

EFFECTS OF RHIZOBIAL INOCULATION, STARTER NITROGEN, PHOSPHATE-SOLUBILIZING BACTERIA, AND PHOSPHORUS FERTILIZATION ON NUTRIENT UPTAKE, NODULATION, AND YIELD OF BAMBARA GROUNDNUT [*VIGNA SUBTERRANEA* (L.) VERDC.]

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Abstract

Bambara groundnut [*Vigna subterranea* (L.) Verdc.] is an underutilized African legume with high nutritional value and resilience to marginal environments. However, poor soil fertility, particularly nitrogen (N) and phosphorus (P) deficiencies, constrains productivity in smallholder systems. This study comprised of two experiments which evaluated the effects of rhizobial inoculation and biological nitrogen fixation, and phosphate-solubilizing bacteria (PSB) and phosphorus on nodulation, nutrient uptake, and yield of Bambara groundnut in Minjibir, Kano State. Field experiments were conducted using a randomized complete block design with four replications. In Experiment I, treatments included rhizobia inoculation with or without starter nitrogen (20 kg N/ha). Rhizobia significantly increased nodulation, %Ndfa, shoot N concentration, and grain yield. The combined rhizobial + starter N treatment produced the highest yield (1756 kg/ha), representing a 125% increase over the control (780 kg/ha). In Experiment II, PSB inoculation was combined with phosphorus rates of 0, 20, 40, and 60 kg P/ha. PSB enhanced phosphorus uptake, root colonization, and yield. The most favourable response was observed at 40 kg P/ha + PSB, which increased seed yield to 1750 kg/ha compared with 760 kg/ha in the control. These findings demonstrate that combining microbial inoculants with balanced nutrient management substantially improves Bambara groundnut productivity while reducing reliance on inorganic fertilizers. Adoption of locally adapted rhizobial and PSB inoculants offers a promising strategy for sustainable legume production and food security in low-input farming systems across sub-Saharan Africa.

Keywords: Bambara groundnut, rhizobial, phosphate-solubilizing bacteria, nitrogen fixation, phosphorus uptake, yield

1. Introduction

Bambara groundnut [*Vigna subterranea* (L.) Verdc.] is an important indigenous African grain legume widely valued for its adaptability to drought-prone and low-input environments and its contribution to food security in sub-Saharan Africa (Bamshaiye *et al.*, 2021; Kundy *et al.*, 2023).

The crop is predominantly grown by smallholder farmers and plays a vital role in household nutrition and livelihood resilience under marginal growing conditions (Tan *et al.*, 2020). Its seeds are rich in protein, carbohydrates, essential amino acids, and micronutrients, making it a nutritionally valuable but still underutilized legume (Maphosa *et al.*, 2022).

Legume productivity remains low in sub-Saharan Africa due to low soil fertility and inadequate agronomic management practices (Muoni *et al.*, 2022). Nitrogen and phosphorus are among the most limiting nutrients for Bambara groundnut production in tropical agroecosystems. Nitrogen is essential for vegetative growth, protein formation, and seed development, while phosphorus plays a key role in energy transfer, root development, nodulation, and biological nitrogen fixation (Pueyo *et al.*, 2021).

In many West African soils, phosphorus availability is strongly constrained by fixation with iron and aluminium oxides, leading to low phosphorus-use efficiency despite apparently adequate total soil phosphorus levels (Pouangam Ngalani *et al.*, 2023). Biological nitrogen fixation through rhizobial symbiosis offers a sustainable strategy for improving nitrogen availability in legumes. Effective rhizobial inoculation enhances nodulation, nitrogen fixation, plant growth and grain yield. However, its effectiveness is influenced by soil fertility, environmental conditions, inoculant quality and host–microbe compatibility (Fwanyaga *et al.*, 2021; Bitire *et al.*, 2022).

Similarly, phosphate-solubilizing bacteria (PSB) are increasingly recognized for their ability to enhance phosphorus availability through the secretion of organic acids and phosphatases, thereby improving nutrient uptake and crop productivity (Singh *et al.*, 2021). The integration of beneficial microbial inoculants is therefore considered a promising approach for improving fertiliser uptake and sustainable crop production in legumes (Alzate Zuluaga *et al.*, 2024). Despite evidence of positive effects of rhizobial inoculation, and phosphate-solubilizing bacteria on legumes performance, limited information exists on the response of Bambara groundnut to microbial inoculation combined with different mineral nutrient application under Nigerian field conditions. Rhizobial inoculation with starter nitrogen, and PSB inoculation with phosphorus fertilizer applications represent distinct nutrient-management strategies that require independent evaluation. Therefore, the study evaluated the effects of rhizobial inoculation and starter nitrogen application, determined the effects of phosphate-solubilizing bacteria inoculation and phosphorus fertilizer rates on nodulation, nutrient acquisition and grain yield of Bambara groundnut under field condition of Minjibir, Kano State, Nigeria.

2. Literature Review and Theoretical Framework

Bambara groundnut is increasingly recognized as an important underutilized grain legume with considerable potential to enhance food and nutritional security in sub-Saharan Africa because of its adaptability to marginal environments and capacity for biological nitrogen fixation. Despite these advantages, its productivity remains low, largely because of poor soil fertility, particularly deficiencies in nitrogen (N) and phosphorus (P), which limit nodulation, nutrient acquisition, and grain yield. Recent studies have demonstrated that the effectiveness of biological nitrogen fixation in Bambara groundnut

depends not only on the presence of compatible rhizobia but also on adequate nutrient availability, especially phosphorus, which plays a central role in nodule formation and nitrogenase activity (Abdulai *et al.*, 2024).

Consequently, reliance on either mineral fertilizers or microbial inoculants alone may not fully exploit the crop's production potential under smallholder farming conditions. The present study is underpinned by the Integrated Nutrient Management (INM) framework, which advocates the complementary use of biological and inorganic nutrient sources to improve nutrient availability, nutrient use efficiency, soil health, and crop productivity while minimizing environmental impacts. Within this framework, rhizobial inoculation promotes biological nitrogen fixation through symbiotic association with legume roots, whereas phosphate-solubilizing bacteria (PSB) enhance phosphorus availability by converting poorly available phosphorus forms into plant-accessible forms. Studies across several grain legumes indicate that small starter nitrogen applications can support early vegetative growth without significantly suppressing biological nitrogen fixation, although the magnitude of this response varies with host genotype, soil fertility, and environmental conditions (Ciampitti & Salvagiotti, 2018; Han *et al.*, 2026).

These observations reinforce the conceptual basis for integrating biological inoculants with judicious nutrient management rather than considering them as alternative technologies. Evidence from both national and international studies further supports the role of phosphate-solubilizing microorganisms in improving phosphorus nutrition, particularly in highly weathered tropical soils where phosphorus is strongly fixed by iron and aluminium oxides.

Alori *et al.* (2017) demonstrated that microbial phosphorus solubilization enhances nutrient availability through biochemical mechanisms that improve phosphorus uptake and plant growth, while Li *et al.* (2021) further emphasized the agronomic potential of phosphate-solubilizing microorganisms for sustainable crop production. Similarly, recent syntheses have shown that microbial inoculants can enhance nutrient acquisition and contribute to soil ecosystem functioning and sustainable crop production, potentially reducing reliance on mineral fertilisers (O'Callaghan *et al.*, 2022).

However, most of these studies have focused on major legumes such as soybean, chickpea, and common bean, with comparatively limited attention given to Bambara groundnut, despite its strategic importance for climate-resilient agriculture. Although research on rhizobial inoculation has expanded considerably in recent years, important knowledge gaps remain. Existing studies have largely evaluated rhizobia or phosphate-solubilizing bacteria independently, whereas relatively few have investigated their combined application in Bambara groundnut under field conditions. Furthermore, inoculant performance is highly influenced by host genotype, indigenous microbial populations, soil physicochemical properties, and environmental conditions, making it inappropriate to directly extrapolate findings from other legume species to Bambara groundnut. Recent reviews have also highlighted uncertainties regarding the persistence of introduced inoculant strains, their competitiveness with native microbial communities, and their long-term effectiveness in low-input production systems across Africa (Fasusi *et al.*, 2023; Fwanyanga *et al.*, 2022).

These unresolved issues underscore the need for location-specific evaluations that integrate microbial inoculation within broader nutrient management strategies. Against this background, the present study contributes to the advancement of current knowledge by evaluating the combined effects of rhizobial

and phosphate-solubilizing bacterial inoculation on Bambara groundnut under an integrated nutrient management framework. By focusing on an under-researched indigenous legume grown under Nigerian conditions, the study extends current understanding of beneficial plant–microbe interactions beyond extensively studied legumes and provides empirical evidence on the potential of combined microbial inoculants to enhance nutrient uptake, improve fertiliser use efficiency, and sustain crop productivity in low-input farming systems.

The findings are expected to strengthen the scientific basis for developing nutrient management strategies that support sustainable agricultural intensification and food security in sub-Saharan Africa.

3. Materials and Methods

3.1. Study design and context

Experimental Site

Two independent field experiments were conducted concurrently during the 2025 cropping season at Minjibir, Kano State, Nigeria. The experimental site is located within the Sudan Savanna agro-ecological zone at latitude 12.0°N and longitude 8.5°E. The area experiences an average annual rainfall of 800 – 900 mm, concentrated between June and September, with average daily temperatures ranging from 30°C to 35°C. The soil of the area is predominantly sandy loam with relatively low fertility, a characteristic common to the Sudan Savanna region of northern Nigeria. Experiment I evaluated the effects of rhizobial inoculation and starter nitrogen application and yield of Bambara groundnut. The treatments comprised a non-inoculated control, rhizobial inoculated alone, starter nitrogen application at 20 kg N/ha, and a combination of rhizobial inoculation with 20 kg N/ha. Experiment II independently evaluated the response of Bambara groundnut to phosphate-solubilizing bacteria (PSB) inoculation in combination with different phosphorus fertiliser rates. The treatments comprised the uninoculated control, 20 kg P/ha + PSB, 40 kg P/ha + PSB, 60 kg P/ha + PSB, and 40 kg P/ha applied without PSB. Each experiment was arranged as a Randomized Complete Block Design (RCBD) with four replications.

3.2. Data, variables, and sampling

Certified seeds of Bambara groundnut were obtained from the Genetic Resources Unit of the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. Effective strains of Brady rhizobium inoculants and Bacillus were sourced from the IITA Microbiology Unit. Nitrogen fertilizer was supplied as urea (46% N), while phosphorus fertilizer was applied in the form of Single Superphosphate (SSP). Prior to land preparation, composite soil samples were collected from the experimental field at a depth of 0 – 15 cm using a soil auger. Several soil cores were randomly collected across the field and bulked into a composite sample. The samples were air-dried, crushed and sieved through a 2-mm mesh before laboratory analysis. The soil samples were analysed at the IITA Analytical Services Laboratory following standard procedures. Particle size distribution was determined using the hydrometer method. Soil pH was measured in a 1:1 soil-water suspension using a glass electrode pH meter. Total nitrogen was determined by the Micro-Kjeldahl digestion method, while available phosphorus was analysed using the Bray-1 extraction procedure. Exchangeable potassium (K), sodium (Na), calcium (Ca), and magnesium (Mg) were extracted using neutral ammonium acetate (NH₄OAc). Potassium and sodium concentrations were determined using a flame photometer, while calcium and magnesium were determined using an atomic absorption spectrophotometer. Exchangeable acidity was determined by

extracting 2.5 g of soil with 25 mL of 1 N KCl and titrating 10 ml of the extract with 0.01 M NaOH using phenolphthalein as an indicator. Effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable bases and exchangeable acidity. Percentage base saturation was calculated using the equation: Base Saturation (%) = $[(Ca + Mg + K + Na) / ECEC] \times 100$.

Experiment I: Rhizobial + Nitrogen

The treatments consisted of control, Rhizobial inoculation, 20 kg N/ha, Rhizobial inoculation + 20 kg N/ha. Each plot measured 4 m × 4 m (16 m²). A 1 m alley separated adjacent plots and blocks to minimize treatment interference. The experimental field was manually cleared and subsequently ploughed and harrowed to obtain a fine seedbed. Glyphosate herbicide was applied at the rate of 3 – 4 L/ha two weeks before planting to control existing vegetation. The field was then marked out into plots according to the experimental layout using measuring tapes, pegs, and ropes. Bambara groundnut seeds were sowed manually by dibbling at a spacing of 0.5 m × 0.5 m. Each plot consisted of 64 plants, resulting in a total of 1,024 plant populations. The rhizobial inoculant used in Experiment I was *Bradyrhizobium japonicum* strain FA3. The FA3 inoculant was applied as a seed coating using an inoculant slurry immediately before planting. The inoculum concentration was standardized to approximately 10⁸ CFU mL⁻¹ (colony-forming units per millilitre). The coated seeds were allowed to dry briefly under shade before planting. The inoculated procedure was intended to facilitate establishment of the rhizobial inoculant and promote nodulation and biological nitrogen fixation. Manual weeding was carried out at three-week intervals after planting to maintain weed-free plots. The field was regularly monitored for insect pests and diseases, and appropriate integrated pest management (IPM) measures were implemented whenever necessary. The experiment was conducted under rain-fed conditions. The crop was harvested at physiological maturity approximately 120 days after sowing. Nodulation Parameters: Nodulation assessment was carried out at 45 and 75 days after planting (DAP). Five plants were randomly selected from each plot and carefully uprooted. Root systems were washed gently under running water to remove adhering soil particles without damaging nodules. The number of nodules per plant was counted manually, after which the nodules were detached and oven-dried at 65°C until constant weight to determine nodule dry weight. Yield and Yield Components: At harvest, the following yield parameters were recorded: Nodule per plant, Number of nodule dry weight, %Ndfa, Shoot N, Number of pods per plant, Pod weight per plant (g), 100-seed weight (g) and Total seed yield per plot (kg). Seed yield obtained from each plot was converted to kilogram per hectare (kg/ha) for statistical analysis. Nitrogen Uptake and Biological Nitrogen Fixation were determined by collecting the Shoot samples at flowering, were oven-dried, milled, and analysed for total nitrogen concentration using the Kjeldahl digestion procedure. Biological nitrogen fixation was estimated using the isotope dilution technique and expressed as percentage nitrogen derived from the atmosphere (%Ndfa). %Ndfa was calculated using the formula: $\%Ndfa = (1 - \delta^{15}N_{legume} / \delta^{15}N_{reference}) \times 100$. Where: $\delta^{15}N_{legume}$ is the isotopic value of Bambara groundnut, $\delta^{15}N_{reference}$ is the isotopic value for sorghum (a non-fixing crop grown in the same area). The %Ndfa values were used to evaluate the effectiveness of rhizobial inoculation in enhancing atmospheric nitrogen fixation by Bambara groundnut.

Experiment II: Phosphate-Solubilizing Bacteria (PSB) + Phosphorus Fertilizer

Sowing of seeds

Phosphate-solubilizing bacteria (PSB) used in Experiment II was *Bacillus megaterium* obtained at the Soil Microbiology Laboratory, International Institute of Tropical Agriculture (IITA) were used as the microbial inoculant. The PSB inoculant was applied to Bambara groundnut seeds as a coating immediately before planting using an inoculant slurry. The inoculated seeds were allowed to dry briefly under shade before sowing. The PSB inoculation was intended to enhance phosphorus acquisition by the crop. Bambara groundnut seeds were sown in plots treated with phosphorus fertilizer supplied as single superphosphate (SSP) at varying levels of 20, 40 and 60 kg P/ha. A randomized complete block design (RCBD) with five treatments and four replicates was used. This gave a total of 20 plots. Each plot measured 4 m x 4 m (16 m²) with both rows and columns separated by 1 meter. Bambara groundnuts were sown at a spacing of 0.5 m x 0.5 m, which gave 64 plants per plot. The total plant population contained 1,280 plant populations. Treatments include: Control, 20 kg P/ha + PSB inoculation, 40 kg P/ha + PSB inoculation, 60 kg P/ha + PSB inoculation and Sole 40 kg P/ha. Data were collected on pod number per plant, pod weight, 100-seed weight, total seed yield per plot, harvest index. For PSB treatments, seeds were similarly coated with phosphate-solubilizing bacterial inoculants immediately before planting. Molybdate-blue assay was used to determine the nutrient uptake parameters (shoot and seed phosphorus concentration). Phosphorus uptake (shoot and seed P), root colonization percentage, and yield components (pods per plant, 100-seed weight, seed yield).

3.3. Analytical methods

Data obtained from each experiment were subjected to analysis of variance. The two experiments were analysed separately because they represented independent experiments with different treatment structures. Treatment means were separated using Duncan's Multiple Range Test (DMRT) at 5% probability level when significant treatment effects were detected. Statistical significance was declared at $P < 0.05$.

4. Results

Table 1 below shows the soil physical and chemical properties of the experimental site before sowing. The soil is near neutral with a pH of 6.4. The organic carbon content (15.2 g/kg) of the soil, which is beneficial for soil fertility and nutrient availability. The total nitrogen content (0.28 g/kg) of the soil is relatively low, indicating that there may be a need for nitrogen fertilizer application. The available phosphorus content (4.0 mg/kg) of the soil is low, indicating that it may be necessary to apply phosphorus fertilizer to improve crop productivity. The exchangeable cations (Ca, Mg, K and Na) are low in concentration.

Table 1. Pre-planting soil physical and chemical properties of the experimental site

Soil Parameter	Values
pH (H ₂ O) 1:1	6.4
Organic carbon (g kg ⁻¹)	15.2
Total Nitrogen (g kg ⁻¹)	0.3
Available phosphorus (mg kg ⁻¹)	4
Exchangeable cations (cmol kg⁻¹)	
Calcium	3.5

Soil Parameter	Values
Magnesium	1.1
Potassium	0.2
Sodium	0.7
Exchangeable Acidity (cmol kg ⁻¹)	0.5
Particle size distribution (g kg⁻¹)	
Sand	838.0
Silt	46.0
Clay	116.0
Textural class	Sandy loam

Source: Authors' field sampling and laboratory analysis (2025).

Note: g kg⁻¹ – gram per kilogram, mg kg⁻¹ – milligram per kilogram, cmol kg⁻¹ – centimole per kilogram

Experiment I: Rhizobial Inoculation and Starter Nitrogen.

As shown on Table 2, Rhizobial inoculation significantly influenced the measured nodulation and nitrogen fixation compared with the control. At 45 days after planting (DAP), inoculated plants produced 50 nodules per plant with a dry weight of 0.24 g, while the control had only 18 nodules and 0.08 g dry weight. The combined treatment of rhizobia + starter nitrogen (20 kg N/ha) gave the highest response, with 62 nodules per plant, 0.26 g dry weight, and 77% Ndfa, compared with 44% Ndfa in the control. Shoot nitrogen concentration increased from 20 g kg⁻¹ in the control to 34 g kg⁻¹ under rhizobia + N treatment.

Table 2. Nodulation and Nitrogen Fixation

Treatments	No. of nodule/plant	Nodule dry wt.(g/plant)	%Ndfa	Shoot N (g/kg)
Control	18 ^a	0.08 ^a	44 ^a	20 ^a
Rhizobia	50 ^b	0.24 ^b	70 ^b	30 ^b
20 kg N/ha	24 ^c	0.14 ^c	58 ^b	26 ^c
Rhizobia + 20 kg N/ ha	62 ^d	0.26 ^d	77 ^c	34 ^d
SEM (±)	11.5	0.02	13.0	1.5

Means in the same column followed by different superscript letters are significantly different by DMRT at (P<0.05).

Note: No. – Number, wt. – weight, g – gram, kg – kilogram, %Ndfa – percentage of nitrogen derived from the atmosphere, N – nitrogen, ha – hectares, SEM (±) – standard error of mean

In Table 3, the yield components followed a similar trend. Rhizobial inoculation alone increased seed yield from 780 kg/ha (control) to 1160 kg/ha, while starter N alone produced 1120 kg/ha. The combined rhizobia + N treatment achieved the highest yield of 1756 kg/ha, with improved pod number (27 pods per plant) and seed weight (60 g per 100 seeds). These results demonstrate the synergistic effect of rhizobia and starter nitrogen in enhancing Bambara groundnut productivity.

Table 3. Yield Components (Rhizobia x Nitrogen)

Treatments	Pods/plant	100-seed wt. (g)	Seed yield (kg/ha)
Control	16 ^a	52 ^a	780 ^a
Rhizobia	22 ^c	56 ^c	1160 ^c
20 kg N/ha	18 ^b	54 ^b	1120 ^b

Treatments	Pods/plant	100-seed wt. (g)	Seed yield (kg/ha)
Rhizobia + 20 kg N/ha	27 ^d	60 ^d	1756 ^d
SEM (±)	1.2	1.0	120

Means in the same column followed by different superscript letters are significantly different by DMRT at ($P < 0.05$).

Note: wt. – weight, g – gram, kg – kilogram, N – nitrogen, ha – hectares, SEM (±) – standard error of mean

Experiment II: Phosphate-Solubilizing Bacteria (PSB) and Phosphorus Fertilizer.

As presented on Table 4, phosphate-solubilizing bacteria (PSB) inoculation significantly influenced phosphorus uptake and root colonization responses.

Table 4. Phosphorus Uptake and Root Colonization

Treatments	Shoot P (mg/kg)	Seed P (mg/kg)	Root Colonization (%)
Control	2410 ^e	3400 ^e	12 ^e
20 kg P + PSB	3000 ^c	3680 ^d	42 ^b
40 kg P + PSB	3650 ^b	4560 ^b	60 ^a
60 kg P + PSB	4050 ^a	5050 ^a	64 ^a
Sole 40 kg P	3180 ^d	4110 ^c	18 ^d
SEM (±)	150	180	4.0

Means in the same column followed by different superscript letters are significantly different by DMRT at ($P < 0.05$).

Note: Mg/kg– milligram per kilogram, P – phosphorus, PSB – phosphate solubilizing bacteria, SEM (±) – standard error of mean

Shoot phosphorus concentration increased from 2410 mg/kg in control to 4050 mg/kg under 60 kg P/ha + PSB. Seed phosphorus content recorded lowest value of 3400 mg/kg in control and highest value of 5050 mg/kg under 60 kg P/ha + PSB. Root colonization was highest under the same treatment compared with only 12% in the control. Sole phosphorus application resulted in lower colonization (18%) despite moderate P uptake.

Table 5 shows the yield components which also improved significantly with PSB inoculation. The control produced 760 kg/ha, while 40 kg P/ha + PSB treatment recorded the highest numerical seed yield (1750 kg/ha), with increased pod number (28 pods per plant) and seed weight (63 g per 100 seeds). Higher phosphorus rates of 60 kg/ ha + PSB (1,744 kg/ha) did not further increase yield substantially, suggesting that 40 kg P/ha combined with PSB was the most efficient treatment.

Table 5. Yield Components (PSB x P)

Treatments	Pods per plant	100-seed wt. (g)	Seed yield (kg/ha)
Control	16 ^e	52 ^e	760 ^d
20 kg P + PSB	20 ^d	55 ^d	1256 ^c
40 kg P + PSB	28 ^b	63 ^a	1750 ^a
60 kg P + PSB	27 ^a	62 ^b	1744 ^a
Sole 40 kg P	23 ^c	58 ^c	1460 ^b
SEM (±)	1.5	1.2	130

Means in the same column followed by different superscript letters are significantly different by DMRT at ($P < 0.05$).

Note: kg/ha – kilogram per hectare, wt. – weight, g – gram, P – phosphorus, SEM (±) – standard error of mean

5. Discussion

The soil at the experimental site was classified as sandy loam, with a high sand content (838.0 g/kg), low silt (46 g/kg), and minimal clay (116 g/kg). This texture, while promoting aeration and drainage, is known for poor water retention, which can limit moisture availability during pod formation. However, Bambara groundnut has demonstrated adaptability to such soils, especially when amendments are used to improve moisture conservation. The slightly acidic pH (6.4) falls within the optimal range for Bambara groundnut cultivation.

These results (Table 2 and 3) indicate that the application of a modest starter nitrogen dose promoted early plant establishment without inhibiting Rhizobia infection and subsequent symbiotic nitrogen fixation. This finding agrees with Han *et al.* (2026), who reported that efficient Rhizobia–legume symbiosis enhances nodulation, nitrogen fixation, and nitrogen assimilation through coordinated molecular signalling between the host plant and rhizobial strains. Similarly, Kaschuk *et al.* (2022) demonstrated that Rhizobial inoculation significantly improves nodule formation, nitrogenase activity, and plant nitrogen accumulation, particularly when integrated with complementary agronomic practices. The sole application of 20 kg N/ha increased shoot nitrogen concentration relative to the control but resulted in fewer nodules and lower nodule dry weight than the Rhizobia-inoculated treatments. This observation supports the well-established concept that the availability of mineral nitrogen reduces the dependence of legumes on biological nitrogen fixation because plants preferentially absorb readily available soil nitrogen, thereby suppressing nodule initiation and activity (Barbieri *et al.*, 2023). However, the relatively low nitrogen rate used in this study appeared to function effectively as a starter fertiliser when combined with Rhizobial inoculation, providing sufficient nitrogen for early vegetative growth while allowing active nitrogen fixation after nodulation was established. The improvements in nodulation and nitrogen fixation were reflected in the yield components. The superior yield under the combined treatment suggests that improved nitrogen availability throughout the crop growth cycle enhanced photosynthetic capacity, biomass accumulation, assimilate translocation, and seed filling.

These findings are consistent with those of Ciampitti *et al.* (2021), who reported that sustained biological nitrogen fixation improves biomass production, nitrogen partitioning, and grain yield by ensuring adequate nitrogen supply during critical growth stages. Likewise, Ciampitti and Salvagiotti (2018) observed that integrating effective Rhizobial symbiosis with appropriate nitrogen management enhances reproductive development, seed filling, and final grain yield in legumes. The substantial increase in seed yield obtained under the combined treatment therefore highlights the agronomic advantage of integrating Rhizobial inoculation with a low rate of starter nitrogen to maximize productivity while reducing dependence on synthetic nitrogen fertilizers.

The enhanced phosphorus uptake observed following the combined application of phosphorus fertilizer and phosphate-solubilizing bacteria (PSB) highlights the complementary roles of mineral phosphorus and beneficial rhizosphere microorganisms in improving plant phosphorus nutrition. Phosphorus is an essential macronutrient involved in energy transfer, photosynthesis, nucleic acid synthesis, and root development; however, much of the phosphorus applied to agricultural soils is rendered unavailable through fixation with calcium, iron, and aluminium compounds. Phosphate-solubilizing bacteria overcome this limitation by secreting organic acids, phosphatases, and other metabolites that solubilize insoluble phosphate compounds and mineralize organic phosphorus, thereby increasing the pool of

plant-available phosphorus (Sharma *et al.*, 2013). This finding is consistent with the report of Alori *et al.* (2017), who demonstrated that inoculation with phosphate-solubilizing microorganisms enhances phosphorus availability, improves phosphorus acquisition, and increases fertilizer uptake under diverse soil conditions. The greater phosphorus accumulation in plant tissues following integrated phosphorus and PSB application further suggests that microbial inoculation enhanced the utilization of applied phosphorus fertilizer rather than merely increasing phosphorus supply. Beneficial microorganisms improve phosphorus use efficiency by continuously mobilizing sparingly soluble phosphorus fractions and maintaining phosphorus availability throughout crop growth, thereby minimizing phosphorus fixation losses.

Similar observations have been reported, with phosphate-solubilizing microorganisms contributing to phosphorus transformation and increasing phosphorus availability and plant uptake, thereby supporting plant growth and crop productivity (Zhu *et al.*, 2024).

Likewise, Li *et al.* (2021) reported that integrating phosphate-solubilizing microorganisms with phosphorus fertilization enhances phosphorus uptake, improves nutrient use efficiency, and reduces the need for excessive phosphorus fertilizer application, thereby contributing to environmentally sustainable crop production. The improved root colonization observed under the integrated treatments further emphasizes the importance of successful establishment of phosphate-solubilizing bacteria within the rhizosphere. Effective colonization enables these microorganisms to maintain close associations with plant roots, facilitating continuous phosphorus solubilization and efficient nutrient transfer throughout the growing season. In addition to increasing phosphorus availability, phosphate-solubilizing bacteria stimulate root proliferation, enhance rhizosphere microbial activity, and produce plant growth-promoting substances that collectively improve nutrient acquisition and plant performance. These findings agree with Pang *et al.* (2024), who reported that successful colonization of the rhizosphere by beneficial microorganisms strengthens plant–microbe interactions, enhances nutrient acquisition, and improves crop productivity through increased biological activity in the root zone. The positive association between root colonization and phosphorus uptake observed in the present study therefore indicates that effective microbial establishment was a major contributor to the improved phosphorus nutrition and fertilizer use efficiency achieved under integrated nutrient management. The combined application of mineral phosphorus and PSB enhances phosphorus bioavailability, improves fertilizer use efficiency, and promotes greater nutrient acquisition, thereby supporting higher crop productivity while minimizing phosphorus losses and reducing the environmental impacts associated with excessive phosphorus fertilizer use (Alori *et al.*, 2017; Rashid *et al.*, 2024).

6. Conclusions

The study demonstrated that rhizobial inoculation and starter nitrogen application influenced nodulation, nitrogen acquisition and yield of Bambara groundnut in Experiment I. The study demonstrated that integrating microbial inoculants with balanced nutrient management significantly improved nutrient acquisition, biological nitrogen fixation, and productivity of Bambara groundnut under the low-fertility conditions of the Sudan Savanna of Nigeria. Rhizobial inoculation, particularly when combined with a starter nitrogen application of 20 kg N/ha, enhanced nodulation, percentage nitrogen derived from the atmosphere (%Ndfa), shoot nitrogen concentration, and grain yield compared with the uninoculated control. In Experiment II, PSB inoculation combined with phosphorus

fertilizer influenced phosphorus-related responses and yield, with 40 kg P/ha + PSB recording the highest numerical seed yield, although it was statistically comparable with 60 kg P/ha + PSB.

6.1. Practical and policy implications

The results of this study have important implications for farmers, extension services, researchers, and agricultural policymakers. The combination of rhizobial inoculation with a low starter nitrogen rate (20 kg N/ha) and the integration of phosphate-solubilizing bacteria with 40 kg P/ha represent practical nutrient management options capable of improving nutrient uptake, nutrient use uptake, and Bambara groundnut productivity under low-input farming conditions. Adoption of these practices can reduce fertilizer requirements, lower production costs, improve soil biological activity, and enhance the sustainability of grain legume production. The responses observed with rhizobial inoculation plus starter nitrogen and PSB combined with phosphorus fertilizer application warrant further evaluation under different soil, climatic and management conditions.

6.2. Limitations and future research

The study was conducted at one location during a single cropping season; consequently, the observed treatment responses may vary under different soil, climatic and management conditions. In addition, the two experiments were conducted independently and did not constitute a single factorial experiment involving rhizobial, PSB, nitrogen and phosphorus. Therefore, direct interactions among all four factors cannot be inferred. Further studies should evaluate microbial inoculant performance across multiple locations and seasons and should employ factorial designs where the objective is to quantify interactions among microbial inoculant and mineral nutrients.

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