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Enhancing soybean yields with plant growth-promoting rhizobacteria

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ABSTRACT

Soybean is a vital legume crop renowned for its high protein (42%) and oil (19.5%) contents. Despite its nutritional and economic significance, soybean production in Africa remains low. This study evaluated the effects of rhizobium inoculation rates (0, 0.5, 0.75, and 1.0 g per 10 g seeds) on yields of five soybean varieties (Sam soy-2, TGX-1448-2E, TGX-1479, Local, and TGX-1740) under field condition at National Center for Agricultural Mechanization (NCAM), Idofian and screenhouse conditions at Kwara State University, Malete in southern Guinea savannah environment of Nigeria. The two experiment (field and screen house) were laid out in a 5 x 4 split-plot arrangement fitted into randomized complete block design for the field and the screenhouse experiment was arranged in a complete randomized design with three replications. Results showed that *Rhizobium* inoculation significantly improved yield components, including nodulation, pod weight, seed weight, and hundred-seed weight, with the highest performance observed at 1.0 g inoculant rate. TGX-1479 exhibited superior yield traits in the field, while TGX-1740-1E performed the best in the screenhouse. Environmental factors influenced field performance more than genetic variation, whereas genetic composition dominated in the screenhouse. The study concludes that utilization of rhizobium inoculation at 1.0 g per 10 g seeds is a strategy to enhance soybean productivity, recommending TGX-1479 and TGX-1740-1E for optimal yields in the tropical agroecology. These findings might support sustainable soybean production to improve food security in the resource-limited regions.

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Introduction

Soybean (*Glycine max*) is an important legume crop that is cultivated all over the world as a major source of livestock feed, food for human consumption, soil fertility improvement and industrial products such as candles and paints (Adjei-Nsiah *et al*., 2019). Soybean has a high protein content (40%) of good nutritional quality, and oil content (20%) which make soybean the crop of choice for improving the diets of people in developing countries (Murithiab *et al*., 2016). Soybean seeds can be processed into soybean meal and oil, used as animal feed, human food and biodiesel (FAO, 2014).

The rainfall required for favorable cultivation is usually between 300 to 1200 mm per annum, and loam soil with the pH of 6 to 6.5 (Mathenge *et al*. 2019). Soybean thrives in warm climates that range from low to medium altitudes 21°C to 30°C (Cordeiro and Echer, 2019; Gikonyo *et al*. 2014).

The United States of America is the leading producer and exporter of soybean worldwide (USDA, 2016). The crop and its derivatives accounts for over 10% of the total value of global agricultural trade (Abuli, 2016). Africa, however accounted for 0.4 – 1% of the total world production of soybean with Nigeria, South Africa, Uganda, and Zimbabwe as the main producers in the continent. Nigeria contributes 50% of Africa's output, accounting for only 0.3% of the world soybean output (USDA, 2017). Soybean is mainly produced in the Northern part of Nigeria, with the North Central and North West zones accounting for approximately 97% of the total production. The major producing States are Benue, Kaduna, Kano, Taraba and Nassarawa (USAID, 2016).

Global soybean production reached 396.93 million metric tons (FAO, 2025). The yield of soybean has remained 1.0 tons per hectare on growers' farms compared to 3.0 tons per hectare realized under experimental conditions (Kamara, 2007). Seed yield in soybean is complex like other crop plants with the total seed yield determined by types of cultivars, the rhizobium strain(s) used, fertilizers used and their interactions (Adeyeye *et al*., 2017; Giller *et al*. 2013). It thrives in warm climates that range from low to medium altitudes (21 to 30). It is important to note that high altitude zones negatively affect the flowering and maturity of soybeans, while high temperature affects the initiation of flowering (Gikonyo *et al*. 2014; Cordeiro and Echer, 2019). For improvement of soil fertility, it is advisable to improve atmospheric nitrogen fixation and preferably grow the crop in a pure stand (Pedrozo, *et al*., 2018).

The use of rhizobium is the most profitable way to increase soybean production due to its low cost (Ronnera *et al*. 2016). Inoculation is aimed at providing a viable and effective rhizobium to induce colonization of the rhizosphere allowing nodulation to take place immediately after germination (Hartman *et al*. 2011).

High fertilizer prices and scanty information on availability of soybean rhizobia have led to low yields of soybean (Ronnera *et al*, 2016; Ahiabor *et al*. 2014). Soybean plays an important role in the global and agricultural N cycles by converting it into plant-available N (Nasir *et al*., 2017). Recent awareness of potential soil degradation and pollution of ground water by the inorganic nitrates, much attention has been given to biological nitrogen fixation (BNF) (Palaniappan, 2010; Ouma *et al*., 2016). BNF is an agriculturally and ecologically crucial and efficient process in terms of supplying N to the plants which is worthy to be embraced (diCenzo *et al*., 2019).

Soybean yields are determined by the effects of genotypes, the rhizobium strain(s) and fertilizers used, and their interactions. Hence, a profitable way to increase soybean production involves the uses of rhizobium due to its low cost (Ronnera *et al*. 2016). Rhizobium application stimulates BNF. Therefore, in order to identify the most adaptable variety under ideal rhizhobial inoculation, this study sought to examine the best adaptable variety with high seed yield and the interaction effects of rhizhobium on certain soybean varieties.

Materials and Methods

The study area

The field study was conducted in the Southern Guinea Savannah agro-ecology of Nigeria at the National Center for Agricultural Mechanization (NCAM) experimental field in Idofian, Kwara State. NCAM has a latitude of 08°13'N and 08°23'N and longitudes of 04°25'E and 04°43'E of the equator, with 327 meters above sea level and receives 1154.15 mm of rainfall annually. The rainy season has temperatures between 34 and 35.5 ºC and relative humidity between 75 and 88% (Ajadi and Adeniyi, 2017). While the screen house study was conducted during the dry season at the screen house of Kwara State University (KWASU), Malete, located in the Southern Guinea Savannah agroecology of Nigeria, at an elevation of 316.37 m. a.s. l. Within latitudes 08°42'N to 08°43'N and longitudes 04°282'E to 4°283'E of the equator, the field experiment began in September 2020 and ended in December 2020. The climate is tropical, with a daily photo period of 7.1 hours, annual rainfall (1500 mm), maximum temperature (38ºC), and maximum relative humidity (75 %) (Olarenwaju, 2009). November 2020 marked the beginning of this screen house experiment, which ended in February 2021.

Treatments and experimental design

The experiments (field and screen house) were laid out in a 5 x 4 split-plot arrangement fitted into a randomized complete block design for the field and the screen house in a completely randomized design with three replications. Treatments tested were four inoculation rates (0, 0.5, 0.75 and 1.0 g inoculation) and five soybean varieties: Sam soy-2, TGX-1448-2E, TGX-1479, Local, and TGX-1740.

The peat and aqueous rhizobium solution inoculants were added to the soybean seeds in a container after moistening the seeds with water containing Gum Arabic. The inoculants and the seeds were mixed thoroughly until the seeds were uniformly coated with the inoculants, and it was covered with a cloth for 10 minutes, and direct sunlight was avoided. The inoculated soybean seeds were planted immediately into moist soil. The treatment with a 100% inoculation rate received 1.0 g of inoculants per 10 g of seeds; the 75% inoculation rate received 0.75 g of inoculants per 10 g of seeds, while the 50% inoculation rate was done by 10 g of seeds with 0.5 g of inoculants as recommended by IITA, Ibadan. The plot size was 1 by 1.5 m, spacing between plots and blocks was 1 and 2 m, respectively.

Soil samples were collected before planting for chemical and physical analyses using the procedure described by Okalebo *et al*. (2002) at Deimage Laboratory Services, Ibadan. The physical properties that were analyzed are sand, silt and clay while the chemical properties include, organic carbon, total nitrogen, and available phosphorus, soil pH, exchangeable magnesium, exchangeable potassium, exchangeable calcium, exchangeable sodium, available manganese, iron, copper and zinc. However, the values of total nitrogen and available phosphorus, and potassium of the experimental soil were below the critical level as recorded by Abdulkareem and Aliyu (2024), making it necessary for the application of soil amendment in the form of inorganic or organic fertilizers.

The mean rainfall during the experiment was 25.03 mm, with the mean temperature ranging between 21.06°C to 29.29°C during the field experiment and 23.50°C to 38.33°C during the screen house. Also, the mean relative humidity ranges between 23.33 % to 22.71% during the field experiment and 25.73% to 16.48% during the screen house

The land was ploughed and harrowed. Two (2) seeds were sown per hole at a spacing of 75 by 5 cm to give 533,333 plants per hectare (pph) and later thinned down to one seedling/stand in the second week after planting. Perforated pots of 10 liters were filled with 5 kg of sterilized topsoil was used in the screen house. Each hole was seeded with four (4) seeds, which were subsequently thinned to two seedlings two weeks later. The plants were irrigated as and when due to the field capacity of the pots.

Data collection and analysis

Data were collected on nine yield components: Shoot dry weight (g), number of nodules per plant, nodules dry weight per plant (g), number of pods per plant, pod weight per plant (g), number of seeds per pod, number of seeds per plant, seed weight at harvest (g) and hundred seed weight (g) All data collected were summarized, computed and analyzed using descriptive statistics (mean, range, standard deviation and coefficient of variation), Analysis of variance (combined), Duncan Multiple Range Test using GENSTAT statistical software 17th edition VSNI,2006.

Results

Mean square values and descriptive statistics of yield components in the field

Table 1 shows the analysis of variance (ANOVA) for the yield components of five soybean varieties in the field. It shows that variety, inoculants also recorded significant variation for yield parameters except for hundred-seed weight. Interaction between variety and inoculants shows significant variation for the yield characters except the number of pods ($p < 0.05$). The descriptive statistics (standard deviation and coefficient of variation) also recorded significant variation among the yield characters.

Interaction between variety and inoculant concentration (V×I) in the field

Figure 1 to 3 shows the values of the yield characters for the interactions between variety and inoculants. Data from the interaction between variety and inoculants showed that most of the soybeans recorded significantly better performance at 1.0 g of rhizobium inoculation. TGX 1479 recorded the highest number of seeds per pod, number of seeds per plant, nodules weight, pod weight and hundred seeds weight (2.56, 48.98, 1.21g, 5.31 g, and 11.04 g, respectively) at 1.0 g of rhizobium inoculation compared to other treatment levels.

At no (0 g) rhizobium inoculation (I_0), TGX 1448- recorded highest number of seeds per pod (2.12) While at 0.5 g rhizobium inoculation (I_1), TGX 1740-1E recorded the highest number of pods, hundred seed weight (14.39, 10.81 g), SOYA recorded the highest pod weight (4.25 g). Whereas at 0.75 g of rhizobium inoculation (I_2), TGX 1479 recorded highest number of seed per plant, nodule weight, pod weight and hundred seed (39.75, 0.80 g, 4.98 g and 10.37 g respectively), SOYA had the highest number of pods and number of seed per pods (15.57 and 2.54). However, SAMSOY-2 recorded the lowest number of seeds per plant, number of pods and pod weight (17.16, 8.57 and 2.19 g, respectively). TGX 1740- 1E recorded the lowest number of seeds per pod (1.61) at 0 g of rhizobium inoculation (I_0). While TGX1448-2E recorded the lowest hundred-seed weight at 0.5 g of rhizobium inoculation (I_1) compared to other varieties

Table 1. ANOVA findings of the field-based yield components of five soybean genotypes inoculated with various rhizobium level

SV	Df	Shoot dry weight (g)	No. of nodules	Nodules dry weight (g)	Number of pods	Pod weight (g)	No of seeds/ per pod	No of seeds per plant	Hundred seed weight (g)
Replication	2	2.81	34.21	0.141	60.99	3.21	0.19	176.90	0.55
V	4	8.15**	76.85ns	0.52*	234.01***	36.18***	1.15***	1774.40***	39.60***
Error	8	0.69	37.90	0.07	9.99	0.40	0.06	25.64	1.10
I	3	46.60***	177.56ns	1.81***	381.08***	28.23***	3.43***	4569.52***	6.74ns
V× I	12	1.33ns	48.68ns	0.16***	14.92ns	2.10***	0.38***	146.89*	4.56**
Error	30	0.81	39.21	0.10	11.21	0.71	0.14	27.28	1.31
SD		1.67	4.72	0.33	5.68	1.79	0.47	15.40	1.81
CV (%)		28.90	34.05	38.70	32.17	34.64	15.62	39.21	15.23

*, **, *** and ns mean significant $p<0.05$, 0.01, 0.001 and not significant, respectively. CV: Coefficient of variation. SV: Source of variation. SD: Standard deviation, V: Variety, I: Inoculant.

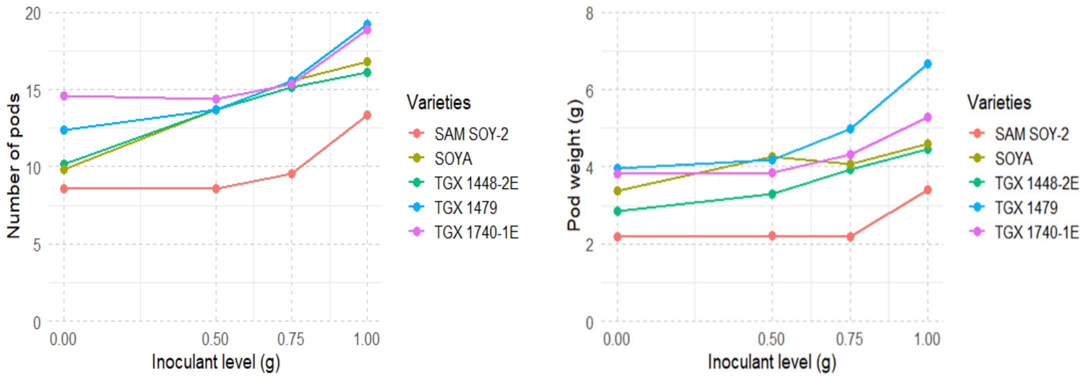

Fig. 1. Interaction between variety and inoculant for the number of pods and pod weight

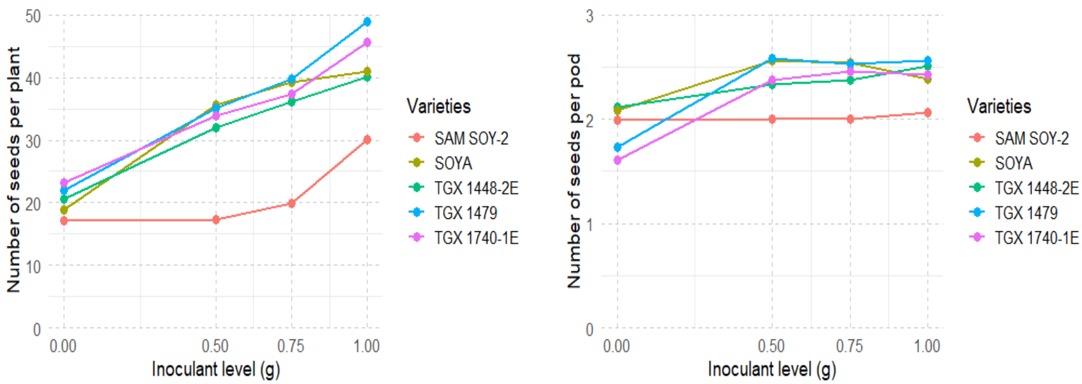

Fig. 2. Interaction between variety and inoculant for the number of seeds per plant and number of seeds per pod

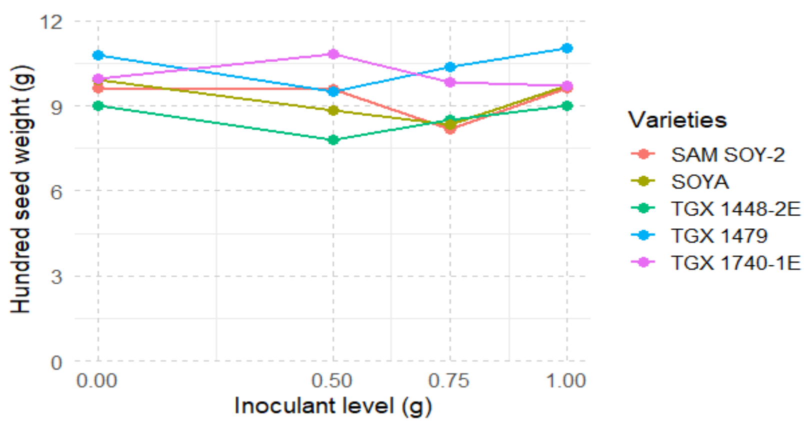

Fig. 3. Interaction between variety and inoculant for hundred seed weight (g)

Mean square values and descriptive statistics of yield components in the screen house

Table 2 shows the analysis of variance (ANOVA) for the yield component of 5 soybean varieties. It shows that variety had significant variation on all yield parameters, which include (number of pods, pod weight, number of seeds per pod, number of seeds per plant, and hundred seed weight). Inoculant concentration also shows significant variation for pod weight, and hundred-seed weight. Interaction between varieties and inoculants concentration showed significant variation in the number of pods, pod weight, seed weight per plant and hundred seed weight ($p < 0.05$). The descriptive statistics (mean, range, standard deviation, and coefficient of variation) also recorded significant variation among the yield components.

Interaction between variety and inoculant concentration (V×I) for yield components in the screen house

Fig. 4 to 5 shows the mean value of the yield character for the interactions between variety and inoculant. Data from the interaction between varieties and inoculant showed that most of the soybean recorded significant better performance at 1.0 g rhizobium inoculation (I_3). TGX 1740-1E recorded highest number of pods per plant, pod weight, and hundred seed weight (7.54, 2.85 g, and 10.49 g respectively) at 1.0 g rhizobium inoculation (I_3) compared to other treatments levels.

At zero (0 g) rhizobium inoculation (I_0), TGX 1479 recorded highest pod weight (2.26 g). While at 0.5 g rhizobium inoculation (I_1) TGX 1479 recorded the highest number of pods, pod weight, and hundred seed (7.29, 1.61 g, and 9.61 g respectively).

Table 2. ANOVA findings of the screen house-based yield components of five soybean genotypes inoculated with various rhizobium level

SV	Df	Shoot dry weight (g)	No. of nodules	Nodules dry weight (g)	Number of pods	Pod weight (g)	No of seeds per pod	No of seeds per plant	Hun-dred-seed weight (g)
Replication	2	18.34	609.92	1.07	33.50	3.47	7.17	82.29	101.61
V	4	3.100s	101.93ns	0.03ns	111.19***	16.73***	14.75*	395.37***	261.13**
Error	8	5.08	26.11	0.13	6.95	1.13	1.74	19.16	29.49
I	3	50.17***	101.77	1.16***	23.14ns	5.18**	2.83ns	76.33ns	84.43***
V x I	12	1.83ns	27.09ns	0.13ns	31.90**	3.50***	0.68ns	59.24ns	53.02***
Error	30	1.95	33.10	0.12	18.61	1.36	1.03	55.23	16.05
CV (%)		52.48	49.52	51.61	149.60	142.16	111.21	127.24	98.24

*, **, *** and ns mean significant p<0.05, 0.01, 0.001 and not significant, respectively. CV: Coefficient of variation. SV: Source of variation. SD: Standard deviation, V: Variety, I: Inoculant.

However, SAMSOY-2 recorded lowest, hundred-seed weight (0.03 g, 1.85 g) at 0 g rhizobium inoculation (I_0) and number of pods (0.42) at 0.5 g rhizobium inoculation while TGX1448-2E had the lowest pods weight (0.19 g) at 0.5g rhizobium inoculation (I_1)

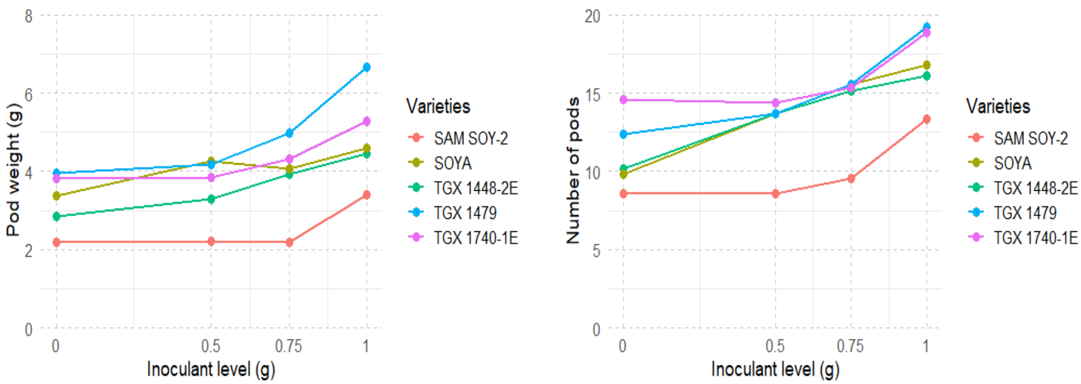

Fig. 4. Interaction between variety and inoculant for pod weight (g) and number of pods

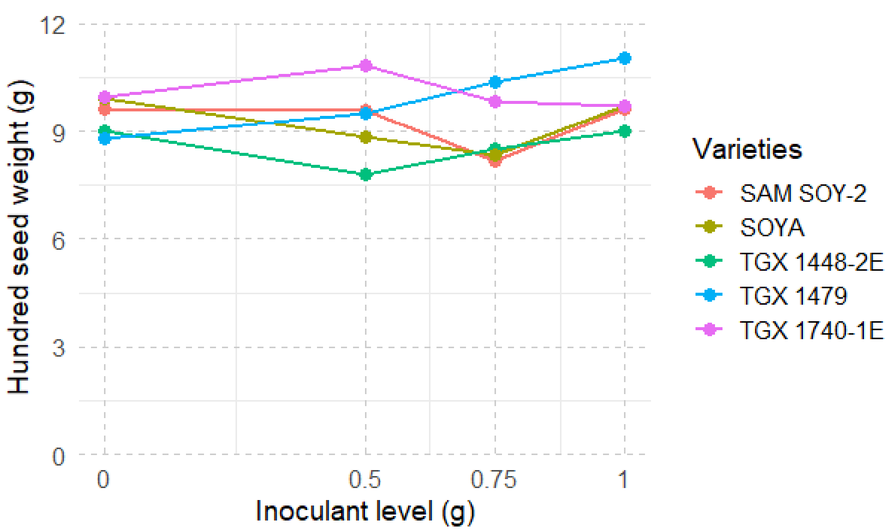

Fig. 5. Interaction between variety and inoculant for hundred seed weight (g)

Discussion

In the present study, all five varieties produced higher yields when inoculants were applied in the field and screen house relative to un-inoculated seeds. It showed differential yield responses of varieties of soybean to rhizobium inoculation levels, indicating the significance of variety specific inoculation in view of yield production. The low performance of some genotypes, such as SAM SOY-2 may relate to genetic factors limiting nodulation efficiency or nutrient uptake since there is wide genetic variability among legumes. As reported by (Abdulkareem and Aliyu, 2024). However, the study elucidates the use of rhizobium inoculants as a viable alternative to enhancing growth and improving the yield of soybeans. This agrees with the report of (Ulzen *et al*., 2016) that the total number of nodules and yield increases with inoculated seeds as opposed to non-inoculated. Notably, on the field and screen house, 1.0g of rhizobium inoculants produced the highest for the yield components in agreement with the IITA recommendation for tropical soils.

The interaction between varieties and inoculants showed that TGX 1479 recorded the highest of the yield components at 1.0g of rhizobium inoculants compared to other varieties. While in the screen house, TGX 1740- 1E recorded the highest. The yield enhancements observed in this study are attributed to an increased symbiotic relationship of rhizobia (bacteria) with the roots of the soybean, which is a leguminous crop, resulting in a possible fixation of atmospheric nitrogen into the roots of the soybean, which is an attribute of rhizobia inoculation. The increase in the yield components leading to higher yield through rhizobia inoculation is in agreement with the results of other workers (Sylvain, 2020).

However, seed weight per plant in the field was about thrice higher than screen house experiment, which might be as a result of diverse micro-organism in the field which enhances the availability of the nutrients for plant use compare to the screen house; also, the micro-organism is also influenced by environmental factor. Temperature which is one of the major environmental factors that affect microbial activities and plant growth was higher (than the optimum requirement) in the screen house compared to the field. It agrees with (Pedrozo *et al*., 2018), which states that rhizobia is dependent on the host for the energy which is required in biological nitrogen fixation; any factor that hinders normal growth and development will ultimately influence BNF and the availability of nutrients. Also, (Mathenge *et al*., 2019) reported that several factors, including dryness and temperature, are linked to poor survival of bacteria inoculated in seeds. Therefore, environmental factors, which include relative humidity, temperature and rainfall, should be considered when applying nutrients (inoculants) to the soybean plant.

This agrees with the report of (Harold and Fudi, 1992), which reported that experiments from multi-site standardized field inoculation trials with several legumes have revealed that 59% of the variation in inoculation responses could be due to the number of indigenous rhizobia. Also, the field is known to have been cropped with cowpea in the season prior to this experimental planting and the presence of legumes in the cropping system is known to enhance the number of compatible rhizobia in the soil, which significantly enhanced seed yield. (jabletey 1995) found that soil planted with cowpea as the previous crop contained twice as much native Bradyrhizobium sp. as other soils with non-legume as the previous crop.

Conclusions

This study demonstrates that rhizobium inoculation significantly enhances soybean yield and yield components, with 1.0 g inoculant for 10 g of seeds proving most effective under both field and screenhouse conditions. Such practice could be considered as a sustainable strategy to enhance soybean productivity, with varietal selection tailored to environmental conditions. Future efforts should focus on integrating inoculants into soybean varieties and expanding access to adapted varieties like TGX 1479 and TGX 1740- 1E to ensure food security in the tropical regions.

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Conflict of interest

The authors declare there are no conflict of interest.

Authorship

- All listed authors made substantial contributions to:
  - Study conception/design (Yusuf Folorunsho Abdulkareem)
  - Data acquisition (Yusuf Folorunsho Abdulkareem)
  - Analysis/interpretation (Yusuf Folorunsho Abdulkareem)
  - Drafting/revisions (Olawale Mashood Aliyu)
- All authors approved the final version

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