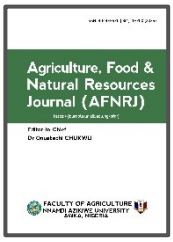
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Original Article

Influence of groundnut varieties and bradyrhizobium-phosphorus combination on soil nitrogen content in Maiduguri, Nigeria

OPEN ACCESS

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ABSTRACT

A field experiment was conducted at the University of Maiduguri Teaching and Research Farm to evaluate the effects of Bradyrhizobium inoculation and phosphorus application on soil nitrogen content. Treatments comprised a factorial combination of three groundnut varieties (SAMNUT24, Bomboy and Exdakar) and six inoculant-phosphorus combinations ($Br_0 + P_0$, $Br_0 + P_{40}$, $Br_0 + P_{60}$, $Br_1 + P_0$, $Br_1 + P_{40}$ and $Br_1 + P_{60}$), where Br_0 and Br_1 represent uninoculated and inoculated plants, respectively, while P_0, P_{40} and P_{60} denote phosphorus application rates of 0, 40 and 60 kg P_2O_5 ha^{-1}, arranged in a Randomized Complete Block Design with three replications. Nitrogen concentration and content in groundnut, biological nitrogen fixation, and soil nitrogen content before and after the experiment were assessed. Data were analysed using analysis of variance at the 5% significance level. Bradyrhizobium-phosphorus combinations significantly influenced nitrogen derived from the atmosphere (Ndfa) and soil nitrogen content. Varietal effects on nitrogen fixation were significant, with Bomboy recording the highest nitrogen fixed (47.428 kg N ha^{-1}) and Ndfa (82.746%). SAMNUT24 contributed 1.135 g kg^{-1} soil nitrogen, representing a 63.06% increase over the initial value. Variety × inoculant-phosphorus interactions significantly affected root nitrogen content ($p = 0.034$), Ndfa ($p = 0.023$) and soil nitrogen content ($p = 0.001$). Bomboy + $Br_1 + P_{40}$ maximised nitrogen fixation, whereas SAMNUT24 + $Br_1 + P_0$ produced the highest post-harvest soil nitrogen content (1.77 g kg^{-1}). These combinations are recommended for improving nitrogen fixation and soil nitrogen status, respectively, under similar conditions.

KEYWORDS: *Arachis hypogaea, Bomboy, Exdakar, Ndfa, N-fixed, SAMNUT24*

INTRODUCTION

The major part of the elemental nitrogen that finds its way into the soil is entirely due to its fixation by certain specialized group of microorganisms which some, form a symbiotic relationship with legumes (McInnes & Haq, 2007). Biological Nitrogen Fixation (BNF) is considered to be an important process which determines nitrogen balance in soil ecosystem. The process is one way of converting elemental nitrogen into plant usable form (Gothwal *et al.,* 2007). The major portion of biological nitrogen fixation is carried out by the symbiotic nitrogen fixers such as *rhizobium* (Pervin *et al*., 2017). Nitrogen-fixing bacteria (NFB), transform inert atmospheric N_2 to organic compounds (Sara & Kawtar, 2014), through which the aerobic nitrogen is fixed, thereby reaching the soil via nodules (Mohammad *et al*., 2012). The process is mediated by nitrogennase enzymes and is very important to the biological activity of soil (Sadik *et al*., 2016). Based on ability to fix nitrogen, *Rhizobia* are classified into slow

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(*Bradyrhizobium*) and fast growing *(Rhizobium)* species (Mamun *et al*., 2013; Kumar *et al*., 2014).

Under field condition, groundnut, though a legume with huge gap in biological nitrogen fixation to meet its demands (Sharma, 2020), may establish symbiosis with both native and introduced *rhizobia* strains (Andrade *et al*., 2023) and may result in abundant nodule formation (Jovino *et al*., 2022). Nodules are the sites of nitrogen fixation, from which fixed nitrogen reaches the soil. Each major legume crop is nodulated by distinct species of *rhizobium* (Shefali, 2011).

The effectiveness of *Bradyrhizobia* populations in fixing nitrogen is correlated with soil fertility status where acidic soils have been reported to contain less effective *Bradyrhizobia* strains (Lebrazi *et al*., 2014). Soils of Sudan savanna, though slightly acidic to neutral have been reported to contain less effective *Bradyrhizobia* populations and also, information about their contribution to soil nitrogen content has not been well documented. The use of adequate population of *Bradyrhizobia* in the presence of phosphorus may enhance nitrogen fixation to improve the soil nitrogen status of soils (Adjei-Nsiah *et al*., 2018).

In the semi-arid Sudan Savanna agro-ecological zone of Maiduguri, crop production is heavily constrained by severely depleted soil fertility, characterized by extremely low organic and declining nitrogen content. Available phosphorus, which plays a vital role in establishing an effective symbiotic relationship between a legume and a given R*hizobium*, is also low in soils of the Sudan savanna.

Although groundnut (*Arachis hypogaea* L.) can fix atmospheric nitrogen through rhizobial symbiosis, the extent to which this fixed nitrogen translates into post-harvest soil nitrogen enrichment depends on cultivar-specific nitrogen partitioning. While certain genotypes retain most fixed nitrogen within their harvested tissues, others significantly replenish the soil nitrogen pool through root exudation, nodule turnover, and root decomposition.

Moreover, interactive effects of groundnut genotype, Bradyrhizobium inoculation, and phosphorus fertilization on residual post-harvest soil nitrogen restoration remain inadequately documented in semi-arid soils. Therefore, this study evaluated the factorial combinations of three groundnut varieties (SAMNUT24, *Bomboy*, and *Exdakar*), Bradyrhizobium seed inoculation, and phosphorus application rates to identify optimal management pairings specifically tailored for maximizing post-harvest soil nitrogen build-up in Maiduguri, Nigeria

MATERIALS AND METHOD

Study Site

The experiment was conducted during the 2024 rainy season at the University of Maiduguri Teaching and Research Farm (11˚47′53″N – 11˚47′58″N and 13˚11′48″E – 13˚11′50″E). The area characterized by a semi-arid tropical climate. Recently, seasonal climate in Maiduguri was characterized by a delayed onset of rains and a compressed wet season, which created a shorter window for agricultural activities. Despite these shorter durations, above-average rainfall volumes were experienced (historical baseline; 650 mm), leading to a high-intensity weather event. Furthermore, elevated temperatures exceeding historical baselines (34^{o}C) were also recorded (Nigerian Meteorological Agency, 2025). The region lies within the Sudan savanna agro-ecological zone. The soils in Maiduguri are largely Entisols from aeolian sands, formed by wind-drift from the Sahel (Food and Agriculture Organization [FAO] & International Crops Research Institute for the Semi-Arid Tropics [ICRISAT], 2019).

Experimental Materials and Design

Native Bradyrhizobium sp. inoculant was trapped and isolated from root nodules of groundnuts using method described by Motsara & Roy (2008) while P_2O_5 was from single super phosphate fertilizer. Three groundnut varieties were evaluated: SAMNUT24, an improved cultivar released by the Institute for Agricultural Research (IAR), Samaru, Zaria (Ajeigbe *et al.*, 2014); and two locally adapted varieties, *Bomboy* and *Exdakar*, commonly grown in Borno State and obtained from the Borno State Agricultural Development Programme (BOSADP). The experiment was laid out in a randomized complete block design (RCBD) with three replications. Treatments consisted of factorial combinations of three groundnut varieties and six Bradyrhizobium–phosphorus levels:

i. $Br_0 + P_0$ (uninoculated seeds – 0ml slurry mixture of inoculant/kg seed + 0 kg P_2O_5 ha^{-1}),
ii. $Br_0 + P_{40}$ (uninoculated seeds – 0ml slurry mixture of inoculant/kg seed + 40 kg P_2O_5 ha^{-1}),
iii. $Br_0 + P_{60}$ (uninoculated seeds – 0ml slurry mixture of inoculant/kg seed + 60 kg P_2O_5 ha^{-1}),
iv. $Br_1 + P_0$ (inoculated seeds – 60ml slurry mixture of inoculant/kg seed + 0 kg P_2O_5 ha^{-1}),
v. $Br_1 + P_{40}$ (inoculated seeds – 60ml slurry mixture of inoculant/kg seed + 40 kg P_2O_5 ha^{-1}),
vi. $Br_1 + P_{60}$ (inoculated seeds – 60ml slurry mixture of inoculant/kg seed + 60 kg P_2O_5 ha^{-1}).

Each plot measured 3 m × 3 m (9 m²), with inter-block and intra-block spacings of 1.0 m and 0.5 m, respectively. Millet was grown in adjacent plots as a reference (non-fixing) crop for nitrogen fixation calculations.

Seed Inoculation for Sowing in the Field

Thirty grams (30 g) of carrier-based *Bradyrhizobium* inoculant, was added to sticker solution (made with 60 ml of water, one percent (1 %) sucrose and 1 % gum Arabic) and it was thoroughly mixed. To this mixture, a 1 kg of groundnut seed was added, mixed, dried under shade and sown immediately. This was done to each of the varieties.

Determination of Some Soil Properties

Samples of soils from the experimental site were collected before sowing and were analyzed for particle sizes, soil pH, electrical conductivity, exchangeable cations (Ca, Mg, K and Na), organic matter/organic carbon, available phosphorus and total nitrogen using standard methods as described by Durak *et al*. (2007). After harvest, soil samples from each plot were collected for determination of total soil nitrogen content. Total nitrogen was determined using the Kjheldal distillation method as presented by Kacar (1997).

Agronomic Practices

All agronomic management practices followed International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) recommendations for groundnut production in Sudan Savannah (Ajeigbe *et al*. 2014).

Data Collection and computations

Total plant nitrogen content: This parameter was determined using Kjeldahl method.

Shoot and root nitrogen concentrations (g kg^{-1}): These were determined separately. Nitrogen content in each of the fractions (kg N ha^{-1}) was computed as:

$$Total\ N\ in\ Plant = \frac{Dry\ matter\ weight\ x\ concentration\ of\ N\ in\ plant\ (g\ kg{-}1)}{1000} \quad (1)$$

The amount of N fixed and the percent N derived from fixation (%Ndfa): These were estimated using reference crop method (Mary *et al*., 1995).

$$N\ fixed = Total\ N\ in\ legume - Total\ N\ in\ reference\ crop \quad (2)$$

$$\%\ Ndfa = \frac{Total\ N\ in\ legume - Total\ N\ in\ reference\ crop}{Total\ N\ in\ legume}\ x\ 100 \quad (3)$$

Reference crop = Millet. Millet dry weight = 1048.53 kg/ha. Concentration of N in millet = 7.6 g/kg. Total N in reference crop = 7.97 kg/ha (computed using the equation above for total N in plant). N in millet plots = 1.8 g/kg

Contribution to soil nitrogen content: The amount of N contributed to soil was computed as:

$$Nitrogen\ contributed\ (g\ kg - 1) = Soil\ N\ in\ groundnut\ plots - Soil\ N\ in\ millet\ plots \quad (4)$$

Data Analysis

Data were subjected to Analysis of Variance (ANOVA) using *Statistix 10.0*. Means comparison was done using the Least Significant Difference (LSD) test at 5% significance level.

RESULTS AND DISCUSSIONS

Baseline Soil Properties

Baseline soil properties show conditions typical of a Sudan Savanna agro-ecological zone. The soil was sandy loam, neutral (pH = 6.91) and non-saline (electrical conductivity = 0.09 dS m^{-1}) with very low available phosphorus, necessitating addition of phosphorus to support the growth of pulses in the soils and effective rhizobial symbiosis (Adjei-Nsiah *et al*., 2018). The baseline soil total nitrogen content before sowing was (1.80 g/kg) which is a medium concentration of total nitrogen for Sudan Savanna soils. However, in absolute agronomic terms for tropical semi-arid soils, total soil N consists predominantly of organic forms that are not immediately available for crop uptake without ongoing microbial mineralization. Organic matter (0.67 %) and organic carbon (0.39 %) were extremely low, reflecting a poor structural stability and limited capacity to sustain high biological activity. However, the neutral pH of the soil is favourable for microbial activity and nutrient availability (Brady & Weil, 2012), therefore, partially compensating for the low organic matter status of the soil. The cat-ion exchange capacity was moderate (13.03 $cmol^{(+)}$ kg^{-1}) while percentage base saturation was high, with calcium and magnesium ions being the dominant cations (Table 1).

Table 1: Particle Size Analysis and some selected chemical properties of the experimental site

Soil Property	Value
% Clay	19.7
% Sand	67.8
% Silt	12.5
Soil Textural Class	Sandy Loam
Soil pH in H_2O (1:2.5)	6.91
Electrical Conductivity, EC (dSm^{-1})	0.09
Organic Carbon, O.C (g/kg)	3.9
Organic Matter, O.M (g/kg)	6.7
Nitrogen, N (g/kg)	1.80
C:N	2.17
Phosphorus, P (mg/kg)	2.8
Calcium ion, Ca^{2+} ($cmol^{(+)}$/kg Soil)	8.2
Magnesium ion, Mg^{2+} ($cmol^{(+)}$/kg Soil)	4.2
Potassium ion, K^{+} ($cmol^{(+)}$/kg Soil)	0.52
Sodium ion, Na^{+} ($cmol^{(+)}$/kg Soil)	0.11
Cation Exchange Capacity, CEC ($cmol^{(+)}$/kg Soil)	13.03

Influence of Groundnut Variety and Bradyrhizobium-Phosphorus Combinations on Nitrogen Content and Fixation by Groundnut

Table 2 summarised results for nitrogen content and fixation in groundnut. Effect of variety on concentration of N in shoot (g kg^{-1}), shoot N content (kg ha^{-1}), Total N in groundnut and N-fixed were statistically significant ($P < 0.05$). *Bomboy* cultivar recorded

the highest values across these parameters consistently, including the highest Ndfa (82.746 %) and highest total N-fixed (47.428 kg N ha^{-1}). Concentration of N in root (g kg^{-1}) was not significantly affected by the variety while the effects on root N content (kg N ha^{-1}) were significant. *Exdakar* and *Bomboy* were observed to be statistically similar in Ndfa, and both were superior than SAMNUT24. The significant effects of variety on shoot N concentration, shoot and total N content, and biological nitrogen fixation shows that the compatibility of variety and Bradyrhizobium is a primary limiting factor for nitrogen fixation in groundnut under Sudan Savanna conditions. The superiority of the *Bomboy* cultivar in all fixation-related parameters is consistent with the widely reported influence of crop genotype on symbiotic effectiveness (Abi-Ghanem *et al.*, 2011; Yakubu *et al.*, 2010).

Effects of Bradyrhizobium-P treatments concentration of nitrogen in shoots and roots were non-significant. However, shoot N content was significantly higher under $Br_1 + P_{40}$ compared to $Br_1 + P_{60}$. Total N in groundnut and N-fixed were highest under $Br_1 + P_{40}$ and $Br_0 + P_{40}$ were $Br_1 + P_{60}$ had lowest values. Nitrogen derived from atmosphere, Ndfa (%) was significantly ($P < 0.05$) influenced, with uninoculated control treatment having the lowest value (72.937 %). The non-significant effect of Bradyrhizobium-P combinations in the current study, on nitrogen concentration in shoot and root tissues, despite its significant effect on Ndfa, suggests that inoculation and phosphorus supplementation enhanced the fixation process itself but did not always translate into proportionally higher nitrogen concentration in plant tissue. This may reflect internal dilution effects as biomass increased, hence, aligning with findings of Andrade *et al.* (2023), who observed non-significant effects of Bradyrhizobium inoculation on shoot and root nitrogen concentration in groundnut. In contrast, the significant effect of Bradyrhizobium-P treatments on Ndfa observed in the present study is consistent with the role of an adequate, compatible *Bradyrhizobia* population in enhancing symbiotic nitrogen fixation when supported by sufficient phosphorus (Adjei-Nsiah *et al.*, 2018).

Variety × Bradyrhizobium-P interaction was significant for root nitrogen content and nitrogen derived from atmosphere, Ndfa (Table 3). *Bomboy* + $Br_1 + P_{40}$ combination recorded the highest root nitrogen content (177.80 kg ha^{-1}), followed by *Bomboy* + $Br_0 + P_{40}$ (147.53 kg ha^{-1}). For Ndfa, higher fixation values were observed across most interaction combinations, with the notable exception of SAMNUT24 under $Br_0 + P_0$, $Br_0 + P_{40}$, and $Br_1 + P_0$, and *Exdakar* under $Br_1 + P_{60}$, which were observed to have recorded comparatively lower values.

The significant variety × Bradyrhizobium-P interaction for root nitrogen content and Ndfa shows that the effect of inoculation and phosphorus is not uniform across varieties. The combination *Bomboy* + $Br_1 + P_{40}$ achieving the highest root nitrogen content and among the highest Ndfa values, is an indication of an optimum P level of 40 kg P_2O_5 ha^{-1} for this cultivar when inoculated. This is supported by Naabe *et al.* (2021), who demonstrated that both P fertilisation and Bradyrhizobium inoculation, at appropriate rates, can promote nitrogen accumulation. The observed decrease in Ndfa under *Exdakar* + $Br_1 + P_{60}$ suggests that at higher phosphorus levels, the competitive advantage of symbiotic fixation may diminish, possibly due to suppression of nodulation by elevated inorganic N availability.

Table 2: Influence of variety and Bradyrhizobium-phosphorus combinations on nitrogen content and fixation in groundnut

Treatment	N Shoot (g kg^{-1})	Shoot N content (kg N ha^{-1})	N Root (g kg^{-1})	Root N content (kg N ha^{-1})	Total N in groundnut (kg N ha^{-1})	N-fixed (kg N ha^{-1})	Ndfa (%)
Variety (V)							
SAMNUT24	19.261^{b}	29.317^{b}	26.600^{a}	7.303^{b}	36.621^{b}	28.651^{b}	75.842^{b}
Bomboy	25.978^{a}	44.096^{a}	31.372^{a}	11.302^{a}	55.398^{a}	47.428^{a}	82.746^{a}
Exdakar	20.528^{b}	35.705^{ab}	28.967^{a}	8.499^{b}	44.204^{b}	36.234^{b}	79.069^{ab}
SE±	2.180	4.5586	3.514	1.1442	4.7096	47.096	2.1347
Bradyrhizobium + Phosphorus (F)							
$Br_1 + P_{60}$	20.067^{a}	28.687^{b}	29.478^{a}	7.447^{b}	36.132^{b}	28.162^{b}	75.203^{bc}
$Br_1 + P_{40}$	23.711^{a}	39.957^{ab}	34.111^{a}	11.073^{a}	51.028^{a}	43.058^{a}	82.812^{a}
$Br_1 + P_0$	24.189^{a}	36.111^{ab}	27.889^{a}	9.776^{ab}	45.888^{ab}	37.918^{ab}	81.273^{ab}
$Br_0 + P_{60}$	21.778^{a}	39.338^{ab}	25.589^{a}	7.854^{ab}	47.194^{ab}	39.224^{ab}	81.087^{ab}
$Br_0 + P_{40}$	22.167^{a}	42.292^{a}	29.233^{a}	10.074^{ab}	52.369^{a}	44.399^{a}	82.000^{a}
$Br_0 + P_0$ (Control)	19.622^{a}	31.852^{ab}	27.578^{a}	7.982^{ab}	39.836^{ab}	31.866^{ab}	72.937^{c}
SE±	3.083	6.4469	4.970	1.6181	6.6604	6.6604	3.0189
Interaction							
V x F	NS	NS	NS	*	NS	NS	*

*Means followed by the same letter(s), within each column, are not statistically different at 5% level of significance according to Least Significant Difference (LSD) test. Br_0 = not inoculated, Br_1 = inoculated with Bradyrhizobium spp., P0 = 0 kg P2O5/ha, P40 = 40 kg P2O5/ha, P60 = 60 kg P2O5/ha, NS = not significant, * = significant at 5% level of Significance.*

Table 3: Interaction between variety and Bradyrhizobium-phosphorus combinations for root nitrogen content and nitrogen derived from atmosphere (Ndfa)

Variety	SAMNUT24		*Bomboy*		*Exdakar*	
Br + P	Root N content (kg ha^{-1})	Ndfa (%)	Root N content (kg ha^{-1})	Ndfa (%)	Root N content (kg ha^{-1})	Ndfa (%)
$Br_o + P_o$	46.07^{d}	60.677^{d}	97.63^{bcd}	79.31^{ab}	95.77^{bcd}	78.823^{ab}
$Br_o + P_{40}$	69.03^{cd}	76.867^{bc}	147.53^{ab}	87.297^{ab}	85.67^{cd}	81.837^{ab}
$Br_o + P_{60}$	104.87^{bc}	82.527^{ab}	64.43^{cd}	77.39^{ab}	66.33^{cd}	83.343^{ab}
$Br_1 + P_o$	89.5^{cd}	76.763^{bc}	93.23^{bcd}	84.317^{ab}	110.53^{bc}	82.74^{ab}
$Br_1 + P_{40}$	70.47^{cd}	79.563^{ab}	177.8^{a}	87.78^{a}	83.93^{cd}	81.093^{ab}
$Br_1 + P_{60}$	58.23^{cd}	78.653^{ab}	97.47^{bcd}	80.38^{ab}	67.7^{cd}	66.577^{cd}
SE ±	28.026	5.2288	28.026	5.2288	28.026	5.2288

Means followed by the same letter(s), within each column, are not statistically different at 5% level of significance according to Least Significant Difference (LSD) test. Br_o = not inoculated, Br_1 = inoculated with Bradyrhizobium spp., P_0 = 0 kg P_2O_5/ha, P_{40} = 40 kg P_2O_5/ha, P_{60} = 60 kg P_2O_5/ha

Influence of Variety and Bradyrhizobium-Phosphorus Combinations on Post-harvest Soil Nitrogen Content

Effect of variety and combined application of Bradyrhizobium with phosphorus on soil nitrogen content is presented in Table 4. The result showed that varietal effects on soil nitrogen were significant ($P < 0.05$). SAMNUT24 significantly contributed to the soil N content, with a record of 2.935 g kg^{-1} post-harvest soil N level, corresponding to a contribution of 1.135 g kg^{-1} and a 63.06% increase above the reference crop plots (1.8 g kg^{-1}). Least contribution to soil nitrogen (0.852 g kg^{-1}; 47.33% increase) was observed with Bomboy cultivar, despite having the highest nitrogen fixed, suggesting that higher proportion of the fixed nitrogen was retained within the cultivar's tissue rather than releasing to the soil. This difference in nitrogen release dynamics suggests that SAMNUT24 possibly released high N-rich compounds through root exudates, nodule turnover and root decomposition, whereas *Bomboy* variety may retain a great portion of fixed N within its tissues. Hence, the concepts of differential N use partitioning among different legume genotypes (Brady & Weil, 2012).

Effect of Bradyrhizobium-P on soil N content (g kg^{-1}) was shown in Table 4. Treatment combinations $Br_1 + P_0$ (2.987 g kg^{-1}) and $Br_0 + P_{60}$ (2.988 g kg^{-1}) recorded the highest soil nitrogen levels and were both significantly greater than $Br_1 + P_{40}$ (2.633 g/kg). Moreover, these two treatments were also observed to record highest amount of N contribution to the soil, with 1.187 g/kg and 1.188 g/kg contributions respectively and a corresponding percentage increase of 65.94 % and 66.00 % respectively.

There was contribution to soil N level with Bradyrhizobium-P combinations with reference to millet plots soil N. The study showed that the native Bradyrhizobium specie found on the experimental site are capable of increasing soil nitrogen content through fixation, when their population is adequate and a compatible variety is grown.

Table 4: Influence of Bradyrhizobium combined with phosphorus on soil nitrogen content

Treatment	Soil N (g/kg)	[x]Amount of N Contributed (g/kg)	[y]Percentage increase in soil N
Variety (V)			
SAMNUT24	2.935^{a}	1.135^{a}	63.06
Bomboy	2.652^{b}	0.852^{b}	47.33
Exdakar	2.853^{a}	1.053^{ab}	58.50
SE±	9.952 x 10^{-2}	9.952 x 10^{-2}	-
Bradyrhizobium + Phosphorus (F)			
$Br_1 + P_{60}$	2.787^{a}	0.987^{ab}	54.83
$Br_1 + P_{40}$	2.633^{b}	0.833^{b}	46.28
$Br_1 + P_0$	2.987^{a}	1.187^{a}	65.94
$Br_0 + P_{60}$	2.988^{a}	1.188^{a}	66.00
$Br_0 + P_{40}$	2.771^{a}	0.971^{ab}	53.94
$Br_0 + P_0$ (Control)	2.714^{a}	0.914^{ab}	50.78
SE±	0.141	0.141	-
Interaction			
V x F	**	**	

*Means followed by the same letter(s), within each column, are not statistically different at 5% level of significance according to Least Significant Difference (LSD) test. Br_o = not inoculated, Br_1 = inoculated with Bradyrhizobium spp., P_0 = 0 kg P_2O_5/ha, P_{40} = 40 kg P_2O_5/ha, P_{60} = 60 kg P_2O_5/ha, NS = not significant, * = significant at 5% level of Significance. ** = significant at 1% level of Significance [x]Amount of N Contributed (g/kg) in relation to Millet Plots Soil N (1.8g/kg N). [y]Percentage increase in soil N in relation to Millet Plots Soil N.*

More so, P was shown to be very vital in enhancing the soil N level. Performance of treatments $Br_1 + P_0$ and $Br_0 + P_{60}$ with respect to their soil nitrogen-building abilities (2.987 – 2.988 g kg^{-1}) suggests that either Bradyrhizobium inoculation alone or application of phosphorus alone (at 60 kg P_2O_5 ha^{-1}) can give similar results with respect to soil nitrogen contributions but through different pathways. Inoculation enhances symbiotic nitrogen fixation through an increased in effective symbiotic bacterial population, while phosphorus fertilization improves energetics of fixation by phosphorus required for generation of ATP. The reduced soil nitrogen observed under treatment $Br_1 + P_{40}$ may suggest intermediate phosphorus level at which neither of the nutrient acquisition mechanism operates at efficiency.

The variety × Bradyrhizobium–P interaction for soil nitrogen content and nitrogen contribution was highly significant (Table 5). The highest soil nitrogen values were recorded under SAMNUT24 + $Br_1 + P_0$ (3.57 g kg^{-1}; N contributed = 1.77 g kg^{-1}), SAMNUT24 + $Br_0 + P_{60}$ (3.363 g kg^{-1}; 1.563 g kg^{-1}), and *Exdakar* + $Br_1 + P_{60}$ (3.347 g kg^{-1}; 1.547 g kg^{-1}), which were statistically similar to one another. The highly significant variety × Bradyrhizobium-P interaction for soil nitrogen content confirms that the response of individual varieties to inoculation and phosphorus is context-specific. The consistently superior performance of SAMNUT24 + $Br_1 + P_0$ across all interaction combinations identifies it as the most practical combination for soil nitrogen improvement. The fact that SAMNUT24 + $Br_0 + P_{60}$ and *Exdakar* + $Br_1 + P_{60}$ were statistically equivalent to this best combination offers farmers multiple viable agronomic options, which is valuable where either inoculant or phosphorus fertilizer may be locally unavailable.

Table 5: Interaction between variety and Bradyrhizobium combined with phosphorus for Soil N content (g/kg) and [x]Amount of N (g/kg) contributed to soil N content

Variety	SAMNUT24		*Bomboy*		*Exdakar*	
Br + P	Soil N (g/kg)	[x]Amount of N Contributed (g/kg)	Soil N (g/kg)	[x]Amount of N Contributed (g/kg)	Soil N (g/kg)	[x]Amount of N Contributed (g/kg)
$Br_0 + P_0$	2.613^{cd}	0.813^{cd}	2.66^{cd}	0.86^{cd}	2.87^{bcd}	1.07^{bcd}
$Br_0 + P_{40}$	2.947^{bc}	1.147^{bc}	2.567^{cd}	0.767^{cd}	2.8^{cd}	1.00^{cd}
$Br_0 + P_{60}$	3.363^{ab}	1.563^{ab}	2.94^{bcd}	1.14^{bcd}	2.66^{cd}	0.86^{cd}
$Br_1 + P_0$	3.57^{a}	1.77^{a}	2.66^{cd}	0.86^{cd}	2.73^{cd}	0.93^{cd}
$Br_1 + P_{40}$	2.67^{cd}	0.87^{cd}	2.52^{cd}	0.72^{cd}	2.71^{cd}	0.91^{cd}
$Br_1 + P_{60}$	2.447^{d}	0.647^{d}	2.567^{cd}	0.767^{cd}	3.347^{ab}	1.547^{ab}
SE ±	0.244	0.244	0.244	0.244	0.244	0.244

Means followed by the same letter(s), within each column, are not statistically different at 5% level of significance according to Least Significant Difference (LSD) test. Br_o = not inoculated, Br_1 = inoculated with Bradyrhizobium spp., P_0 = 0 kg P_2O_5/ha, P_{40} = 40 kg P_2O_5/ha, P_{60} = 60 kg P_2O_5/ha. [x]Amount of N Contributed (g/kg) in relation to Millet Plots Soil N (1.8g/kg N).

CONCLUSION AND RECOMMENDATION

The findings demonstrate that groundnut cultivars exhibit distinct nitrogen-use partitioning strategies. The variety SAMNUT24 contributed the highest post-harvest soil nitrogen content (2.935 g/kg N), representing a 1.135 g/kg (63.06 %) increase over the baseline soil level, driven by root exudation, nodule turnover, and root decomposition. Among treatment interactions, the SAMNUT24 + $Br_1 + P_0$ combination achieved the highest post-harvest soil nitrogen enrichment (3.57 g/kg total N with 1.77 g/kg contributed N), followed closely by SAMNUT24 + $Br_0 + P_{60}$ (3.363 g/kg N) and *Exdakar* + $Br_1 + P_{60}$ (3.347 g/kg N). Based on the findings of this study, it is recommended that Farmers aiming to enrich soil nitrogen for subsequent cereal crop rotation in the Sudan savanna should adopt SAMNUT24 inoculated with Bradyrhizobium. Where bio-inoculants are unavailable, applying 60 kg P_2O_5 ha^{-1} to uninoculated SAMNUT24 or combining inoculation with 60 kg P_2O_5 ha^{-1} on *Exdakar* are highly effective alternative choices.

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Authors' contributions

MIY managed data collection, analysis and interpretation of the data and wrote the first draft of the manuscript. ALN managed the development of methodology and provided guidance on use of analytical software for data analysis. RA managed material

support and review of manuscript. AKH & IMB participated in the laboratory work and management of crop at the field.

Ethical Statement

Not applicable.

AI Declaration Statement

The authors declare that no Artificial Intelligence (AI) tools were used in the generation, analysis, interpretation or writing of this manuscript. However, a portion of drafted manuscript was uploaded to notebookLM to provide some grounded responses based on the content of original writeup.

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