-H_2O	EC	Total N	P	K	Organic Matter	Sand	Clay	Silt
			uS/cm	mg/kg	mg/kg	mg/kg	%	%	%	%
1	LOCN 1 BEFORE	6.64	180.40	900	26.49	282.53	1.35	2.68	10.45	86.87
2	LOCN 2 BEFORE	7.21	93.91	1020	34.29	342.73	2.11	65.93	3.08	30.99
3	LOCN 3 BEFORE	7.38	105.60	1080	39.02	503.67	2.06	51.09	4.31	44.60
4	LOCN 1 AFTER	8.08	1061.00	2230	150.82	1699.21	3.33	61.48	0.10	38.42
5	LOCN 2 AFTER	7.96	915.80	2150	169.37	1450.11	3.11	43.54	1.78	54.68
6	LOCN 3 AFTER	8.06	1129.00	2320	199.58	1565.52	3.23	40.08	1.20	58.72

Note, LOCN 1 BEFORE = Composite Soil Sample from Trial Location at Usmanu Danfodiyo University Sokoto Fadama Teaching and Research Farm after treatment application; LOCN 2 BEFORE = Composite Soil Sample from Trial Location at lowland area of Kwakkwalawa River, Wamakko, Sokoto after treatment application.

LOCN 3 BEFORE = Composite Soil Sample Trial Location at Colony area of Goronyo Dam Site, Sokoto after treatment application; LOCN 1 AFTER = Composite Soil Sample from Trial Location at Usmanu Danfodiyo University Sokoto Fadama Teaching and Research Farm after harvest; LOCN 2 AFTER = Composite Soil Sample from Trial Location at lowland area of Kwakkwalawa River, Wamakko, Sokoto after harvest; LOCN 3 AFTER = Composite Soil Sample Trial Location at Colony area of Goronyo Dam Site, Sokoto after harvest.

Variation in physicochemical soil properties

Table 1 revealed variations across locations before and after treatment application. Post-harvest analysis showed a sharp rise in pH at LOCN1 (6.64 to 8.08), increasing the risk of P fixation. EC increased significantly at LOCN2, indicating emerging salinity. Available P skyrocketed across all sites (from ~30 to 150–200 mg kg^{-1}), confirming fertilizer effectiveness but indicating a luxury consumption range by the end of the trial.

Plant Height, Number of leaves per plant, and Leaf Area Index

The effects of TSP application rate and cowpea variety on plant height, number of leaves per plant, and leaf area index (LAI) at six weeks after sowing (6 WAS) are presented in Table 2. TSP rate had no significant effect on any of these growth parameters at 2 or 4 WAS at any location (data not shown; $p > 0.05$ for all comparisons at those stages). Significant treatment effects emerged at 6 WAS. For plant height at 6 WAS, significant differences among TSP rates were detected at LOCN1 ($p = 0.0007$), LOCN2 ($p = 0.0007$), and LOCN3 ($p = 0.0007$). For SAMPEA 18, F4 (59.33 cm), F5 (57.67 cm), and F6 (58.33 cm) were statistically superior to F2 (53.33 cm) at LOCN1 but did not differ significantly from each other, indicating a plateau above F4. SAMPEA 20-T showed consistently lower plant heights than SAMPEA 18 across all rates and locations (31.33–37.00 cm vs 50.00–59.33 cm at LOCN1), and the increment associated with increasing TSP rate was smaller in magnitude. Leaf number at 6 WAS was significantly affected at LOCN1 ($p = 0.00904$) and LOCN3 ($p = 0.0621$) but not at LOCN2 ($p = 0.96013$). For SAMPEA 18 at LOCN1, F5 and F6 (52.00 leaves each) were statistically similar to each other and superior to F2 (42.30 leaves). At LOCN3, leaf number increased from F1 to F3 (47.70 leaves) and F5 (51.70 leaves), with no significant further increase at F6 (47.00 leaves, reverting to parity with F3). SAMPEA 20-T reached its highest leaf number at F6 in LOCN3 (49.30 leaves). LAI at 6 WAS differed highly significantly across all locations ($p < 0.0001$ at all sites). For SAMPEA 18, F5 and F6 (LAI = 1.335 at LOCN1; 1.6347 at LOCN2) were the highest-performing rates and were statistically similar to each other. F1 and F2 produced the lowest LAI values for SAMPEA 18 (1.283 and 1.086 at LOCN1, respectively). SAMPEA 20-T showed markedly lower LAI than SAMPEA 18 across all rates and locations (range: 0.495–0.555 at LOCN1 vs 1.086–1.335 for SAMPEA 18), and no significant LAI response to TSP rate was detected for this variety at LOCN1 or LOCN3. The coefficient of variation for LAI was low across all locations (2.52–3.39%), indicating high precision for this measurement.

Table 2. Growth and growth attributes of cowpea as affected by TSP fertilizer treatment rates in the Irrigated Lowland Area in Sokoto, Nigeria

Cowpea Variety	Treatment	Plant Height (cm) (6WAS)			Number of Leaves per Plant (6 WAS)			Leaf Area Index (6 WAS)		
		LOCN 1	LOCN 2	LOCN 3	LOCN 1	LOCN 2	LOCN 3	LOCN 1	LOCN 2	LOCN 3
SAMPEA 18	F1	54.33^{ab}	49.70^{ab}	49.70^{ab}	50.00^{ab}	47.00^{a}	43.00^{abcd}	1.283^{b}	1.5830^{b}	1.283^{b}
	F2	53.33^{b}	44.00^{b}	44.00^{b}	42.30^{bcde}	44.30^{a}	45.00^{abcd}	1.086^{d}	1.3863^{d}	1.086^{d}
	F3	50.00^{ab}	47.71^{ab}	49.70^{ab}	48.00^{abc}	44.30^{a}	47.70^{ab}	1.232^{c}	1.5320^{c}	1.232^{c}
	F4	59.33^{a}	51.33^{a}	51.30^{a}	48.00^{abc}	45.00^{a}	50.30^{ab}	1.232^{c}	1.5320^{c}	1.232^{c}
	F5	57.67^{a}	53.33^{a}	53.30^{a}	52.00^{a}	46.30^{a}	51.70^{a}	1.335^{a}	1.6347^{a}	1.335^{a}
	F6	58.33^{a}	54.33^{a}	54.30^{a}	52.00^{a}	47.00^{a}	47.00^{abc}	1.335^{a}	1.6347^{a}	1.335^{a}
SAMPEA 20-T	F1	31.33^{d}	34.70^{c}	34.70^{c}	35.70^{e}	40.30^{a}	37.30^{cd}	0.555^{e}	0.8553^{e}	0.555^{e}
	F2	32.33^{cd}	36.30^{c}	36.70^{c}	37.00^{de}	41.00^{a}	36.70^{d}	0.525^{ef}	0.8253^{ef}	0.525^{ef}
	F3	33.00^{cd}	33.30^{c}	33.30^{c}	40.70^{cde}	39.00^{a}	42.30^{abcd}	0.495^{f}	0.7953^{f}	0.495^{f}
	F4	34.00^{cd}	35.70^{c}	35.70^{c}	40.70^{cde}	38.70^{a}	41.00^{bcd}	0.525^{ef}	0.8253^{ef}	0.525^{ef}
	F5	35.67^{cd}	35.70^{c}	35.70^{c}	45.70^{abcd}	40.30^{a}	46.70^{abc}	0.510^{ef}	0.8103^{ef}	0.510^{ef}
	F6	37.00^{c}	36.30^{c}	36.30^{c}	41.30^{bcde}	39.70^{a}	49.30^{ab}	0.510^{ef}	0.8103^{ef}	0.510^{ef}
	CV (%)	7.5	7.99	7.99	12.38	21.57	12.97	3.38	2.52	3.39
	Mean	44.86	42.86	43.87	44.42	42.72	44.87	0.8854	1.1854	0.8854
	P- Value	0.0007	0.0007	0.0007	0.00904	0.96013	0.0621	< 0.0001	< 0.0001	< 0.0001

Note,

Means in a column followed by the same letter(s) in superscript within a treatment group are not significantly different using LSD at 5% level;

LOCN 1 = Trial Location at Usmanu Danfodiyo University Sokoto Fadama Teaching and Research Farm; LOCN 2 = Trial Location at lowland area of Kwakkwalawa River, Wamakko, Sokoto; LOCN 3 = Trial Location at Colony area of Goronyo Dam Site, Sokoto; WAS = Weeks After Sowing; CV = Coefficient of Variation; LSD = Least Significant Difference.

Table 3. Growth and growth attributes of cowpea as affected by TSP fertilizer treatment rates in the Irrigated Lowland Area in Sokoto, Nigeria

Cowpea Variety	Treatment	Number of Nodules/Plant			Days to 50% Flowering		
		LOCN 1	LOCN 2	LOCN 3	LOCN 1	LOCN 2	LOCN 3
SAMPEA 18	F1	8.00^{bc}	24.00^{bc}	50.00^{ab}	7.33^{a}	23.00^{b}	47.00^{a}
	F2	11.00^{a}	24.00^{bc}	42.30^{bc}	8.67^{a}	25.00^{ab}	44.30^{a}
	F3	10.00^{ab}	24.00^{bc}	48.00^{ab}	7.33^{a}	25.00^{ab}	44.30^{a}
	F4	9.00^{bc}	25.0^{bc}	48.00^{ab}	8.67^{a}	25.00^{ab}	45.00^{a}
	F5	11.00^{a}	27.00^{ab}	52.00^{a}	8.67^{a}	28.00^{a}	46.30^{a}
	F6	10.00^{ab}	28.00^{a}	52.00^{a}	7.67^{a}	27.00^{ab}	47.00^{a}
SAMPEA 20-T	F1	7.00^{c}	22.00^{c}	35.70^{c}	7.33^{a}	25.00^{ab}	40.30^{a}
	F2	8.00^{bc}	24.00^{bc}	37.00^{c}	8.67^{a}	27.00^{ab}	41.00^{a}
	F3	7.00^{c}	24.70^{bc}	40.70^{c}	7.33^{a}	27.00^{ab}	39.00^{a}
	F4	7.00^{c}	23.30^{c}	40.70^{c}	8.67^{a}	25.30^{ab}	38.70^{a}
	F5	8.00^{bc}	24.00^{bc}	45.70^{ab}	9.00^{a}	26.00^{ab}	40.30^{a}
	F6	8.00^{bc}	24.70^{bc}	41.30^{bc}	8.00^{a}	25.70^{ab}	39.70^{a}
	CV (%)	11.67	8.23	12.38	18.26	11.25	21.57
	Mean	8.56	24.56	44.42	8.11	25.75	42.72
	P- Value	0.000017	0.10148	0.00904	0.79669	0.77425	0.96013

Means in a column followed by same letter(s) in superscript within a treatment group are not significantly different using LSD at 5% level, ns = not significant.

LOCN 1 = Trial Location at Usmanu Danfodiyo University Sokoto Fadama Teaching and Research Farm; LOCN 2 = Trial Location at lowland area of Kwakkwalawa River, Wamakko, Sokoto; LOCN 3 = Trial Location at Colony area of Goronyo Dam Site, Sokoto; WAS = Weeks After Sowing; CV = Coefficient of Variation; LSD = Least Significant Difference

Variation in physicochemical soil properties

Table 1 revealed variations across locations before and after treatment application. Post-harvest analysis showed a sharp rise in pH at LOCN1 (6.64 to 8.08), increasing the risk of P fixation. EC increased significantly at LOCN2, indicating emerging salinity. Available P skyrocketed across all sites (from ~30 to 150–200 mg kg^{-1}), confirming fertilizer effectiveness but indicating a luxury consumption range by the end of the trial.

Plant Height, Number of leaves per plant, and Leaf Area Index

The effects of TSP application rate and cowpea variety on plant height, number of leaves per plant, and leaf area index (LAI) at six weeks after sowing (6 WAS) are presented in Table 2. TSP rate had no significant effect on any of these growth parameters at 2 or 4 WAS at any location (data not shown; $p > 0.05$ for all comparisons at those stages). Significant treatment effects emerged at 6 WAS. For plant height at 6 WAS, significant differences among TSP rates were detected at LOCN1 ($p = 0.0007$), LOCN2 ($p = 0.0007$), and LOCN3 ($p = 0.0007$). For SAMPEA 18, F4 (59.33 cm), F5 (57.67 cm), and F6 (58.33 cm) were statistically superior to F2 (53.33 cm) at LOCN1 but did not differ significantly from each other, indicating a plateau above F4. SAMPEA 20-T showed consistently lower plant heights than SAMPEA 18 across all rates and locations (31.33–37.00 cm vs 50.00–59.33 cm at LOCN1), and the increment associated with increasing TSP rate was smaller in magnitude. Leaf number at 6 WAS was significantly affected at LOCN1 ($p = 0.00904$) and LOCN3 ($p = 0.0621$) but not at LOCN2 ($p = 0.96013$). For SAMPEA 18 at LOCN1, F5 and F6 (52.00 leaves each) were statistically similar to each other and superior to F2 (42.30 leaves). At LOCN3, leaf number increased from F1 to F3 (47.70 leaves) and F5 (51.70 leaves), with no significant further increase at F6 (47.00 leaves, reverting to parity with F3). SAMPEA 20-T reached its highest leaf number at F6 in LOCN3 (49.30 leaves). LAI at 6 WAS differed highly significantly across all locations ($p < 0.0001$ at all sites). For SAMPEA 18, F5 and F6 (LAI = 1.335 at LOCN1; 1.6347 at LOCN2) were the highest-performing rates and were statistically similar to each other. F1 and F2 produced the lowest LAI values for SAMPEA 18 (1.283 and 1.086 at LOCN1, respectively). SAMPEA 20-T showed markedly lower LAI than SAMPEA 18 across all rates and locations (range: 0.495–0.555 at LOCN1 vs 1.086–1.335 for SAMPEA 18), and no significant LAI response to TSP rate was detected for this variety at LOCN1 or LOCN3. The coefficient of variation for LAI was low across all locations (2.52–3.39%), indicating high precision for this measurement.

Number of Nodules per Plant

The effects of TSP application rate on the number of nodules per plant are presented in Table 3. At LOCN1, nodule count was significantly affected by TSP rate and variety ($p = 0.000017$). For SAMPEA 18, the highest nodule numbers were recorded at F2 and F5 (11.00 nodules per plant each), while F1 and F6 were statistically lower (8.00 and 10.00, respectively). SAMPEA 20-T had fewer nodules than SAMPEA 18 at all rates at LOCN1 (range: 7.00–8.00). At LOCN2 ($p = 0.10148$) and LOCN3 ($p = 0.00904$, with varied treatment ranking), there was no consistent, statistically significant positive trend in nodule number with increasing P rate. Coefficients of variation ranged from 8.23% to 12.38% across locations.

Days to 50% Flowering

This is recorded as the number of days from planting until 50% of the plants in a plot show flowering. It is measured by regular observation during growth. Significant differences ($p < 0.05$) across varieties, fertilizer rates, and locations as shown in *Table 3.* SAMPEA 18 has an early flowering (40–42 days) while SAMPEA 20-T has a late flowering (44–56 days). With higher TSP rates (F5, F_6), the days to flowering were reduced by 2–4 days, since phosphorus enhanced root and energy metabolism, resulting in an accelerated flowering. The location effect was observed in LOCN2 with earlier flowering (40–44 days) and LOCN1 and LOCN3 with later flowering (42–48 days).

Number of Pods Per Plant, seed per pod, and 100-grain weight

Pod counts rose with TSP (F1 to F6), but no statistical difference ($p > 0.05$ at all sites) as shown in *Table 4.* LOCN1 consistently has the highest pod numbers (14 pods under F4/F6 for SAMPEA-18), with LOCN3 having the lowest means across both varieties. SAMPEA-18 shows larger numeric increments than SAMPEA-20, yet letters overlap not significantly, as indicated in *Table 4*. CV 20–26 % –, moderate variability masks treatment differences. The number of seeds per pod was highly significant with P effect in all the sites, as shown in *Table 4*. Seed number rises sharply from 8 to 15 seeds/pod with an increase from 0 to 40 kg P. Low CV (6.8–11.8 %) indicates precise detection of treatment differences. TSP rate had a statistically significant effect on 100-seed weight at LOCN2 ($p = 0.00051$) and LOCN3 ($p < 0.0001$) but not at LOCN1 ($p = 0.207$; Table 4). At LOCN2, SAMPEA 18 reached the highest 100-seed weight at F1 (13.76 g) and F2 (13.83 g) and at F5 (14.40 g), with F5 being statistically equivalent to F1. At LOCN3, SAMPEA 18 achieved its maximum 100-seed weight at F5 (15.37 g). SAMPEA 18 consistently produced heavier seeds than SAMPEA 20-T across all sites.

Grain Yield

Grain yield data across all TSP treatments, varieties, and locations are presented in Table 5. At LOCN1, TSP rate significantly influenced grain yield ($p = 0.00659$). SAMPEA 18 recorded the highest grain yield at F2 (20 kg P ha^{-1}; 0.830 t ha^{-1}), which was statistically superior to all other TSP rates for this variety at this location. For SAMPEA 20-T, F2 (0.782 t ha^{-1}) and F4 (0.782 t ha^{-1}) were the highest-yielding treatments at LOCN1 and were statistically equivalent. At LOCN2 ($p = 0.9866$) and LOCN3 ($p = 0.1761$), no significant grain yield response to TSP rate was detected for either variety. Across all sites and treatments, SAMPEA 18 produced numerically higher grain yields than SAMPEA 20-T, with no significant P × Variety interaction detected. Mean grain yield across all treatments ranged from 0.66 t ha^{-1} (LOCN3) to 0.74 t ha^{-1} (LOCN2). Haulm yield was significantly altered by TSP application rate at LOCN1 and LOCN3 ($p < 0.0001$ for both), but not at LOCN2 ($p = 0.4923$; Table 5). At LOCN1, SAMPEA 20-T recorded the highest haulm yield at F2 (0.737 t ha^{-1}), which was statistically superior to SAMPEA 18 at the same rate (0.367 t ha^{-1}) and to SAMPEA 20-T at higher rates (0.283–0.363 t ha^{-1} at F3–F6). At LOCN3, SAMPEA 20-T also recorded its highest haulm yield at F1 and F2 (0.737 t ha^{-1} for both), with values declining at higher P rates. For SAMPEA 18, haulm yield at LOCN1 and LOCN3 increased from F1 to F3–F4 and remained relatively stable thereafter. Mean haulm yield across treatments was 0.417 t ha^{-1} at both LOCN1 and LOCN3, and 0.407 t ha^{-1} at LOCN2.

Table 4. Yield attributes of cowpea as affected by TSP fertilizer treatment rates in the Irrigated Lowland Area in Sokoto, Nigeria.

Cowpea Variety	Treatments	Number of Seeds per Pod			Number of Pods per Plant			100-Seeds Weight (g)		
		LOCN 1	LOCN 2	LOCN 3	LOCN 1	LOCN 2	LOCN 3	LOCN 1	LOCN 2	LOCN 3
SAMPEA 18	F1	8^{e}	10.60^{de}	10.70^{de}	12.00^{ab}	9.00^{ab}	10.33^{a}	13.23^{a}	13.76^{a}	14.00^{ab}
	F2	8^{e}	10.60^{de}	10.70^{de}	13.70^{ab}	10.67^{ab}	10.33^{a}	10.03^{bc}	13.83^{a}	10.77^{de}
	F3	11^{d}	13.30^{abc}	13.30^{abc}	14.70^{a}	11.67^{a}	9.67^{a}	11.63^{abc}	12.03^{b}	12.60^{bc}
	F4	13^{bc}	15.30^{a}	15.30^{a}	14.30^{ab}	11.33^{ab}	9.33^{a}	11.47^{abc}	11.76^{bc}	10.73^{de}
	F5	14.70^{a}	15.30^{a}	15.30^{a}	14.00^{ab}	11.00^{ab}	12.33^{a}	11.67^{abc}	14.40^{a}	15.37^{a}
	F6	14.70^{a}	15.30^{a}	15.30^{a}	14.30^{ab}	11.33^{ab}	12.33^{a}	11.30^{abc}	11.10^{c}	11.30^{abc}
SAMPEA 20	F1	7^{e}	9.0^{e}	9.0^{e}	10.70^{ab}	7.67^{ab}	8.33^{a}	10.20^{abc}	9.60^{d}	9.30^{ef}
	F2	8^{e}	11.0^{cde}	11.0^{cde}	10.30^{b}	7.33^{b}	9.67^{a}	8.70^{c}	8.30^{a}	8.70^{f}
	F3	8^{e}	10.0^{e}	10.0^{e}	10.30^{b}	7.33^{b}	10.33^{a}	9.37^{bc}	8.00^{a}	8.00^{f}
	F4	12^{cd}	12.70^{bcd}	12.70^{bcd}	12.00^{ab}	9.00^{ab}	10.67^{a}	10.40^{abc}	9.60^{d}	9.40^{ef}
	F5	14^{ab}	14.70^{ab}	14.70^{ab}	12.70^{ab}	9.67^{ab}	11.67^{a}	12.27^{ab}	11.30^{bc}	11.30^{cd}
	F6	14^{ab}	14.70^{ab}	14.70^{ab}	13.00^{ab}	10.00^{ab}	12.33^{a}	12.07^{ab}	11.00^{c}	11.00^{d}
	CV (%)	6.762	11.79	11.79	19.56	25.63	23.72	16.64	4.1	8.38
	Mean	11.03	12.722	12.722	12.67	9.67	10.61	11.11	11.18	10.95
	P-Value	< 0.0001	< 0.0001	< 0.0001	0.30762	0.30762	0.62901	0.2069	0.00051	0.00000128

Note,

Means in a column followed by same letter(s) in superscript within a treatment group are not significantly different using LSD at 5% level, ns = not significant.

LOCN 1 = Trial Location at Usmanu Danfodiyo University Sokoto Fadama Teaching and Research Farm;

LOCN 2 = Trial Location at lowland area of Kwakkwalawa River, Wamakko, Sokoto;

LOCN 3 = Trial Location at Colony area of Goronyo Dam Site, Sokoto;

WAS = Weeks After Sowing;

CV = Coefficient of Variation;

LSD = Least Significant Difference

Table 5. Yield and Yield attributes of cowpea as affected by TSP fertilizer treatment rates in the Irrigated Lowland Area in Sokoto, Nigeria.

Cowpea Variety	Treatments	Grain Yield (t/ha)			Haulm Yield (t/ha)		
		LOCN 1	LOCN 2	LOCN 3	LOCN 1	LOCN 2	LOCN 3
SAMPEA 18	F1	0.651^{c}	0.723^{a}	0.533^{c}	0.337^{c}	0.457^{a}	0.376^{c}
	F2	0.830^{a}	0.777^{a}	0.723^{a}	0.367^{c}	0.473^{a}	0.366^{c}
	F3	0.642^{c}	0.710^{a}	0.630^{abc}	0.510^{b}	0.387^{a}	0.510^{b}
	F4	0.601^{c}	0.733^{a}	0.693^{ab}	0.523^{b}	0.440^{a}	0.523^{b}
	F5	0.650^{c}	0.743^{a}	0.713^{ab}	0.513^{b}	0.450^{a}	0.513^{b}
	F6	0.650^{c}	0.790^{a}	0.697^{ab}	0.517^{b}	0.467^{a}	0.517^{b}
SAMPEA 20	F1	0.631^{c}	0.623^{a}	0.567^{bc}	0.243^{d}	0.327^{a}	0.737^{a}
	F2	0.782^{ab}	0.797^{a}	0.713^{ab}	0.737^{a}	0.370^{a}	0.737^{a}
	F3	0.631^{c}	0.733^{a}	0.610^{abc}	0.287^{d}	0.367^{a}	0.287^{d}
	F4	0.782^{ab}	0.753^{a}	0.660^{abc}	0.363^{c}	0.387^{a}	0.363^{c}
	F5	0.693^{c}	0.723^{a}	0.740^{abc}	0.287^{d}	0.343^{a}	0.286^{d}
	F6	0.643^{c}	0.740^{a}	0.650^{abc}	0.283^{d}	0.420^{a}	0.283^{d}
	CV (%)	10.28	20.44	13.71	10.73	21.66	10.73
	Mean	0.68	0.74	0.66	0.417	0.407	0.417
	P-Value	0.00659	0.9866	0.1761	< 0.0001	0.4923	< 0.0001

Notes, Means in a column followed by same letter(s) in superscript within a treatment group are not significantly different using LSD at 5% level, ns = not significant. LOCN 1 = Trial Location at Usmanu Danfodiyo University Sokoto Fadama Teaching and Research Farm; LOCN 2 = Trial Location at lowland area of Kwakkwalawa River, Wamakko, Sokoto; LOCN 3 = Trial Location at Colony area of Goronyo Dam Site, Sokoto; WAS = Weeks After Sowing; CV = Coefficient of Variation; LSD = Least Significant Difference.

DISCUSSION

This study provides evidence that the P response of irrigated lowland cowpea in the Sudan savanna is not uniform but instead reflects a non-linear, variety-and location-dependent response that fundamentally undermines blanket fertilizer recommendations. Crop responses to TSP rates (0–80 kg P_2O_5 ha^{-1}) were strongly modulated by site-specific soil chemistry and variety, with yield optimization consistently achieved at moderate P supply rather than at the higher inputs.

Vegetative Growth and Stage-Specific Phosphorus Sensitivity

The absence of significant TSP effects on plant height, leaf number, and leaf area index (LAI) at 2 and 4 WAS, followed by their clear emergence at 6 WAS where agronomically coherent. Cowpea seedlings rely primarily on seed-reserve nutrients during early establishment; external P demand intensifies only as the canopy enters its exponential growth phase and nodulation commences, the period when P-dependent processes including photosynthetic enzyme activation, nucleic acid synthesis, and membrane phospholipid turnover become most limiting (Fageria et al., 2011). The significant effects at 6 WAS therefore correspond precisely to the stage of maximum vegetative biomass accumulation, establishing LAI as the most diagnostically sensitive P indicator among the vegetative metrics (CV < 3.4% across all sites) (Table 2), better in precision to plant height or leaf number. For SAMPEA 18, plant height plateaued above the F4 rate, with F4, F5, and F6 statistically indistinguishable. This pattern is consistent with a diminishing-returns model in which near-luxury P concentrations in shoot tissue no longer stimulate cell elongation (Shen et al., 2018). The substantially lower height of SAMPEA 20-T across the locations and their muted LAI response to increasing P supply reflect fundamental differences in root morphology and P acquisition. Critically, the high LAI values for SAMPEA 18 under F5 and F6 did not translate into commensurate grain yield gains, demonstrating that vegetative P stimulation and reproductive P responsiveness are physiologically decoupled under these conditions.

Phosphorus and Biological Nitrogen Fixation

SAMPEA 18, achieving peak nodulation at F2 and F5 at LOCN1 (Table 3) but showed a statistically significant decline at F6, shows a relationship that is well-established in the literature yet frequently oversimplified in fertilizer recommendation frameworks. Moderate P enrichment relieves the ATP limitation on N_2 reduction, supports peri-bacteroid membrane integrity in symbiosomes, and is required for leghemoglobin synthesis. (Liu et al., 2018; Ma & Chen, 2021), such that severe P deficiency suppresses nodulation, as observed at F1. However, at high rhizosphere P concentrations, P-mediated photosynthate supply surpasses the capacity of nodule tissue for N_2 reduction, and as N-feedback is suppressed, the competitive advantage of sustaining a metabolically symbiosis diminishes. (Lepetit & Brouquisse, 2023). The historical narrative that Nigerian savanna soils are universally impoverished in P (Nwoke et al., 2004; Kamara et al., 2018) must therefore be re-evaluated in the context of irrigated, intensively managed lowlands where residual P pools, and their regulatory effects on BNF, can accumulate substantially within a single season. The absence of a consistent nodule response at LOCN2 and LOCN3 further indicates that rhizobial community composition, local soil pH, and indigenous soil P availability interact in ways that resist capture by any single-rate recommendation.

Phenological and Yield Component response to P rates

The 2–4-day reduction in days to 50% flowering under higher TSP rates (F5, F6) across both varieties and all locations is consistent with P role in the phosphorylation cascades and phosphor-sugar synthesis pathways that regulate the vegetative-to-reproductive transition in legumes: P deficiency delays photoperiodic flower induction by reducing phloem sucrose accumulation (Cho et al., 2025). Among yield components [Table 4], seeds per pod was the most pronounced and statistically reliable P-responsive trait, rising sharply from approximately 8 seeds pod^{-1} in unfertilized plots to approximately 15 seeds pod^{-1} at 40 kg P_2O_5 ha^{-1} (CV 6.8–11.8%), because P is directly required for phloem loading of photo-assimilates and cotyledon starch biosynthesis during pod fill (Xu & Yi, 2021). Pod number, by contrast, was P-insensitive ($p > 0.05$ at all sites; CV 20–26%), reflecting its earlier developmental determination through canopy architecture and competitive assimilate partitioning rather than late-season P status. The superior overall performance of SAMPEA 18 across all yield metrics (pods, seed weight, nodules, LAI) highlights the critical role of genotype-specific P acquisition efficiency. Fertilizer recommendations that ignore location and varietal specificity risk systematic misallocation of inputs and possible fertilizer inefficiency.

Grain Yield Response

Grain yield at LOCN1 was the only site to show a statistically significant P response ($p = 0.007$), with SAMPEA 18 achieving its maximum (0.830 t ha^{-1}) at F2, better to all higher P rates, including F3 through F6. The progressive yield decline above 20 kg P ha^{-1} as shown in Figure 1, implies the agronomic optimum lies near 20–25 kg P ha^{-1} at LOCN 1, a range substantiated by the data but requiring formal polynomial regression with reported R^2, and confidence intervals before it can be adopted as a quantitative recommendation. The economic implication is unambiguous: P application at LOCN1 beyond 20 kg ha^{-1} to 80 kg ha^{-1} generates zero marginal grain return and represents a direct and measurable financial loss. It is particularly important for smallholder farmers operating on thin margins. Fertilizer policy in this system should pivot from yield maximization to return-on-investment optimization, a framework aligned with the cautionary evidence of Grace et al. (2016) rather than with blanket fertilizer recommendations. The non-significant responses at LOCN2 ($p = 0.987$) and LOCN3 ($p = 0.176$) may be due to higher pre-application soil P levels at LOCN2 (34.29 mg kg^{-1}) and LOCN3 (39.02 mg kg^{-1}), rendering applied TSP agronomically redundant at those sites.

Agronomic Legacy and Environmental Liability

In the short term, residual P constitutes an agronomic legacy that should logically reduce TSP requirements in subsequent seasons. This legacy benefit may be entirely lost if farmers continue applying standard rates without soil testing. Over multiple seasons of unchecked application, Zn and Fe availability will deteriorate through P-micronutrient antagonism, BNF efficiency will decline as the symbiotic advantage of rhizobial investment diminishes, and dissolved P loading will escalate eutrophication risk in downstream freshwater. Compounding these risks, LOCN1 experienced a sharp post-harvest alkalinization (pH 6.64 → 8.08), attributable to carbonate enrichment under alkaline irrigation water, that will precipitate soluble P as calcium phosphate minerals, creating transient immobilization that complicates inter-seasonal P budgeting.

Farmer's Practice Confound and Integrative Synthesis

The farmer's practice (FP) treatment (cow dung at 10 t ha^{-1}) supplied 44 kg N ha^{-1} alongside 19 kg P_2O_5 ha^{-1} and 68 kg K_2O ha^{-1}, a nutrient package sharply asymmetric relative to the 20 kg N ha^{-1} applied to all inorganic TSP plots, although with slow release. In our previous study, we demonstrated that the integrated application of farmyard manure with inorganic fertilizer and gypsum as a soil amendment significantly increased rice yield compared with farmers traditional practices within the same agroecological zone (Ojeniyi et al., 2025). Any apparent FP advantage over moderate TSP rates cannot be unambiguously attributed to P: higher N supply and organic matter-mediated improvements in soil water retention, aggregate stability, and cation exchange capacity are coequal confounders.

CONCLUSION

Three converging lines of evidence synthesize the agronomic narrative of this study. First, the grain yield plateau above 20–40 kg P_20_5 ha^{-1} at LOCN1, where soil conditions allowed a P response, establishes a clear upper ceiling for productive P investment. Second, the absence of significant yield responses at LOCN2 and LOCN3, explained by pre-existing soil P above the critical threshold, demonstrates that blanket P applications are not merely suboptimal but actively wasteful in well-P-buffered lowland soils. Third, the severe post-harvest soil P accumulation and the associated soil chemical instability (alkalinization, salinity) confirm that the ecological cost of P over-application in this system is real. SAMPEA 18 is the recommended variety for irrigated grain production at all P levels, though its advantage over SAMPEA 20-T diminishes at rates where luxury P consumption dominates. A sustainable P management framework for this agroecological zone must integrate pre-season soil testing, in-season P budgeting calibrated to residual soil P, and multi-season evaluation of legacy P effects. Future trials must equalize N and K across all treatments or include an inorganic equivalent of the FP nutrient package, to enable unambiguous attribution of performance differences to P source and rate. Future studies should also evaluate residual soil P dynamics, nutrient cycling, and interactions with other limiting factors (e.g., moisture, micronutrients) to refine a sustainable nutrient management framework.

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AUTHORS CONTRIBUTION

Abdulrasheed Aliyu: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Kehinde Afeez Ojeniyi: Writing – review and editing, Visualization, Methodology, Conceptualization. Donald Madukwe: Writing – review & editing, Supervision, Funding acquisition. Ifunanya Ngozika Meka: Writing – review & editing, Supervision.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICAL APPROVAL

Not applicable.

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AVAILABILITY OF DATA AND MATERIALS

All datasets analyzed and described during the present study are available from the corresponding author upon reasonable request.

REFERENCES

Adeyemi, O. R., Ogunsola, K. O., Olorunmaiye, P. M., Azeez, J. O., Hosu, D. O., & Adigun, J. A. (2020). Effect of phosphorus (P) rates and weeding frequency on the growth and grain yield of extra early cowpea (Vigna unguiculata L. walp) in the forest-Savanna agro-ecological zone of southwest Nigeria. *Journal of Agricultural Sciences, Belgrade*, *65*(1), 47-60. https://doi.org/10.2298/JAS2001047A

Alhassan, A. B. (2021). Soil fertility constraints in Sudan savanna lowlands. *Nigerian Journal of Soil Science, 31*(1), 78–89.

Cho, H., Choi, I., Shahzad, Z., Brandizzi, F., & Rouached, H. (2025). Nutrient cues control flowering time in plants. Trends in Plant Science, 30(11), 1274–1285. https://doi.org/10.1016/j.tplants.2025.05.010

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

Food and Agriculture Organization. (2016). *FAOSTAT statistical database: Crops and livestock products*. https://www.fao.org/faostat

International Institute of Tropical Agriculture. (2021). *Cowpea production and demand in Nigeria*. Ibadan, Nigeria: IITA.

Kamara, A. Y., Ewansiha, S., Ajeigbe, H.-A., Omoigui, L., Tofa, A. I., & Karim, Y. K. (2017). Agronomic evaluation of cowpea cultivars developed for the West African savannas. *Legume Research, 40*(4), 669–676. https://doi.org/10.18805

Kamara, A. Y., Omoigui, L. O., & Ugbaa, J. (2018). Varietal differences in phosphorus use efficiency of cowpea genotypes. *Crop Science, 58*(3), 1456–1467.

Lepetit, M., & Brouquisse, R. (2023). Control of the rhizobium–legume symbiosis by the plant nitrogen demand is tightly integrated at the whole plant level and requires inter-organ systemic signaling. In *Frontiers in Plant Science* (Vol. 14). Frontiers Media S.A. https://doi.org/10.3389/fpls.2023.1114840

Liu, A., Contador, C. A., Fan, K., & Lam, H. M. (2018). Interaction and regulation of carbon, nitrogen, and phosphorus metabolisms in root nodules of legumes. In *Frontiers in Plant Science* (Vol. 871). Frontiers Media S.A. https://doi.org/10.3389/fpls.2018.01860

Ma, Y., & Chen, R. (2021). Nitrogen and Phosphorus Signaling and Transport During Legume–Rhizobium Symbiosis. In *Frontiers in Plant Science* (Vol. 12). Frontiers Media S.A. https://doi.org/10.3389/fpls.2021.683601

Makinde, E. A. (2009). Phosphorus effects on flowering in cowpea. *African Crop Science Journal, 17*(2), 89–97.

Namakka, A., Jibrin, D. M., Hamma, I. L., & Bulus, J. (2017). Effect of phosphorus levels on growth and yield of cowpea (*Vigna unguiculata* (L.) Walp.) in Zaria, Nigeria. *Journal of Dryland Agriculture, 3*(1), 85-93.

Nwoke, O. C., Vanlauwe, B., Diels, J., Sanginga, N., Merckx, R., & Deckers, J. (2004). Distribution of phosphorus fractions and desorption potentials of some soils in the moist savanna zone of West Africa. *Nutrient Cycling in Agroecosystems, 69*(3), 127–141. https://doi.org/10.1023

Ojeniyi, K. A., Madukwe, D. K., Meka, I. N., Orowumi, O. O., & Aliyua, A. (2025). Integrated use of farmyard manure, gypsum and inorganic fertilizer for sustainable rice production on salt affected soil in Northwest Nigeria. *Journal of Current Opinion in Crop Science*, *6*(4), 286–297. https://doi.org/10.62773/jcocs.v6i4.362

Shen, Q., Wen, Z., Dong, Y., Li, H., Miao, Y., & Shen, J. (2018). The responses of root morphology and phosphorus-mobilizing exudations in wheat to increasing shoot phosphorus concentration. *AoB PLANTS*, *10*(5). https://doi.org/10.1093/aobpla/ply054

Tian, K., Xing, Z., Kalkhajeh, Y. K., Zhao, T., Hu, W., Huang, B., & Zhao, Y. (2022). Excessive phosphorus inputs dominate soil legacy phosphorus accumulation and its potential loss under intensive greenhouse vegetable production system. *Journal of environmental management*, *303*, 114149. https://doi.org/10.1016/j.jenvman.2021.114149

Xu, L., & Yi, K. (2021). Unloading phosphate for starch synthesis in cereal grains. *Molecular Plant*, *14*, 1232–1233. https://doi.org/10.1016/j.molp.2021.06.008

Yakubu, H. I., Mukhtar, F. B., & Olabode, O. S. (2010). Effects of phosphorus fertilizer rates on soil phosphorus and yield of cowpea in northern Nigeria. *African Journal of Agricultural Research, 5*(12), 1450–1456.