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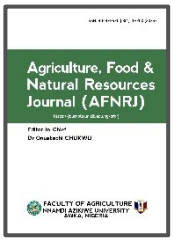

Original Article

Evaluation of arbuscular mycorrhizal fungi on the growth and yield of soybean [*Glycine max* (L.) Merrill]

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Jimoh Jamiu MUHAMMED[1,2]*, Nurudeen Olatunbosun ADEYEMI[2], Abiodun Abass OTUN[3], Gboyega Peter ADEBAYO[4] & Tunde Samuel OLUWATUYI[4]

[1]*International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.*
[2]*Department of Plant Physiology and Crop Production, Federal University of Agriculture, Abeokuta, Nigeria.*
[3]*National Biotechnology Research and Development Agency, FCT, Abuja, Nigeria.*
[4]*Department of Soil Resources Management, Faculty of Agriculture, University of Ibadan, Nigeria.*

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ABSTRACT

Soybean [Glycine max (L.) Merrill] is a vital grain legume and oilseed crop, valued for its protein and oil content, and increasingly cultivated in Nigeria's rainforest and savanna agro-ecological zones. Its productivity is often limited by poor soil nutrient availability, particularly phosphorus. Arbuscular mycorrhizal fungi (AMF) enhance nutrient uptake, water relations, and stress tolerance, thereby improving crop yield. This study evaluated the effects of AMF inoculation on soybean growth and yield under field conditions at the Federal University of Agriculture, Abeokuta, Nigeria. A split-plot randomized complete block design was used, with two soybean cultivars (TGx 1448-2E and TGx 1440-1E) as main plots and four AMF treatments (Funneliformis mosseae, Rhizophagus irregularis, Clariodeoglomus etunicatum, and a non-inoculated control) as subplots. Plant growth variable data was collected and subjected to analysis of variance and significant means were separated using Fisher's Least Significant Difference at $p < 0.05$. Results showed that TGx 1448-2E recorded higher leaf numbers, early leaf area, and yield attributes, while TGx 1440-1E attained greater plant height at 8 weeks after sowing. Inoculation with Funneliformis mosseae and Rhizophagus irregularis produced the most significant improvements in plant growth and yield compared to the control. These findings show the potential of indigenous AMF, particularly Funneliformis mosseae, as sustainable biofertilisers for enhancing soybean productivity in phosphorus-deficient soils. The study provides a foundation for integrating AMF inoculation into soybean production systems, contributing to food security, soil fertility improvement, and climate-resilient agriculture in tropical environments.

KEYWORDS: *Funneliformis mosseae, Inoculation, Soil fertility, Soybean cultivars*

INTRODUCTION

Soybean [*Glycine max* (L.) Merrill] is a globally important legume and oilseed crop, valued for its high protein and oil content, and widely cultivated for food, feed, and industrial purposes. In Nigeria, soybean cultivation has expanded across savanna and rainforest agro-ecological zones due to its economic importance and role in food security (Soretire *et al*., 2020). Despite its potential, soybean productivity is constrained by soil nutrient limitations, particularly phosphorus (P), which is immobile and poorly available in tropical soils (Ngosong *et al*., 2022). Phosphorus deficiency remains a major limiting factor in crop productivity, reducing growth and yield, and necessitating sustainable nutrient management strategies. Phosphorus (P) is an essential macronutrient that plays a critical role in soybean growth, development, and productivity. It is involved in energy transfer and storage through ATP, thereby supporting photosynthesis, root development, flowering, pod formation, and seed maturation. Adequate P availability also enhances root proliferation and is particularly important for

*Corresponding author: muhammedjamiuadam@gmail.com

biological nitrogen fixation because nodulation and N_2 fixation are energy-demanding processes. Phosphorus deficiency can therefore restrict nodulation, nitrogen fixation, biomass accumulation, and ultimately soybean yield. The demand for P increases during reproductive development, particularly during pod formation and seed filling. Consequently, appropriate P management is essential for achieving optimum soybean growth, nutrient uptake, nodulation, and grain yield (Bagale, 2021; Mirriam *et al*., 2023). Soil microorganisms play a critical role in nutrient cycling and plant nutrition. Soil microorganisms, including bacteria, fungi, archaea and protozoa, play important roles in nutrient cycling and plant nutrition. Beneficial groups such as *Rhizobium*, phosphate-solubilising bacteria (PSB), *Bacillus*, *Pseudomonas* and *arbuscular mycorrhizal* fungi (AMF) contribute to nutrient availability and plant growth. AMF were selected in this study because, unlike many other beneficial microorganisms, they form a direct symbiotic association with plant roots and produce extensive extra-radical hyphae that explore soil beyond the root nutrient-depletion zone, thereby enhancing the acquisition of poorly mobile nutrients, particularly phosphorus (P) (Smith *et al.,* 2012; Begum *et al*., 2019; Cardoso *et al*., 2019). Among them, *arbuscular mycorrhizal* fungi (AMF) form symbiotic associations with plant roots, enhancing nutrient uptake, especially phosphorus and improving plant resilience under stress conditions (Springer, 2023). AMF are obligate biotrophs whose hyphae extend root systems, improving nutrient absorption and contributing to ecosystem functions such as soil aggregation, pathogen suppression, and carbon turnover. Recent studies highlight their role in improving soybean tolerance to abiotic stresses such as drought and salinity, while also enhancing yield performance (Baltazar-Bernal *et al*., 2022; Masenya *et al*., 2025). However, the effectiveness of AMF varies across agro-ecological zones, and native species may offer unique advantages in local soils. In Nigeria's transitional rainforest agro-ecology, the potential of indigenous AMF isolates to improve soybean growth and yield remains underexplored. Given the increasing challenges of climate variability, soil nutrient depletion, and rising food demand, identifying cost-effective and environmentally sustainable approaches to enhance nutrient availability is a priority. Evaluating native AMF isolates provides an opportunity to harness naturally adapted microbial resources for improved soybean productivity and sustainable agriculture. The objective of this study is therefore to evaluate the effect of three native arbuscular mycorrhizal fungi species on the growth and yield performance of soybean cultivars in the transitory rainforest agro-ecology.

MATRIALS AND METHODS

Experimental Location

experiment was conducted at the Directorate of University Farms (DUFARMS), Federal University of Agriculture, Abeokuta (FUNAAB), Ogun State, southwestern Nigeria, which lies between latitudes 7°14′04″ and 7°14′07″ N and longitudes 3°26′07″ and 3°26′10″ E. The area experiences a tropical climate characterized by distinct wet and dry seasons, with an annual rainfall of approximately 1,200 – 1,500 mm. Abeokuta has a mean annual temperature of approximately 26.6°C (Ganiyu *et al*., 2019), and relative humidity often above 70% during the wet season. The experiment was conducted between June, 2023 and September, 2023.**Experimental Design and Treatments**

A split-plot randomized complete block design (RCBD), with three replications was used. Main plots consisted of two soybean cultivars (TGx 1448-2E and TGx 1440-1E), while subplots included four *arbuscular mycorrhizal* fungi (AMF) treatments: *Funnerliformis mosseae, Rhizophagus irregulare, Clarioglomus etunicatum* and a non-inoculated control. In total, 24 subplots were established.

Soil Analysis

Composite soil samples (0-15 cm depth) were collected, air-dried, sieved, and analysed for physical and chemical properties prior to planting.

Planting Materials Plots Layout

Certified soybean seeds were obtained from the Institute of Agricultural Research and Training (IART), Ibadan, Oyo State, Nigeria. Each gross plot measured 4 m × 4 m with a net plot of 3 m × 3m. Walkway of 0.5 m separated plots, and 1 m separated replicates. Two seeds were sown per hole at 50 × 10 cm spacing and thinned to one plant per stand at 2 weeks after sowing. This gave a total of 369 plants per plot.

AMF Inoculation

AMF inocula were sourced from the soil Microbiology Department, FUNAAB, originally isolated from local soybean rhizosphere soils. Inocula were multiplied on maize in sterilized sand-soil medium before application.

Cultural Practices

Weeding was done manually at 3, 6, 9, and 12 weeks after sowing (WAS). Harvesting occurred when 95% of pods reached physiological maturity.

Climatic Data

Climatic data for the period of the experiment was obtained from the Water Resources and Agro-meteorology Department (FUNAAB) to compute the average for rainfall, evapo-transpiration, temperature, solar radiation and relative humidity.

Data Collection

Five plants from the net rows per plot were randomly tagged with rope two weeks after sowing for the collection of growth and development parameters while plants on the border rows were harvested periodically for destructive sampling.

Data were collected on the following growth parameters at two weeks interval (4, 6, and 8 WAS).

Plant height (cm): The height of soybean plants was measured using meter rule from the base of the plant to the collar of the topmost leaf in the plant.

Number of trifoliate leaves per plant: This was obtained by counting the number of trifoliate leaves on each tagged plant and then divided by five to obtain a mean value.

Trifoliate leaf area (cm^2): The total leaf area per plant was calculated using the derived equation: A = 0.411 + 2.008 LW; where A = trifoliate leaf area, L and W are the maximum length and width of the terminal leaflet of a trifoliate leaf, respectively, while 0.411 and 2.008 are constants

Leaf area index (LAI): This is the ratio of leaf area to unit land area occupied by the plant and was determined as: LAI = Total Leaf area (cm^2) / Land area (cm^2).

Data were collected on the following yield parameter:

Number of seeds per pod: The number of seeds in each pod from tagged plants from the net plot at harvest was counted and the mean average number of seeds per pod was determined.

Weight of pods per plant (g): The mean weight of pods from tagged plants from the net plot at harvest were taken and weighed after threshing. The mean values were obtained for each plot.

100-seed weight (g): The weight of 100 seeds randomly picked from each net plot at harvest was determined using sensitive weighing scale.

Grain yield (kg/ha): The harvest from each net plot was threshed, weighed and converted to kilograms per hectare to determine grain yield.

Statistical Analysis

Data collected were subjected to analysis of variance (ANOVA) using General Statistics Package (GENSTAT) 4th edition, 2015. Treatment means were separated using Fisher's Least Significant Difference (LSD) test at the 5% probability level ($p \leq 0.05$). The counted data were transformed using square root and the transformed data were used for statistical test.

RESULTS AND DISCUSSION

Results

Pre-planting soil analysis

Table 1 shows the result of physical and chemical properties of the soil obtained from the Directorate of University Farms (DUFARMS) Federal University of Agriculture, Abeokuta during raining season in 2023, where the experiment was conducted. The particle size analysis showed that the soil textural class sandy loam and had a pH of 6.5. It has total nitrogen of 0.80 % and available phosphorus of 5.23 mg kg^{-1} with organic carbon (C) content of 0.65 %. The exchangeable cations (K, Ca, Mg, Na) values were 0.44 cmol kg^{-1}, 2.52 cmol kg^{-1}, 0.73 cmol kg^{-1}, and 0.29 cmol kg^{-1} respectively.

Table 1: Physical and chemical properties of experimental soil

Soil Properties	Unit	Values
Sand	%	87.9
Silt	%	7.49
Clay	%	4.61
Textural Class		Sandy loam
pH	-	6.5
Total N	%	0.80
Organic C	%	0.65
Available P	mg kg^{-1}	5.23
K	cmol kg^{-1}	0.44
Ca	cmol kg^{-1}	2.54
Mg	cmol kg^{-1}	0.73
Na	cmol kg^{-1}	0.29
Mn	mg kg^{-1}	8.14
Cu	mg kg^{-1}	0.29
Exchangeable acidity	cmol kg^{-1}	0.110
Exchangeable CEC	cmol kg^{-1}	3.920

Table 2 shows agro-meteorological weather report of experimental site and the amount of rainfall, min. and max. temperature, relative humidity as well as sunshine hours was recorded from Jan. – Dec. 2023, with the highest amount of rainfall recorded in July (262.75 mm) and also the lowest amount of rainfall recorded in December (8.44 mm). Minimum temperature was recorded to be highest in March (24.19°C) and lowest in January (21.00°C). While the maximum temperature was recorded to be highest in February (29.83°C) and lowest in July (25.00°C). The relative humidity was highest in August (88.00 %) and lowest in September (64.00 %). Lastly, the sunshine recorded was highest in December (8.00 hours). And lowest in August (2.10 hours).

Table 2: Agro-meteorological weather report of the experimental site

Months	Rainfall (mm)	Maximum Temp. (°C)	Minimum Temp. (°C)	Relative humidity (%)	Sunshine (hours)
January	10.51	28.09	21	64.2	3.9
February	30.75	29.83	23.95	70.25	5.5
March	91.85	29.3	24.19	74	5.4
April	106.18	29.8	21.92	72	5.07
May	141.52	25.5	22.18	84	4.44
June	211.15	27	22.66	84	3.62
July	262.75	25	23.02	84	3.2
August	169.75	26	23.34	88	2.1
September	211.35	28	22.22	64	2.8
October	146.57	27.5	22.69	70	4
November	35.83	33	24	81	6
December	8.44	36	23	67	8

Source: Department of Water Resources Management and Agro-meteorology, FUNAAB.

As presented on Table 3 below, the effects of *Arbuscular mycorrhizal* fungi species on growth variables of soybean cultivars obtained were significantly different on plant height and number of leaves. The soybean cultivars significantly ($P < 0.05$) varied in their plant height at 8 WAS with higher plant height (70.5) recorded in TGx 1440- 1E compared to TGx 1448- 2E (66.3). AMF inoculation significantly ($P < 0.05$) influenced the plant height of the soybean cultivar at 4, 6 and 8 WAS. There was no significant difference in plant heights but the tallest plant height was recorded in soybean cultivars inoculated with *Rhizophagus irregulare* and *Funneliformis mosseae*, followed by *Clariodoglomus etunicatum* compared to control. The soybean cultivars significantly ($P < 0.05$) varied in their number of leaves at 8 WAS with higher number of leaves (32.1) recorded in TGx 1448- 2E compared to TGx 1440- 1E (26.8). AMF inoculation significantly ($P < 0.05$) influenced the number of leaves of the soybean cultivars at 6 and 8 WAS. The highest number of leaves was recorded in soybean cultivars inoculated with *Rhizophagus irregulare* and *Funnerliformis mosseae*, followed by *Clariodoglomus etunicatum* compared to control.

The tallest plants were observed under *Rhizophagus irregularis* inoculation. This species is known for its extensive extra-radical hyphal network, which enhances phosphorus and micronutrient uptake, thereby stimulating stem elongation and vegetative growth. Similar findings were reported by Smith and Read (2008), who noted that R. *irregularis* promotes vigorous shoot development due to efficient nutrient acquisition.

Table 3: Effect of Arbuscular Mycorrhiza Fungi species on plant height and number of leaves of soybean cultivars

Treatments	Plant height (cm)			Number of leaves		
	4 WAS	6 WAS	8 WAS	4 WAS	6 WAS	8 WAS
Varieties (V)						
TGx 1448-2E (Check)	35.5	55.7	66.3	6.44	18.8	32.1
TGx 1440-1E	30.5	54.5	70.5	6.06	18.9	26.8
LSD	NS	NS	3.90*	NS	NS	2.25*
AMF Strains (A)						
Control (un-inoculated)	27.8	49.8	61.2	6.44	16.2	24.8
Funneliformis mosseae	33.7	56.9	70.0	6.11	19.6	31.7
Rhizpphagus irregular	33.0	58.6	74.7	5.61	21.9	34.6
Clariodoglomus etunicatum	33.7	55.1	67.8	6.83	17.7	26.7
LSD	4.44*	4.67*	5.51*	NS	2.26*	3.19*
V x A	NS	NS	NS	NS	NS	NS

*NS: not significant, *: Significant at p=0.05*

Table 4 presents the effects of *Arbuscular mycorrhizal* fungi species on growth variables of soybean cultivars obtained on leaf area and above ground dry weight. The soybean cultivars significantly ($P < 0.05$) varied in their leaf area at 4 WAS with the larger leaf area (80.9) recorded in TGx 1448- 2E compared to TGx 1440- 1E (68.9). AMF inoculation significantly ($P < 0.05$) influenced the leaf area of the soybean cultivar at 4, 6 and 8 WAS. The largest leaf area was recorded in soybean cultivars inoculated with *Rhizophagus irregulare* and *Funneliformis mosseae*, followed by *Clariodoglomus etunicatum* compared to the control. AMF inoculation significantly ($P < 0.05$) influenced the above ground dry weight of the soybean cultivar at 6 and 8 WAS. The highest above ground dry weight was recorded in soybean cultivars inoculated with *Rhizophagus irregulare* and *Funneliformis mosseae*, followed by *Clariodoglomus etunicatum compared* to the control.

The significant increases in leaf area and aboveground biomass following AMF inoculation may be attributed partly to improved nutrient acquisition, particularly phosphorus, which supports plant growth and development (Smith & Read, 200). The superior performance of *Funneliformis mosseae* agrees with findings that this fungus increased soybean biomass and influenced rhizosphere soil properties under potted conditions (Chen *et al*., 2018).

Table 4: Effect of Arbuscular Mycorrhiza Fungi species on leaf area and aboveground dry weight of soybean cultivars

Treatments	Leaf Area (cm^2)			Aboveground dry weight (g)		
	4 WAS	6 WAS	8 WAS	4 WAS	6 WAS	8 WAS
Cultivars						
TGx 1448 2E	80.9	154.5	188.2	1.94	6.23	12.0
TGx 1440 1E	68.9	154.1	191.5	1.83	7.17	12.8
LSD	7.46*	NS	NS	NS	NS	NS
AMF inoculation						
Control	61.3	135.5	167.8	1.63	4.76	10.5
Rhizophagus irregulare	78.0	159.2	193.5	1.74	6.82	12.8
Funneliformis mosseae	91.1	171.1	207.8	2.16	9.27	14.6
Clariodoglomus etunicatum	69.4	151.6	190.3	2.00	5.96	11.7
LSD	10.6*	13.8*	19.1*	NS	2.45*	1.63*
V × A	NS	NS	NS	NS	NS	NS

*NS: not significant, *: Significant at p=0.05*

As shown on Table 5, soybean cultivars significantly ($P < 0.05$) varied in their yield components, with higher number of pods 56.1, dry pod weight 38.5g, number of seed 2.75 and seed yield per hectare. 2258 kg was recorded in TGx 1448- 2E compared to leaf area TGx 1440- 1E 37.7, 32.3g, 2.3, 1907 kg respectively. AMF inoculation significantly ($P < 0.05$) influenced the yield attributes of the soybean cultivar. However, it was observed that *Funneliformis mosseae* produced the highest yield attributes (number of pod, dry pod weight, number of seed, 100-seed weight and seed yield per hectare), followed by *Rhizophagus irregular Clariodoglomus etunicatum* compared to the control. *Funneliformis mosseae* has shown to improve assimilate translocation and reproductive allocation, leading to more pods, heavier seeds, and higher grain yield. Its efficiency in enhancing photosynthetic activity and carbohydrate partitioning explains the superior yield performance observed in this study. Comparable results were reported by Wu *et al*. 2019; Ngosong *et al.* 2022, who found that F. *mosseae* inoculation increased seed weight and pod number in legumes through improved reproductive efficiency.

Cultivar responses also differed. TGx 1440-1E attained greater plant height, while TGx 1448-2E produced more leaves and larger leaf area, supporting higher photosynthetic capacity and yield. These cultivar responses reflect genetic differences, where TGx 1440-1E is predisposed to stem elongation and TGx 1448-2E has more in leaf production, which enhances canopy photosynthesis and assimilate supply to reproductive structures. This aligns with reports by Adeyemi *et al.* (2021), who observed cultivar-specific differences in soybean-AMF interactions under phosphorus-deficient soils.

Table 5: Effects of AMF species on yield attributes of soybean cultivars

Treatments	Number of pods	Dry pod weight (g)	Number of seeds	100 Seed weight (g)	Seed yield per hectare (kg)
Cultivars					
TGx 1448 2E	56.1	38.5	2.75	11.9	2258
TGx 1440 1E	37.7	32.3	2.3	10.2	1907
LSD	10.3*	4.86*	0.31*	NS	353*
AMF inoculation					
Control	23.3	27.1	1.86	9.82	866
Rhizophagus irregulare	41.5	28.2	2.32	10.8	2482
Funneliformis mosseae	52.0	33.4	2.86	13.3	2538
Clariodoglomus etuicatum	25.1	28.5	2.2	10.5	1523
LSD	12.5*	6.34*	0.36*	2.85*	342*
V × A	NS	NS	NS	NS	NS

*NS: not significant; WAS: week after sowing: *: Significant at p=0.05*

CONCLUSIONS AND RECOMMENDATION

Indigenous *Arbuscular mycorrhizal* fungi (AMF) significantly improved soybean growth and yield performance under Nigerian rainforest conditions. Native isolates such as *Rhizophagus irregulare, Clariodoglomus etunicatum,* and *Funnerliformis mosseae* enhanced pod formation, seed yield, and overall productivity compared to non-inoculated controls. These results revealed the potential of native AMF as sustainable biofertilisers that reduce reliance on chemical phosphorus inputs.

Farmer and extension services should adopt indigenous AMF inoculants as part of integrated soil fertility management. Further long-term, multi-location trails are recommended to validate their effectiveness across diverse agro-ecological zones and to clearly distinguish the benefits of native species from exotic strains.

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Authors' Contributions

JJM conceptualized the study. NOA & JJM designed the experiment, JJM, AAO & TSO collected data, performed data analysis, and wrote the first draft of the manuscript. JJM & GPA performed literature searches and NOA reviewed the first draft of the manuscript. All authors read and approved the final draft of the manuscript.

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.

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