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Research

Nodulation and Yields of Soybean (*Glycine max* L. Merrill) Varieties at Varying Phosphorus Fertilizer Rates in Lafia, Nigeria

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ABSTRACT

Soybean production in Lafia, southern Guinea savanna zone of Nigeria, is impacted by soil phosphorus deficiency, affecting nodulation, nitrogen fixation, and overall crop productivity. Field experiments were conducted in 2018 and 2019 cropping seasons with different phosphorus fertilizer rates (0, 13, 26 & 39 Kg P_2O_5 ha^{-1}) and six improved soybean varieties (TGX 1985-10F, TGX 1987-10F, TGX 1448-2E, TGX 1987-62F, TGX 1989-19F & TGX 1835-10E) to determine the effects of phosphorus fertilizer rates on nodulation and yields of soybean varieties. The results showed significant variation in soybean nodulation and yields when different phosphorus fertilizer rates were used. Among the six improved soybean varieties tested, TGX 1989-19F and TGX 1987-62F varieties performed best with 39 kg P_2O_5 ha^{-1}. The results also show that plots that received a 39 kg P_2O_5 ha^{-1} produced the highest nodule number (26.3 & 28.7) and nodule weight (203.5 & 221.2 mg/plant) significantly in 2018 and 2019, respectively, compared to those with lower phosphorus rates. The effect of phosphorus fertilizer rates on soybean yields was apparent, with the 39 kg ha^{-1} phosphorus treatment yielding significantly higher yields than the lower phosphorus treatments. Notably, the TGX 1989-19F variety consistently outperformed the others, yielding the highest yield (1624.0 kg/ha). Based on the results, it is recommended that soybean farmers in the Lafia region consider increasing their phosphorus rates to 39 kg ha^{-1} for improved nodulation and subsequent yield gains. The TGX 1989-19F variety, due to its exceptional response to this phosphorus level, could be prioritized for cultivation to maximize returns. However, further research and on-farm trials must validate these findings across multiple growing seasons and farm management practices.

Key words: Lafia, nodulation, phosphorus, soybean, yields

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INTRODUCTION

Soybean (*Glycine max* L. Merrill) holds a prominent position as one of the most essential leguminous crops worldwide, contributing significantly to global food security and agricultural economies (USDA, 2017; Nair *et al*., 2023).

Soybean production has increased globally due to its economic importance, nutritional value, and wide range of domestic applications (David, 2017). It is an important grain legume used as raw material for several processed foods, including soybean oil, soy flour, soy sauce, and soymilk. The crop has been described as the world's cheapest source of edible vegetable oil for human diets because it contains all the essential amino acids (Manral & Sexena, 2003). It was called a miracle golden bean not only for its nutritional benefits but also for its extraordinary medicinal properties to improve the health of the heart and arteries by preventing arteriosclerosis. It also helps reduce the risk of cancers, particularly of the breast, prostate, and colon (Ikeda *et al*., 2006; Kwon *et al*., 2007). In Nigeria, soybean cultivation is crucial in enhancing nutritional intake and providing income opportunities for smallholder farmers, particularly in the southern Guinea savanna zone, where the agroecological conditions are favorable for its growth (Khojely *et al*., 2018). However, despite its importance, soybean productivity in this region is hindered by various factors, with soil phosphorus deficiency emerging as a critical limiting factor.

Phosphorus is an essential nutrient for plant growth and development, vital for various metabolic processes, energy transfer, and synthesis of genetic material (Mirriam *et al*., 2023). In leguminous crops like soybean, an adequate supply of phosphorus is especially crucial for the formation of root nodules, specialized structures hosting symbiotic nitrogen-fixing bacteria (rhizobia) that convert atmospheric nitrogen into a form usable by plants (Mobasser *et al*., 2014; Mirriam *et al*., 2023). This biological nitrogen fixation reduces the need for synthetic nitrogen fertilizers, enhances soil fertility, and contributes to sustainable agricultural practices (Borges & Mallarino, 2003). Nigeria's southern Guinea savanna zone, including the Lafia region, experiences recurring challenges related to phosphorus deficiency in its soils (Dugje *et al*., 2009). As soybeans are highly responsive to phosphorus availability, understanding the influence of varying phosphorus fertilizer rates on soybean nodulation and subsequent yields is imperative to improving crop productivity and supporting farmers in this region. Optimizing phosphorus management practices could enhance soybean yields and contribute to the overall sustainable intensification of agricultural systems, with potential ramifications on food security, environmental conservation, and economic growth (Jarvie *et al*., 2015; Droppelmann *et al*., 2017; Meena, 2022).

The International Institute of Tropical Agriculture (IITA) and other agricultural institutes in Nigeria began breeding programs, which resulted in the introduction of high-yielding, early-maturing cowpea and soybean varieties to replace traditional farmer cultivars. Recent studies have revealed differences in the amount of nitrogen fixed by grain legumes (Osunde *et al*., 2003; Yusuf *et al*., 2008), highlighting the importance of selecting soybean cultivars with superior nitrogen-fixing abilities tailored to specific environments, particularly in Nigeria's dry sub-humid agro-ecological zone. Given these considerations, this research investigates the nodulation process and yields of different soybean varieties under varying phosphorus fertilizer rates in the Lafia region of Nigeria's southern Guinea savanna zone.

MATERIALS AND METHODS

Study area

Field experiments were conducted at the Teaching and Research Farm of the Faculty of Agriculture, Nasarawa State University, Shabu-Lafia Campus, during the 2018 and 2019 cropping seasons. The study area is located in Nigeria's southern Guinea savannah zone, between 08°29'30" N and 08°31'0" E. The average annual rainfall ranges between 1100 mm and 2000 mm, with the season typically beginning in April and ending in October, and the average monthly temperature ranges between 20 and 30 °C (NIMET, 2021).

Experimental materials and design

The experiment consisted of four rates of phosphorus in the form of single super phosphate (0, 13, 26, & 39 Kg P_2O_5 ha^{-1}) and six varieties of soybean (TGX 1985-10F, TGX 1987-10F, TGX 1448-2E, TGX 1987-62F, TGX 1989-19F & TGX 1835-10E). Indorama Eleme Fertilizer and Chemical Limited manufactured the phosphorus used. The twenty-four treatment combinations with three replications were randomly assigned to 72 plots in a Randomized Complete Block Design (RCBD). The gross plot size was 3 m × 2 m (6 m^2), and the net plot size was 2 m × 1.5 m. (3 m^2).

Land preparation and management practices

The field was cleared, ridges were made manually using a hoe, and the site was marked into plots and replications. One-meter unplanted border was maintained between plots, while a 2 m unplanted border was maintained between each replication. Four phosphorus levels were applied based on the treatment combinations and incorporated during land preparation. Four soybean seeds per hole were sown at a recommended planting spacing of 75 cm between rows and 5 cm between plants. Thinning of some seedlings was carried out two weeks after sowing (WAS) to maintain two plants per stand. The incidence of pest and disease infestations was monitored. Hoe weeding was done at 3, 6, and 9 weeks after sowing (WAS) to keep the plots weed-free.

Harvesting

Soybean grains were harvested when they reached full maturity. Each treatment area was defined, leaving two rows on each side to minimize edge effects. The entire plant within the designated area (net plots) was cut at ground level. The harvested plants were spread out in the sun to facilitate the complete drying of the seeds inside. The plants were placed in a sack and gently beaten with a stick. This process was carried out to separate the seeds from the pods. The mixture of seeds and chaff was subjected to manual winnowing. This involved using a winnower to separate the heavier seeds from the lighter chaff, effectively removing impurities.

Data collection

Five randomly selected tagged plants from each plot were used for measuring the following parameters: the number of nodules plant^{-1}, weight of dry nodules plant^{-1} (mg), number of pod plant^{-1}, number of seed pod^{-1}, seed yield plant^{-1}(g) and seed yield (kg ha^{-1}) was obtained from the net plots.

Data analysis

All the data obtained were subjected to a two-way analysis of variance (ANOVA) using the SAS statistical package (version 9.0). The Shapiro-Wilk test performed with Proc Univariate confirmed the normal distribution of the data. The significant difference among the treatment means was separated using the least significant test (LSD) at a 5% probability level.

RESULTS AND DISCUSSION

Soil characteristics

The physical and chemical characteristics of the soil at the experimental site are presented in Figures 1a and 1b. The results revealed that the pH levels in both surface (0-15 cm depth) and subsurface (15-30 cm depth) soils were moderately acidic (5.69 & 5.82), respectively. The organic matter content was also moderate, with 2.99 and 2.95 mg g^{-1} values in surface and subsurface soils, respectively. However, the total nitrogen and available phosphorus contents were notably low, registering 0.21 and 0.28 mg g^{-1} and 2.36 and 2.40 mg g^{-1} for surface and subsurface soils, respectively (Figure 1a).

Base saturation was high on both surfaces, with percentages of 91.00% and 90.00% for surface and subsurface soils, respectively, as shown in Figure 1b. The dominant particle size was sand, particularly at the surface level, accounting for 87.80% of the soil composition, resulting in a sandy loam texture. This aligns with the findings of Chude *et al*. (2012), who similarly categorized the nutrient status of soils in the southern Guinea savanna of Nigeria as very low, low, moderate, or high, depending on the specific nutrient. The initial soil properties of the experimental site laid a foundation for the expected response of soybean varieties to the application of phosphorus, as reflected in the parameters evaluated.

Phosphorus and variety effects on biological N_2 fixation

The number and weight of soybean nodules were significantly influenced by the levels of phosphorus application and the soybean variety ($p<0.05$), as shown in Table 1. The results demonstrated that each increase in the rate of phosphorus applied significantly increased the number of soybean nodules and weight per plant in the 2018 and 2019 cropping seasons. Specifically, plots receiving 39 kg ha^{-1} of phosphorus exhibited a notably higher nodule count and nodule weight, consequently resulting in a higher seed yield. This underscores the effective and positive impact of phosphorus on nodulation in soybeans. Research by Tsvetkova and Georgiew (2003) supported these findings, suggesting that a deficiency in phosphorus leads to inadequate nodulation in leguminous plants. This is further corroborated by the work of Rotaru (2010), who noted a nearly 50 percent reduction in nodule count in phosphorus-deficient soils, ultimately leading to diminished grain yield. The prevailing environmental conditions, along with the presence of native rhizobia populations, played a pivotal role in enhancing nodule formation in the promiscuous legume genotypes throughout the nodulation process. It's worth noting that factors such as low soil moisture, high temperatures, and inadequate soil fertility, particularly in nitrogen, can also contribute to subpar nodulation in leguminous plants, even in ample native rhizobia.

In a study conducted by Mateus and Grandet (2015) focusing on various doses of phosphorus fertilizers, it was observed that phosphorus application had a significant impact on several critical parameters of soybean growth, including biomass yield, 100-seed weight, pod count, grain yield, and nodule weight. Notably, the application of 60 kg ha^{-1} of P_2O_5 resulted in the highest recorded nodule weight (521.70 grams). Similarly, other studies, such as those by Amba *et al*. (2011), Chiezey and Odunze (2009), and Ogoke (2004), have reported an increase in nodule number with varying levels of phosphorus fertilizer. Mugendi (2010) also discovered a correlation between increased nodule weight and higher doses of phosphorus fertilization.

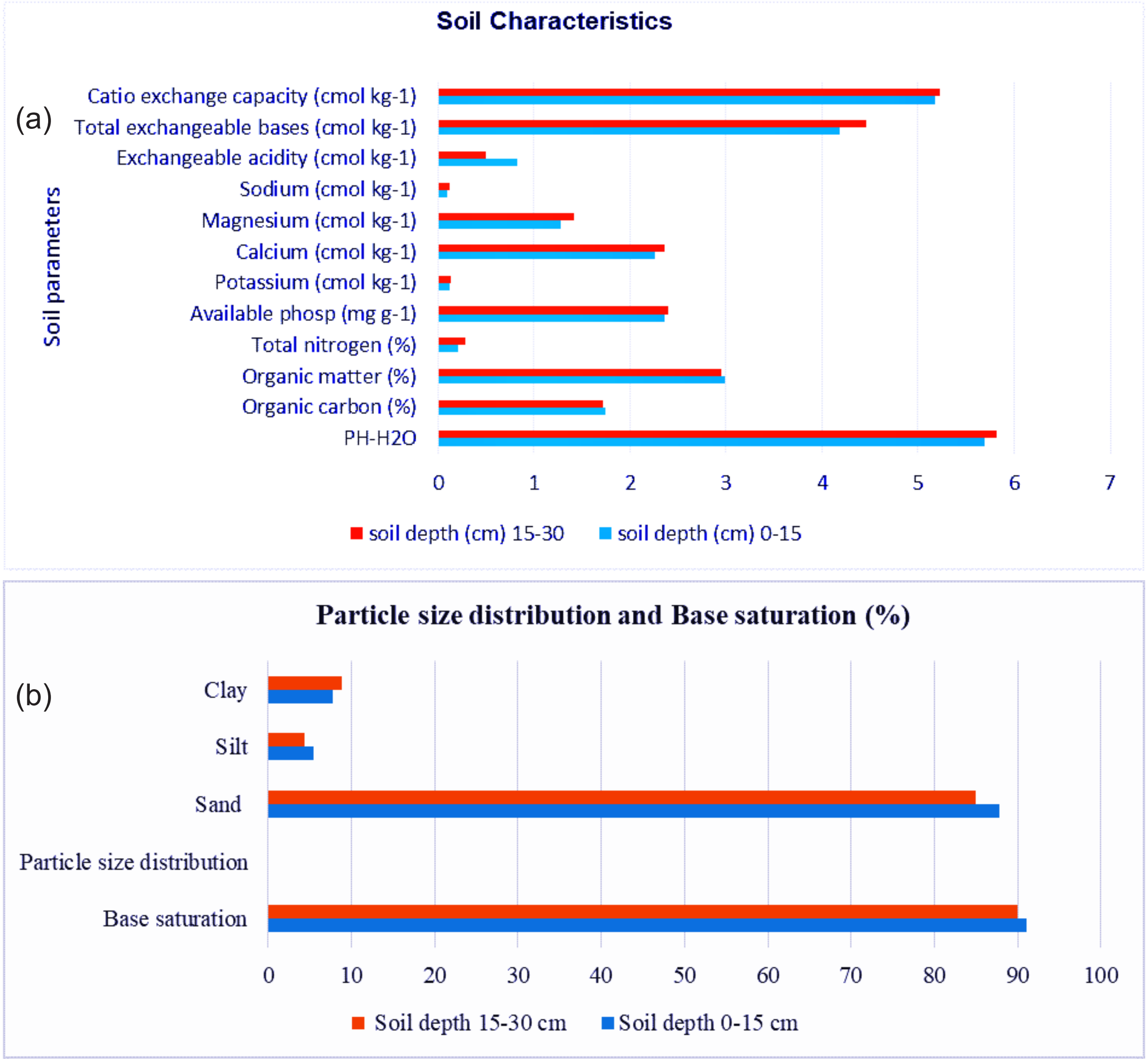

Fig. 1. Soil characteristics at the experimental site

The soybean varieties exhibited significant ($p<0.05$) variation in the number and weight of nodules, as shown in Table 1. In the 2018 growing season, TGX 1989-19F displayed the highest number of nodules per plant at 26.5, followed by TGX 1987-62F with 25.4, while TGX 1835-10E had the lowest count at 10.2. In 2019, TGX 1989-19F and TGX 1987-62F produced similar nodules, recording 27.3 and 27.1, significantly higher ($p<0.05$) than the other varieties. This study is in line with Rechiat's (2015) findings, suggesting that nodulation variation among soybean varieties is influenced by genetic factors and the compatibility of rhizobia bacteria with the host variety. Additionally, the host plant may possess physiological traits that enhance bacterial activity. The range of nodules observed in this study (8.3-28.7) falls within the reported range of previous studies. Olufajo (1990) reported a range of 3-34 nodules per soybean plant, while Okogun (2005) conducted experiments across 20 different locations in the same agro-ecological zone, recording averages of 44.3 and 61.1 nodules per plant for TGX 1448-2E and Samsoy-2 soybean varieties, respectively.

In the 2018 growing season, TGX 1989-19F had the highest nodule weight per soybean plant at 207.9 mg, followed by TGX 1987-62F with 169.7 mg. TGX 1835-10E had the lowest nodule weight at 91.0 mg. In 2019, TGX 1989-19F and TGX 1987-62F showed similar nodule weights of 210.5 mg and 208.1 mg, respectively, significantly higher than the other varieties. This increased nodule weight in TGX 1989-19F and TGX 1987-62F may be attributed to their diverse morphological characteristics, enhanced nodulation efficiency, and ability to utilize available mineral nutrients compared to the other varieties efficiently. This result aligns with previous studies that indicate soybean genotypes tend to form more substantial nodule biomass than cowpeas due to their specific morphological traits (Sanginga, 2003).

The variation in nodule weight among soybean varieties could be linked to differences in maturity time. Researchers suggest that late-maturing varieties are expected to produce more nodule weight because they spend more time accumulating dry matter in the field than early-maturing varieties. Ngalamu *et al*. (2013) reported that late-maturing varieties have sufficient time to utilize available resources optimally. Nodulation is closely linked to root dry matter; an increase in the application of phosphorus (P) leads to higher root dry matter, subsequently resulting in a higher number and weight of nodules.

Table 1. Effect of Phosphorus and Variety on the Number of Nodules and Weight of Dry Nodules (mg) plant^{-1} of Soybean in Lafia during the 2018 and 2019 Cropping Seasons

	Number of Nodules		Weight of Dry Nodules (mg)	
Treatment	2018	2019	2018	2019
Phosphorus (kg ha^{-1})				
0	8.3^{d}	9.3^{d}	93.1^{d}	99.9^{d}
13	10.7^{c}	12.2^{c}	99.6^{c}	103.1^{c}
26	19.7^{b}	18.7^{b}	157.1^{b}	162.7^{b}
39	26.3^{a}	28.7^{a}	203.5^{a}	221.2^{a}
LSD ($P<0.05$)	0.13	0.16	3.7	2.3
Variety (V)				
TGX 1985-10F	11.6^{d}	13.3^{c}	97.3^{d}	106.5^{d}
TGX 1987-10F	13.8^{c}	15.8^{b}	109.0^{c}	146.2^{b}
TGX 1448-2E	13.8^{c}	13.4^{c}	111.4^{c}	115.5^{c}
TGX 1987-62F	25.4^{b}	27.1^{a}	169.7^{b}	208.1^{a}
TGX 1989-19F	26.5^{a}	27.3^{a}	207.9^{a}	210.5^{a}
TGX 1835-10E	10.2^{e}	11.3^{d}	91.0^{e}	97.0^{e}
LSD (P<0.05)	0.16	0.29	5.4	6.1
Interaction				
P × V	*	*	NS	NS

Means of the same letter(s) in each column of the treatment group are not significantly different at a 5% significance level. LSD= Least Significant Difference NS = Not significant * = Significant at a 5% significance level

Table 2 shows the interaction of soybean variety and phosphorus rate on the number of nodules. The interaction of variety with phosphorous rate significantly ($P<0.05$) affected the number of nodules (Table 2). The highest number of nodules (27.3 & 28.3) was recorded for variety TGX 1989-19F with 39 kg P ha^{-1}, while the lowest (6.0 & 7.3) was for variety TGX 1835-10E with 0 kg P ha^{-1} (control) in 2018 and 2019 cropping seasons respectively. The observed increase in nodulation during the 2019 cropping season, irrespective of variety or phosphorus level, might be influenced by other environmental factors such as relative humidity, temperature, and rainfall. These external elements could play a role in stimulating the nodulation process alongside the specified factors of variety and phosphorus rate. The complexity of interactions between these variables makes it challenging to isolate the precise influence of each factor. However, their combined effect could significantly contribute to the observed increase in nodulation during the 2019 cropping season.

Table 2. Interaction between Phosphorus and Variety on the Number of Nodules of Soybean in Lafia during the 2018 and 2019 Cropping Seasons

	2018				2019			
	Phosphorus (kg ha^{-1})							
Variety	0	13	26	39	0	13	26	39
TGX 1985-10F	7.3^{q}	9.0^{o}	14.3^{ij}	15.7^{k}	7.7^{op}	9.7^{mn}	14.7^{hi}	21.3^{e}
TGX 1987-10F	8.0^{qp}	10.3^{n}	14.8^{i}	22.3^{e}	8.7^{on}	11.7^{k}	16.7^{fg}	26.3^{b}
TGX 1448-2E	7.3^{q}	10.3^{n}	17.7^{g}	19.8^{f}	7.3^{p}	10.3^{ml}	15.7^{hg}	20.3^{e}
TGX 1987-62F	8.7^{op}	11.3^{m}	24.3^{d}	26.3^{b}	11.7^{k}	14.3^{ji}	24.7^{d}	28.1^{a}
TGX 1989-19F	12.7^{l}	15.7^{h}	25.3^{c}	27.3^{a}	13.3^{j}	15.7^{hg}	26.3^{c}	28.3^{a}
TGX 1835-10E	6.0^{r}	7.7^{q}	13.3^{kl}	13.7^{kj}	7.3^{p}	11.3^{kl}	14.3^{ji}	17.0^{f}
LSD ($P<0.05$)	0.33				0.40			

Means of the same letter(s) in each column of the treatment group are not significantly different at a 5% significance level. LSD= Least Significant Difference NS = Not significant * = Significant at a 5% significance level

Effects of phosphorus and variety on soybean yields

Table 3 shows the influence of phosphorus levels and different soybean varieties on the pod number per plant for the 2018 and 2019 growing seasons. The results indicate that applying 39 kg of phosphorus per hectare resulted in significantly higher pod counts per plant (41.5 & 44.0) in both seasons. This aligns with the findings of (Mateus & Grandet, 2015), who reported that 40 kg of P_2O_5 per hectare led to a significantly higher pod count per plant (44.68 pods per plant; *p*=0.0101). Similarly, Mugendi (2010) observed a significant increase in pod count with the application of 50 kg of P_2O_5 ha^{-1}. Mobasser *et al*. (2014) also found significant differences in pod count with varying P levels. However, the results of this study contradict the findings of Alemu (2018), who reported that the different phosphorus rates had a non-significant effect on the pod count per plant.

Among the soybean varieties, TGX 1989-19F yielded the highest number of pods per plant (45.2 & 46.7), followed by TGX 1987-62F with (41.7 & 43.0), while TGX 1835-10E produced the lowest pod count per plant (23.3 & 24.1) in the 2018 and 2019 seasons respectively. This finding is consistent with Yeshitila *et al*. (2022), who observed pod yield variation among soybean varieties and suggested that genetic factors likely contributed to the significant differences in pod yield.

Similarly, the application of phosphorus significantly influenced the number of seeds per pod of soybean plants in both the 2018 and 2019 seasons (Table 3). In the 2018 season, phosphorus levels significantly increased the number of seeds per pod. In the 2019 season, 26 and 39 kg P ha^{-1} resulted in a statistically similar number of seeds per pod (2.8), which was significantly higher ($P<0.05$) than the 13 kg P ha^{-1} and control groups. Increasing phosphorus from 13 to 26 kg P ha^{-1} significantly boosted seed production, indicating phosphorus's positive impact on yield. However, there seems to be a point where adding more phosphorus does not significantly increase yield beyond a certain threshold, as observed in this parameter. This might be due to factors like plant nutrient saturation, where too much phosphorus does not enhance productivity further (Masood *et al*., 2011; Aimen *et al*., 2022). Additionally, environmental factors, including soil characteristics depicted in Figures 1a and 1b, could also limit the effectiveness of additional phosphorus. These limitations might lead to a plateau in seed production despite higher phosphorus levels. Although the number of seeds per pod plateaus, different parameters respond differently to increased phosphorus. For example, the number of nodules per plant and seed yield per hectare may continue to increase with higher phosphorus levels. This suggests that while the total production stabilizes, individual plant productivity and the overall field output might still benefit from higher phosphorus levels. This result was consistent with Khanam (2016), who reported that 175 kg ha^{-1} of Triple Super Phosphate (TSP) produced the most seeds per pod (2.98). Similarly, Hernandez and Cueuas (2003) reported a significantly higher number of seeds per pod when the highest rate (100 kg) of P_2O_5 ha^{-1} was used and the lowest value when no phosphorus was used. Additionally, in the 2018 season, TGX 1989-19F, TGX 1987-62F, and TGX 1987-10F varieties all had a similar number of seeds per pod (2.7), which was significantly higher ($P<0.05$) than the other varieties. In the 2019 season, TGX 1989-19F produced a significantly higher number of seeds per pod (2.8) than all other varieties evaluated.

Table 3. Effect of Phosphorus and Variety on the Number of Pods per Plant and Number of Seeds per Pod of Soybean in Lafia during the 2018 and 2019 Cropping Seasons

	Number of Pods per Plant		Number of Seeds per Pod	
Treatment	2018	2019	2018	2019
Phosphorus (kg ha^{-1})				
0	25.8^{d}	24.5^{d}	2.3^{d}	2.3^{c}
13	31.8^{c}	29.2^{c}	2.4^{c}	2.4^{b}
26	32.8^{b}	34.9^{b}	2.8^{b}	2.8^{a}
39	41.5^{a}	44.0^{a}	2.9^{a}	2.8^{a}
LSD ($P<0.05$)	0.19	0.16	0.03	0.03
Variety				
TGX 1985-10F	25.1^{e}	27.5^{e}	2.6^{b}	2.6^{b}
TGX 1987-10F	35.0^{c}	31.1^{c}	2.7^{a}	2.6^{b}
TGX 1448-2E	30.0^{d}	30.7^{d}	2.6^{ab}	2.6^{b}
TGX 1987-62F	41.7^{b}	43.0^{b}	2.7^{a}	2.6^{b}
TGX 1989-19F	45.2^{a}	46.7^{a}	2.7^{a}	2.8^{a}
TGX 1835-10E	23.3^{f}	24.1^{f}	2.5^{c}	2.5^{c}
LSD ($P<0.05$)	0.24	0.19	0.04	0.06
Interaction				
P × V	NS	NS	NS	NS

Means of the same letter(s) in each column of the treatment group are not significantly different at a 5% significance level. LSD= Least Significant Difference NS = Not significant * = Significant at a 5% significance level

Table 4 shows the effect of phosphorus and variety on the soybean seed yield per plant during the 2018 and 2019 cropping seasons. In both years, each increase in the rate of applied phosphorus significantly increased seed yield per soybean plant. The result also showed that the TGX 1987-62F variety produced more seed yield per plant, followed by TGX 1989-19F in 2018, while in 2019, TGX 1987-62F and TGX 1989-19F varieties recorded similar seed yield per plant but significantly higher than any other varieties tested.

The seed yield (kg ha^{-1}) of soybean was significantly (P<0.05) affected by phosphorus fertilizer application and the soybean variety in both the 2018 and 2019 cropping seasons (Table 4). The results indicate that with each increase in the rate of applied phosphorus, there was a significant (P<0.05) increase in seed yield per hectare of soybean in both years. The highest seed yields of 1561.3 and 1606.7 kg ha^{-1} were achieved in 2018 and 2019, respectively, when the crop was treated with 39 kg of phosphorus per hectare (Table 4). This result aligns with the conclusions of Mabapa *et al*. (2010), who reported that the highest soybean seed yields per hectare were obtained after applying 30-45 kg P ha^{-1}. Similarly, Rechiatu (2015) noted that increased phosphorus application led to an increase in seed yield per hectare, up to 40 kg ha^{-1}. There is also notable variation attributed to different levels of phosphorus fertilization in terms of the number of pods per plant, number of seeds per pod, seed yield per plant, and the weight of soybean per hectare. This finding corroborates the results of Dixit *et al*. (2011), who observed significant differences in the number of pods per plant, number of seeds per pod, seed yield per plant, and 100-seed weight of soybean when different phosphorus levels were applied.

In terms of soybean varieties, TGX 1989-19F exhibited the highest seed yield (1591.7 & 1624.0 kg ha^{-1}), followed by TGX 1987-62F (1543.3 & 1526.7 kg ha^{-1}) and TGX 1985-10F (1126.0 & 1160.7 kg ha^{-1}), while TGX 1835-10E showed the lowest yields (786.7 & 803.0 kg ha^{-1}) in the 2018 and 2019 cropping seasons, respectively (Table 4). The outstanding performance of TGX 1989-19F and TGX 1987-62F suggests their strong adaptability to the local agro-climatic conditions and their efficient utilization of applied phosphorus and available mineral resources compared to other varieties studied. Conversely, the lower yield observed in TGX 1835-10E indicates its lesser adaptability to the specific agro-climatic conditions of the study area (Tables 4 & 5). This result is consistent with the findings of Yeshitila *et al*. (2022), who noted significant genotypic variations among different varieties, with the Awassa-04 variety producing notably higher grain yields (1183 kg ha^{-1}) compared to Gazolia (950 kg ha^{-1}) and Nova (566 kg ha^{-1}).

Table 4. Effect of phosphorus and variety on the seed yield plant^{-1} and seed yield kg ha^{-1} of soybean in Lafia during the 2018 and 2019 cropping seasons

	Seed yield plant^{-1}(g)		Seed yield ha^{-1} (kg/ha)	
Treatment	2018	2019	2018	2019
Phosphorus (kg ha^{-1})				
0	8.6^{d}	11.4^{d}	949.0^{d}	958.0^{d}
13	12.3^{c}	13.9^{c}	1068.7^{c}	1110.0^{c}
26	19.2^{b}	18.3^{b}	1289.0^{b}	1306.0^{b}
39	24.7^{a}	25.2^{a}	1561.3^{a}	1606.7^{a}
LSD (P<0.05)	0.12	0.13	0.46	0.42
Variety				
TGX 1985-10F	12.4^{f}	12.2^{d}	834.0^{e}	853.3^{e}
TGX 1987-10F	15.7^{c}	19.9^{b}	1126.0^{c}	1160.7^{c}
TGX 1448-2E	18.1^{d}	18.3^{c}	949.3^{d}	952.0^{d}
TGX 1987-62F	24.2^{a}	26.9^{a}	1543.3^{b}	1526.7^{b}
TGX 1989-19F	25.8^{b}	27.2^{a}	1591.7^{a}	1624.0^{a}
TGX 1835-10E	12.9^{e}	11.6^{e}	786.7^{f}	803.0^{f}
LSD (P<0.05)	0.10	0.62	0.56	0.51
Interaction				
P × V	NS	NS	*	*

Means of the same letter(s) in each column of the treatment group are not significantly different at a 5% significance level LSD= Least Significant Difference NS = Not significant * = Significant at a 5% significance level

Table 5 shows the soybean variety and phosphorus rate interaction for seed yield kg ha^{-1}. The interaction of variety and phosphorous rate had a significant (P<0.05) effect on grain yield kg ha-1 (Table 5). The TGX 1989-19F variety had the highest grain yield kg ha$_{-1}$ (1597.3 & 1637.3) with 39 kg P_2O_5 ha^{-1}, followed by TGX 1987-62F (1556.0 & 1613.3) with 39 kg P_2O_5 ha^{-1}. The TGX 1835-10E variety, on the other hand, had the lowest grain yields (780.7 & 984.0) kg ha^{-1} when no phosphorus (0 kg P_2O_5 ha^{-1}) was applied in the control plots for the 2018 and 2019 cropping seasons, respectively. This increase in yield could be attributed to the greater nutrient availability resulting from higher phosphorus application levels and genetic variability among soybean varieties. Higher phosphorus levels in the soil could create a more conducive environment for the activities of rhizobia bacteria, which help convert atmospheric nitrogen to available nutrients for plant uptake (Fahde *et al*., 2023). This nutrient availability ensures that the plants have abundant resources to promote growth and development, ultimately resulting in increased yield. However, increased phosphorus levels can lead to soil acidification over time. This occurs because many phosphorus-containing fertilizers are acidic (Zama *et al*., 2022). Soil pH can drop due to the accumulation of hydrogen ions, which can negatively affect the availability of certain nutrients and impact microbial activity (Johan *et al*., 2021). This highlights the need to employ sustainable farming practices like liming and crop rotation, which can maintain an environment conducive to rhizobia while ensuring optimal plant growth and soil health. Moreover, different soybean varieties have varying abilities to utilize nutrients (Ene *et al*., 2019; Buah *et al*., 2020). In this study, soybean varieties, like TGX 1989-19F and TGX 1987-62F, might possess a higher inherent capacity to absorb and utilize nutrients efficiently, leading to superior yields when provided with adequate phosphorus. The synergy between phosphorus application and genetic variability among soybean varieties maximizes yield potential by optimizing nutrient uptake and utilization, ultimately translating into improved crop productivity.

Table 5. Interaction between Phosphorus and Variety on the seed yield kg ha^{-1} of soybean in Lafia during the 2018 and 2019 cropping seasons

	2018				2019			
	Phosphorus (kg ha^{-1})							
Variety	0	13	26	39	0	13	26	39
TGX 1985-10F	820.0^{v}	1008.0^{p}	1142.0^{m}	1254.0^{h}	841.3^{v}	1042.7^{q}	1186.7^{n}	1273.3^{g}
TGX 1987-10F	860.0^{t}	1095.0^{l}	1258.0^{g}	1415.0^{c}	855.3^{t}	1116.7^{m}	1271.3^{h}	1508.0^{c}
TGX 1448-2E	848.7^{u}	1066.0^{n}	1189.3^{j}	1306.7^{d}	846.7^{u}	1094.0^{o}	1213.3^{k}	1327.3^{d}
TGX 1987-62F	941.3^{s}	1136.0^{j}	1280.0^{f}	1556.0^{b}	960.7^{s}	1141.3^{l}	1308.0^{f}	1613.3^{b}
TGX 1989-19F	963.3^{r}	1147.3^{i}	1298.3^{e}	1597.3^{a}	971.7^{r}	1162.7^{i}	1320.0^{e}	1637.3^{a}
TGX 1835-10E	780.7^{w}	940.0^{q}	1086.7^{o}	1181.7^{k}	813.3^{w}	984.0^{p}	1132.0^{o}	1221.7^{j}
LSD ($P<0.05$)	1.04				1.13			

Means of the same letter(s) in each column of the treatment group are not significantly different at a 5% significance level. LSD= Least Significant Difference NS = Not significant * = Significant at a 5% significance level.

CONCLUSION

This study underscores the critical role of phosphorus in enhancing soybean nodulation and overall crop productivity in the southern Guinea savanna zone, particularly in the Lafia area of Nigeria. The results show a significant variation in soybean nodulation and yields when different phosphorus fertilizer rates are used. Among the six improved soybean varieties tested, TGX 1989-19F demonstrated exceptional performance consistently and significantly ($P<0.05$), yielding the highest values in all the variables measured when 39 kg P_2O_5 ha^{-1} was applied. The positive response of soybean varieties to higher phosphorus levels in this study could be attributed to the poor soil fertility status of the study site, as indicated in Figures 1a and 1b. However, while the response of soybean varieties to higher phosphorus levels enhanced productivity, it's important to acknowledge the potential long-term consequences. Increased phosphorus levels can inadvertently contribute to soil acidification over time, impacting soil health and necessitating careful monitoring and management. Therefore, it is recommended that alongside adopting the higher phosphorus rate (39 kg P_2O_5 ha^{-1}) in the form of single super phosphate and the TGX 1989-19F variety, smallholder farmers in this region pay attention to sustainable soil management practices. Specifically, implementing measures like liming can mitigate potential soil acidification and sustain soil health. This combination is to optimize soybean nodulation and subsequent yield gains. However, it is imperative to note that further research and on-farm trials are needed to validate these findings across diverse agroecological conditions and farming practices. This evidence-based approach presents a significant opportunity to advance food security, nutrition, and income generation for Nigerian smallholder farmers through improved soybean cultivation.

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ETHICAL STATEMENT

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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