



INTERACTIVE EFFECTS OF RHIZOBIA STRAIN AND ENVIRONMENT ON SOYBEAN PRODUCTIVITY AND NITROGEN FIXATION IN THE NORTHERN GUINEA SAVANNA OF NIGERIA

Fatima Jibrin Abubakar ^{a *}, Ado Adamu Yusuf ^a, Dauda Abdullahi Machido ^b and Aliyu Abdullahi Anchau ^a

^a Department of Soil Science, Institute for Agricultural Research, Ahmadu bello University, Zaria

^b Department of Microbiology, Faculty of Life Science, Ahmadu bello University, Zaria

* zahra8746@yahoo.co.uk; fjabubakar@abu.edu.ng

ABSTRACT

Soybean productivity in the Northern Guinea Savanna of Nigeria is constrained by low soil fertility, particularly nitrogen deficiency, and suboptimal biological nitrogen fixation (BNF). This study evaluated the effectiveness of selected rhizobia inoculant strains on soybean nodulation, biomass accumulation, nitrogen fixation, and grain yield across three locations (Dinki, Mahuta, and Rafin Gora) during the 2017 cropping season. A randomized complete block design was employed with ten treatments, including seven rhizobia strains, a nitrogen-fertilized control, and uninoculated controls with and without phosphorus. Treatments and locations differed significantly ($p < 0.05$) in nodulation, biomass, nitrogen accumulation, and yield. Strains such as NAK 128 and USDA 532c performed best, achieving nodulation, nitrogen fixation, and grain yields comparable to or exceeding mineral nitrogen application. Grain yield increased by up to 54.8% relative to uninoculated controls, and aboveground biomass also increased by 38.5%. Strong location effects indicated that environmental and soil conditions significantly influenced inoculant performance, with Dinki consistently producing the highest yields and biomass. The findings highlight the potential of effective rhizobia inoculation as a sustainable alternative to mineral nitrogen fertilizers, though site-specific adaptation remains critical for optimizing BNF and soybean productivity in savanna agro-ecosystems.

Keywords: Biological nitrogen fixation, effectiveness, inoculant response, nodulation

INTRODUCTION

Soybean (*Glycine max* L.) plays a critical role in enhancing food security, improving soil fertility, and supporting livelihoods in sub-Saharan Africa (SSA). Nigeria is the second-largest soybean producer in SSA, producing as much as 960 kg ha⁻¹ in 2016 (Khojely *et al.*, 2018). Its ability to form symbiotic associations with rhizobia enables biological nitrogen fixation (BNF), thereby reducing dependence on synthetic nitrogen fertilizers. Legumes such as soybean can fix up to 90% of their nitrogen requirement (Vanlauwe *et al.*, 2019). However, in the Northern Guinea Savanna of Nigeria, soybean productivity remains low due to poor soil fertility, limited organic matter, and inadequate populations of effective rhizobia strains.

The soils of this agro-ecological zone are typically characterized by low total nitrogen, low available phosphorus, and low organic carbon, conditions that severely constrain crop growth and nodulation efficiency. Although studies have shown that indigenous rhizobia populations may be present, they are often ineffective or insufficiently competitive, resulting in suboptimal BNF (Abaidoo *et al.*, 2007; Chibeba *et al.*, 2017). Consequently, inoculation with elite rhizobia strains has emerged as a promising strategy to enhance nitrogen fixation, improve plant growth, and increase yields. Despite the demonstrated benefits of rhizobia inoculation, its effectiveness varies widely and depends on multiple factors, including host genotype, soil physicochemical properties, environmental conditions, and competition with native microbial populations (Chibeba *et al.*, 2017). In particular, site-specific variability in soil fertility and microclimate conditions within the savanna region can significantly affect inoculant performance and symbiotic efficiency. Therefore, the combined application of phosphorus and rhizobia inoculant can achieve impressive yield increases (Vanlauwe *et al.*, 2019).

This study aimed to evaluate the effectiveness of selected rhizobia inoculant strains on soybean performance across multiple locations in the Northern Guinea Savanna. Specifically, the study assessed their impact on nodulation, biomass production, nitrogen fixation, and grain yield, and examined how environmental variability influenced inoculation outcomes. The findings are expected to inform location-specific recommendations to optimize BNF and improve soybean productivity in resource-constrained farming systems.

MATERIALS AND METHODS

Experimental Site and Soil Description

The study was conducted in 2017 on three selected farmers' fields in three locations: Dinki (Latitude: 10°96'N, Longitude: 7°62'E), Rafin Gora (Longitude: 7°62'E, Latitude: 11°11'N), and Mahuta (Longitude: 7°67'E, Latitude: 11°27'N) (Figure 1). The sites were randomly selected based on their potential for grain legume production, no history of previous inoculation with rhizobia, and differences in microclimate and soil properties within the same agro-ecological zone. The soils at the sites were slightly acidic, with low organic carbon and available phosphorus. Total nitrogen was low at Rafin Gora and Mahuta, but high at Dinki. Rhizobia populations at each location were <1000/g soil, below the level required for optimum nodulation and nitrogen fixation (Nazih and Weaver 1994).

Experimental Design and Treatment

The trial comprised soybean variety TGx1951-3F and seven inoculant strains arranged in a randomised complete block design (RCBD) and replicated 3 times. Nitrogen was used as a positive control (20 kg N ha⁻¹); the negative control was uninoculated with phosphorus added (40 kg P ha⁻¹), while the absolute control had no fertilizer and no inoculant, and maize was used as a reference crop to quantify nitrogen fixation. The plots measured 6 m by 5 m, with a total of 8 ridges per plot, where the four middle ridges served as the net plot.

Nodules, root and shoot sample collection

At eight weeks after sowing, plant samples were uprooted for the determination of the nodule number, nodule dry weight, nodule score, shoot dry weight and root dry weight. Nodules were scored by randomly selecting twenty nodules and dissecting them to determine if they were actively fixing nitrogen. Those showing red to pink coloration were counted as effective, while those showing green or white were counted as ineffective. The number of effective nodules was then recorded. The roots, nodules, and shoots were then oven-dried at 65 °C to a constant weight.

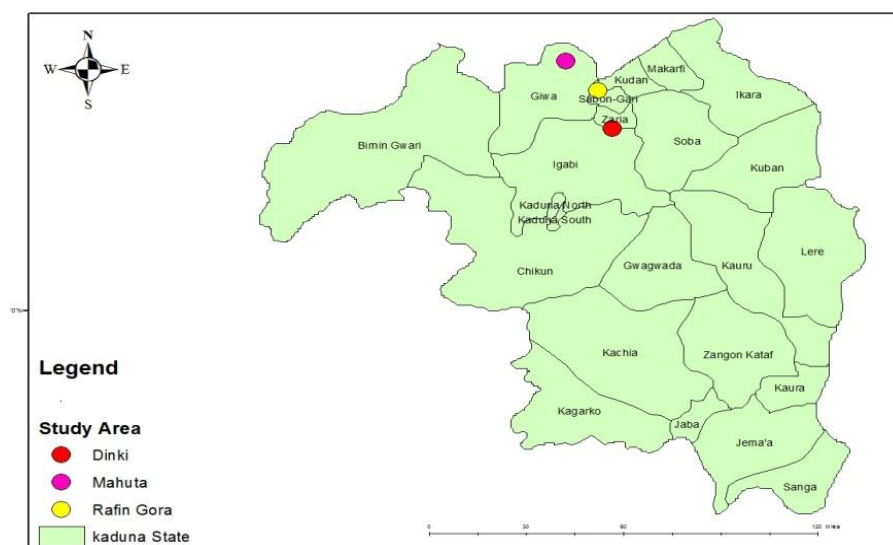


Figure 1. Map of Kaduna state showing the study locations

Determination of leaf chlorophyll content (leaf colour score)

The leaf chlorophyll content was measured using a hand-held chlorophyll meter (SPAD-502, Konica Minolta Co., Ltd., Tokyo, Japan) at 8 weeks after planting. This device measures numerical leaf colour values on a scale from high (green) to low (yellow) by evaluating the light transmittance through a sample leaf at two specific wavelengths (650 nm and 920 nm). By comparing transmittance at these wavelengths, the instrument automatically calculates a numerical value directly proportional to the leaf's chlorophyll content (Gwata *et al.*, 2004). An average of 10 leaves were sampled per plant, and the SPAD readings were recorded.

Harvesting and yield assessment

At physiological maturity, the plants were harvested manually from the net plots (15 m²), then threshed and winnowed. The grains and above-ground plant biomass were air-dried to about 14% moisture content and then weighed. The yield was calculated on a hectare basis after weighing all dried samples using the following expression.

$$\text{Grain yield (kg/ha)} = \frac{\text{Total grain yield(kg)}}{\text{Net plot (m}^2\text{)}} \times 10000 \text{ m}^2$$

Biological Nitrogen Fixation (BNF) assessment

The amount of biological nitrogen fixed was assessed using the Total Nitrogen Difference (TND) method. The total amount of shoot nitrogen (as determined by the Kjeldahl method) in the soybean and the maize (reference crop) was determined, and the amount of N fixed was calculated using the method reported by Murray *et al.* (2008) and the modified equations of Mary *et al.* (1995), also reported by Howieson and Dilworth (2016).

Thus,

Amount of N fixed = Total N in legume – Total N in reference crop

Total N in plants = (Shoot dry weight (kg/ha)X % N in shoot)/100

% Ndfa = [Total N in legume – Total N in reference crop]/(Total N in legume) X 100

Where % Ndfa is the percentage of N derived from the atmosphere

Data analysis

The data collected from the nodulation, nitrogen fixation and yield parameters were subjected to Analysis of variance (ANOVA) using SAS software (version 9.4, 2012). Square root transformation was done where necessary to make assumptions of normality before subjecting to ANOVA (Solomon *et al.*, 2012). Where F values were significant ($p < 0.05$), Duncan's Multiple Range Test was used to separate the means.

RESULTS AND DISCUSSION

Effect of inoculation and location on nodulation, biomass, and nitrogen fixation of soybean

The results showed significant variation among treatments and locations for the measured parameters (Table 1). A highly significant difference ($p < 0.001$) was observed in nodule number, with USDA 532c highest, attributed to the strain's compatibility with the soybean genotype used, which predisposed it to higher rhizobia infection. Another possible reason is that this is a standard strain used for decades to improve inoculation and N fixation in legume-rhizobium symbiosis. Although this was not investigated, competition between the introduced and indigenous rhizobia could also explain the observed result, as some studies have shown that inoculant strains vary in their ability to colonize the rhizosphere and compete against native rhizobia (Mendoza-Suárez *et al.*, 2021). However, these results contrast with Okereke *et al.*

(2000) in Nigeria and Kyei-Boahen *et al.* (2023) in Mozambique, where inoculation with USDA 110 increased nodule number and nodule dry weight more than the other strains. Ineffective native rhizobia strains are adapted to the local environment and often compete well against highly efficient introduced strains, resulting in low inoculant nodule occupancy (Thilakarathna and Raizada, 2017), which may have been the case in this study. The low nodule number observed for the absolute control suggests that soybean nodulation could improve with optimized phosphorus. By location, Dinki and Mahuta were statistically similar and exceeded Rafin Gora ($p < 0.001$). This may be due to a stronger response to rhizobia inoculation in those locations. The interaction between the treatments and locations was highly significant ($p < 0.001$) (Fig 2). IRJ 2180A was highest at Mahuta, followed by USDA 532c at Dinki, while the control was lowest at all the locations. The highly significant interaction observed in this study suggests that inoculant strain performance varied across locations, possibly due to variability in soil and environmental conditions, as similarly reported by Kyei-Boahen *et al.* (2023).

A significant difference ($p \leq 0.01$) was observed in nodule score, with all treatments higher than N-treated plots, and Dinki was the highest among locations. This implies that most nodules were actively fixing nitrogen, regardless of whether the plots were inoculated. Desta *et al.* (2023) also reported internal nodule colour ranging from pink to red, signifying active nitrogen fixation. However, the lowest nodule score in nitrogen-treated plots suggests that nitrogen addition might have suppressed rhizobia activity, which is not surprising, as nitrogen is known to deter the activity of nitrogen-fixing bacteria. The higher number of actively fixing nodules observed at Dinki compared to the other locations could be because the indigenous rhizobia are better adapted to this location. This is because, despite the higher soil nitrogen at Dinki, which is expected to suppress nodulation, other environmental factors may have come into play, influencing the outcome. For instance, suboptimal growing conditions due to environmental challenges have been shown to affect legume-rhizobium symbiosis negatively (Ilangumaran *et al.*, 2021).

Nodule dry weight also showed a highly significant difference ($p < 0.001$), with IRJ 2180A and NAK 128 being higher and similar. Despite having a lower nodule number, these inoculants had higher nodule dry weight, supporting the fact that a high number of nodules does not always translate to high nodule dry weight. This is because factors such as genetic variability among rhizobia strains, environmental stress or even competition for other resources can limit the

growth and development of individual nodules, resulting in lower nodule dry weight despite high nodule numbers. Mendoza-Suárez *et al.* (2021) suggested that nodule formation can be affected by the complexity and genetic diversity within the soil, in addition to soil type. In contrast, excessive nitrogen availability in the soil can inhibit nodule formation, thereby significantly impacting nodule dry weight (Li *et al.*, 2024), which may explain the lowest nodule dry weight observed in nitrogen-treated plots. For location, the high nodule dry weight observed at Dinki ($p < 0.001$) could have resulted from the same factors that influenced nodule number and nodule score, given that this location had significantly higher values for the aforementioned parameters. The interaction between the treatments and locations was highly significant ($p < 0.001$) (Fig 3). NAK 128 peaked at Dinki, which was superior to other locations across treatments. This showed that Dinki produced the highest nodule dry weight regardless of inoculation, suggesting that environmental variables at this location may have favoured rhizobia establishment.

The results also showed a significant difference in chlorophyll content ($p < 0.05$), with nitrogen statistically higher, while the control + P and absolute control were lowest. This suggests that nitrogen addition increased chlorophyll production. Sara *et al.* (2013) also observed that nitrogen supply affects a wide range of physiological processes in higher plants, including chlorophyll formation. Bambara and Ndakidemi (2009) and Mfilinge *et al.* (2014) also reported that rhizobia inoculation significantly increased leaf chlorophyll content in common bean and bush bean, respectively; however, this was not the case in this study, as rhizobia inoculation did not significantly increase leaf chlorophyll content in soybean compared with the controls. However, similar to Bahati (2015), IRJ2180A and RANI 22 also had higher chlorophyll content than other inoculants, which may be attributed to successful BNF with the soybean variety under study. By location, there was also a significant difference ($p < 0.01$), with Dinki being the highest, which was not surprising, as nodulation parameters were also significantly higher at this location. Also, of the three locations, Dinki had the highest initial soil nitrogen, which may have resulted in greater absorption and, hence, better chlorophyll formation.

Shoot dry weight differed significantly ($p < 0.001$), with nitrogen highest, because nitrogen is one of the most essential nutrients for plant growth, suggesting that N addition increased plant growth and biomass production, as reported by Kebede (2020). This contrasts with Ntambo *et al.* (2017), where the shoot dry matter of the inoculated treatments was significantly greater than the control. The variability in shoot dry matter weight could be attributed to differences in responses

to environmental variables, management practices, or the soybean genotype used in the study. Previous studies have shown that legume response to inoculation is generally affected by the legume genotype, the rhizobia strain, environmental factors, amendments, water management, and other management practices involving weeding, spacing, pest and disease control (Giller *et al.*, 2013; Woomer *et al.*, 2014) as well as the nature of existing soil population of rhizobia (Yang *et al.*, 2018; Mathenge *et al.*, 2019). For location, Dinki was significantly higher ($p < 0.001$), suggesting that the higher nodulation parameters at this location may have led to greater biomass accumulation due to improved biological nitrogen fixation. The interaction between treatments and locations was highly significant ($p < 0.001$; Fig. 4). Nitrogen was highest at Mahuta, similar to Dinki, while Rafin Gora was consistently lowest. Observations from most inoculated plots at Dinki suggest the inoculant strains may be adaptable to this location.

A similar trend was observed for root dry weight, where nitrogen was highest and the control lowest ($p < 0.001$). For location, Dinki was significantly higher ($p < 0.001$) than Mahuta and Rafin Gora. The interaction between treatments and locations was highly significant ($p < 0.001$; Fig. 5). Dinki recorded the greatest root biomass, while Rafin Gora was lowest for all treatments. Inoculation of soybean with different rhizobia inoculant strains resulted in significant variation in root dry weight. Earlier reports of inoculating legumes with rhizobium strains showed a positive effect on root dry weight (Kyei-Boahen *et al.*, 2005; Ogutcu *et al.*, 2008), which contrasts with our findings, as some inoculated plots were statistically similar to the controls.

There was also a highly significant difference ($p < 0.001$) observed for shoot nitrogen, where NAK 128 had the highest shoot nitrogen content, although statistically similar to the nitrogen treatment and USDA 110. Control + P and control were statistically similar and the lowest. Location also differed significantly ($p < 0.05$), with Dinki on par with Mahuta, and both higher than Rafin Gora. The interaction between the treatments and locations was also highly significant (Fig 6). NAK 128 performed best at Dinki and Mahuta, and was comparable to nitrogen, RACA 6, USDA 110 and USDA 532c, while controls were lowest across sites. The higher shoot N observed for NAK 128 and USDA 110 suggests that these inoculants were very effective in nitrogen fixation. Sadiq *et al.* (2023) similarly reported higher shoot N in nitrogen-treated plots, attributing this to N supply triggering rhizobia activity and ultimately better N accumulation in leaves and shoots.

For Dinki, NAK 128 was the best-performing inoculant for nitrogen accumulation. Waswa *et al.* (2014) also reported NAK I28 as the most productive among a group of other isolates. However, this contrasts with Bahati (2015), which reported a significant increase in shoot N in plants inoculated with RACA 6 and RANI 22. The lower performance of some inoculants at Rafin Gora may be due to site-specific limitations affecting nitrogen uptake and accumulation. The low shoot N in the control treatments suggests the need for inoculation with suitable rhizobia. The statistical similarity in the interaction observed for nitrogen-treated plots at Mahuta and Rafin Gora could be attributed to similar initial soil nitrogen content at both locations, which may have led to similar uptake and the same response in shoot nitrogen content. Regarding locations, Mahuta had some of the highest shoot N values, possibly indicating favourable conditions for nitrogen uptake.

For the amount of N fixed, we also observed highly significant differences ($p < 0.001$) among all treatments and locations. Nitrogen-treated plots were highest, similar to NAK 128 and RANI 22. By location, Dinki and Mahuta were statistically similar and higher than Rafin Gora. The lowest value in the control plots suggests the need to inoculate such soils with efficient rhizobia to achieve maximum nitrogen fixation.

For the percentage nitrogen derived from the atmosphere (%Ndfa), there was a significant difference ($p < 0.01$), as all treatments were statistically similar except the control. By location, Dinki and Mahuta were statistically similar and higher than Rafin Gora. The interaction between the treatments and locations was also highly significant (Fig 7). Control + P at Rafin Gora showed unexpectedly high %Ndfa, and inoculant performance was generally best at Mahuta.

The higher %Ndfa observed for control at Rafin Gora is unusual and could be due to overestimation during analysis. Moreover, shoot-based estimates of N fixation underestimate total inputs of fixed N because substantial amounts of legume N can also be associated with, or released from, the nodulated roots (Denton *et al.*, 2013). The results show wide variability among treatments and locations. Other investigations (Karaca and Uyanöz, 2012; Waswa *et al.*, 2014) also reported variability in the efficiency of nitrogen-fixing symbioses. Overall, the results suggest that while these inoculants can fix nitrogen, their efficiency depends on the site. The high %Ndfa at Mahuta suggests that this location's soil or environmental conditions support good nitrogen fixation.

Table 1. Effect of treatment and location on nodulation and biomass and nitrogen fixation of soybean

Treatment	Nodule no	Nodule score	Nodule wt (mg)	Chlorophyll	Shoot wt (g)	Root wt (g)	Shoot N (%)	N fixed (mg plant ⁻¹)	%Ndfa
IRJ 2180A	545.89b	17.67a	5730.8a	34.64abc	11.71bc	1.46bc	3.39e	127.41cde	51.20ab
NAK 128	358.67cd	17.33a	5547.8a	34.04bc	10.23cd	1.20cd	5.27a	304.87ab	66.78a
NAK 82	366.89cd	15.11ab	3868.9cd	33.77bc	11.84bc	1.25bcd	3.45e	155.40cde	51.13ab
RACA 6	387.67c	16.56a	3431.1e	33.37bc	10.42c	0.99d	3.94de	182.81bcde	59.93a
RANI 22	226.78e	16.33a	4146.7bc	35.68ab	11.76bc	1.54ab	4.18cd	223.93abc	57.95a
USDA 110	389.22c	15.78a	3870.3cd	33.11bc	12.62b	1.24bcd	4.66abc	203.03bcd	67.16a
USDA532c	581.56a	17a	4333.9b	33.13bc	11.75bc	1.52bc	4.37bcd	212.82bcd	58.35a
Control	75.89g	14.56ab	2657.2f	32.69bc	8.77d	1.01d	2.44f	63.18e	32.30b
Control + P	336.33d	16.11a	3719.4ed	31.42c	11.27bc	1.09d	2.07f	86.54de	73.65a
Nitrogen	112.33f	12.44b	2630.6f	37.61a	16.89a	1.87a	4.89ab	337.61a	73.76a
SE±	12.07	0.941	119.99	1.144	0.537	0.106	0.209	40.444	6.925
LOS	***	**	***	*	***	***	***	***	**
Location									
DINKI	417.30a	18.07a	5567.08a	35.16a	15.93a	2.03a	4.01a	263.61a	62.14a
MAHUTA	400.43a	15.07b	3447.67b	33.86ab	13.20b	1.50b	3.90a	236.82a	64.22a
RAFIN GORA	196.63b	14.53b	2966.25c	32.83b	6.05c	0.42c	3.69b	68.86b	51.30b
SE±	6.61	0.516	65.719	0.627	0.295	0.057	0.115	22.152	3.793
LOS	***	***	***	*	***	***	*	***	*
Treatment X Location									
	***	NS	***	NS	***	***	***	NS	***

Means followed by the same letter (s) in a column are not significantly different at 5% level of probability using Duncan Multiple Range Test (DMRT). NS: Not significant; SE = Standard error; LOS = Level of significance

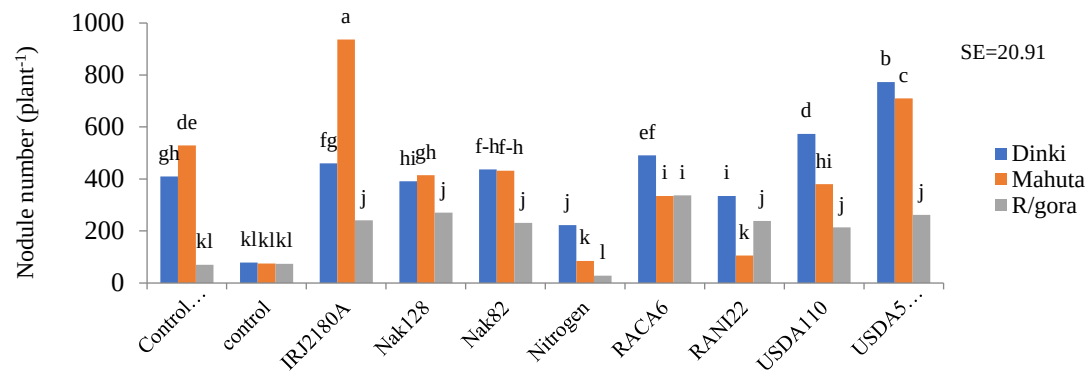


Figure 2. Interaction between treatments and location on nodule number of soybean

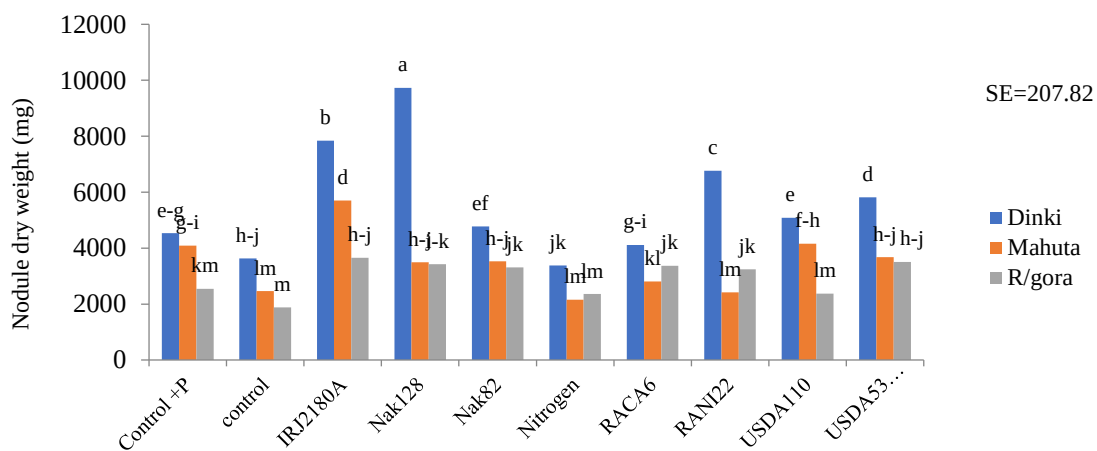


Figure 3. Interaction between treatments and location on nodule dry weight of soybean

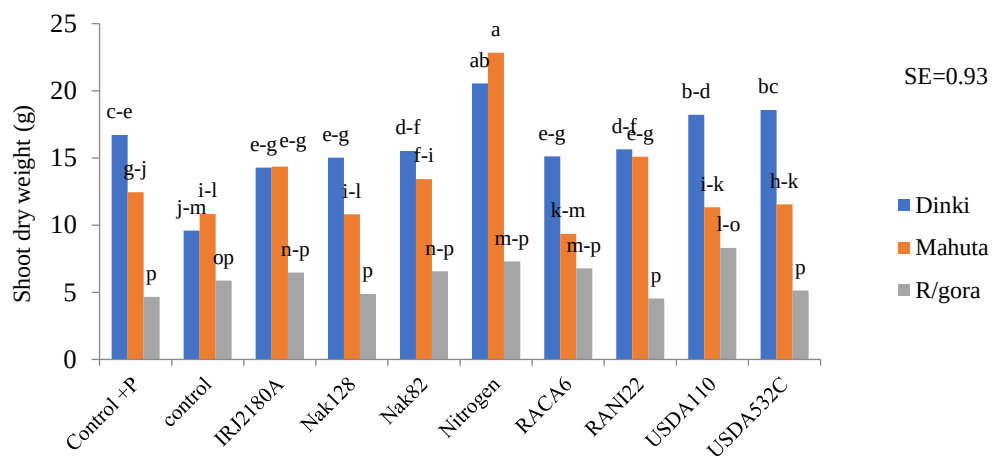


Figure 4. Interaction between treatments and location on shoot dry weight of soybean

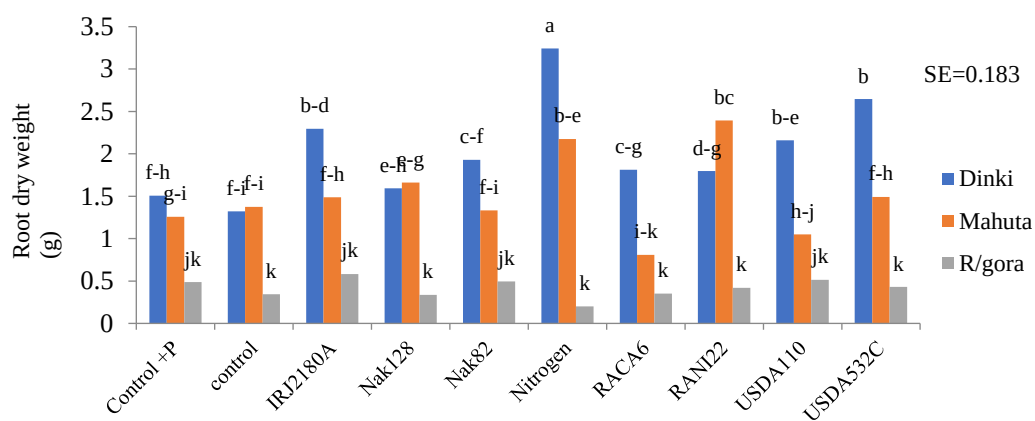


Figure 5. Interaction between treatments and location on root dry weight of soybean

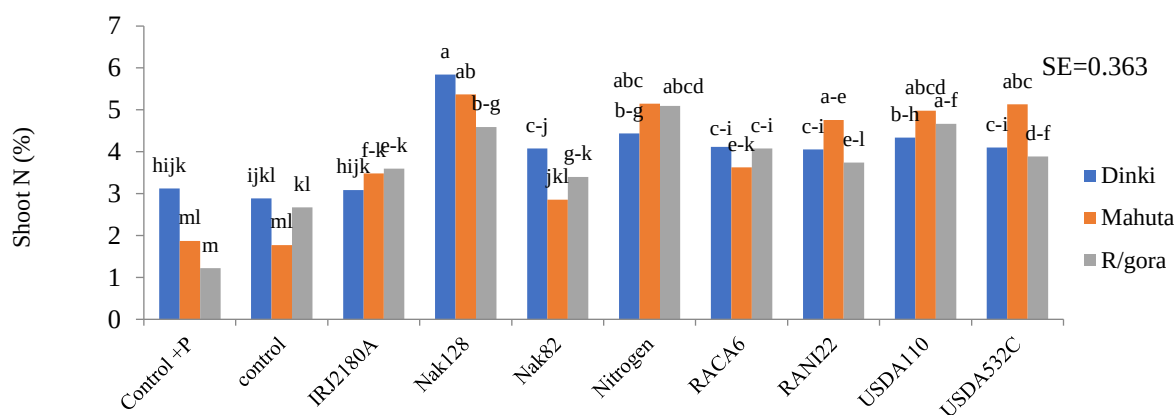


Figure 6. Interaction between treatments and location on shoot nitrogen of soybean

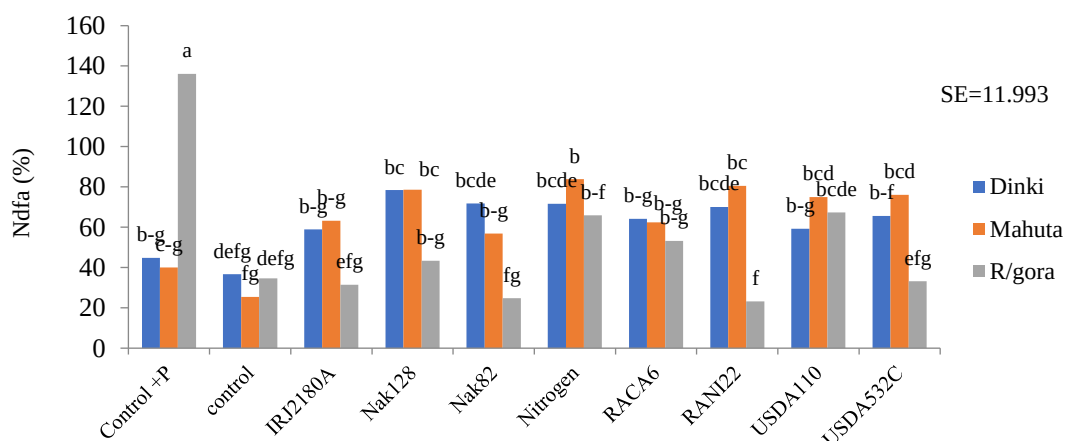


Figure 7. Interaction effects of treatments and location on %Ndfa content of soybean

Effect of inoculation and location on soybean yield

Table 2 shows the effect of treatment and location on soybean yield. There was a significant difference between treatments ($p < 0.05$) in 100-seed weight. Plots treated with nitrogen had the highest mean 100-seed weight, although it was statistically similar to all other treatments except RACA 6 and the control. The percentage difference between the highest mean and the lowest mean was 12.80%, indicating that rhizobia inoculation has a similar effect to nitrogen application, as reported by dos Santos Sousa *et al.* (2022). N'cho *et al.* (2013) also reported poor performance of RACA 6, which they attributed to low P levels in most farmers' fields. The

higher 100-seed weight observed for the control could be associated with the better adaptability of native rhizobia to the ecological surroundings, and thus their ability to infect and form a positive association with legumes under the prevailing conditions (Koskey *et al.*, 2017; Matse *et al.*, 2020). In addition, native rhizobia can form positive interactions with naturally occurring soil microbiota, such as plant-growth-promoting bacteria and arbuscular mycorrhizal fungi, which increase the supply and access to other nutrients (Nyaga and Njeru, 2020). In terms of location, 100-seed weight differed significantly, with Dinki being significantly higher ($p < 0.001$), followed by Mahuta and then Rafin Gora.

For aboveground biomass weight, treatments differed significantly ($p < 0.05$), with plots inoculated with NAK 128 producing the highest weight, although statistically similar to IRJ2180A and nitrogen-treated plots. The percentage difference between the highest and the lowest mean was 38.47%. Differences between strains in above-ground dry matter accumulation may result from different strain potential for biological nitrogen fixation with soybean. Several reports have also shown significant differences between rhizobia strains in soybean dry matter accumulation (Kadiata *et al.*, 2012; Solomon *et al.*, 2012; Bahati, 2015). In terms of location, Dinki also produced the highest above-ground biomass weight (23,986 kg ha⁻¹) with a highly significant difference ($p < 0.001$).

For grain weight, a highly significant difference was observed ($p < 0.01$). Plots inoculated with USDA 532c had the highest grain weight (6,302 Kg ha⁻¹) although it was statistically similar to other inoculated and nitrogen-treated plots. Control + P added recorded the lowest grain weight (3584.6 Kg ha⁻¹) which was statistically similar to other inoculated treatments and nitrogen. There was a percentage difference of 34.12 % between RACA 6 and control, and 54.79 % between the highest and the lowest mean grain weight (Table 2). This shows that inoculation also increased grain yield, as reported by Abdullahi *et al.* (2013), where RACA 6 increased grain yield in the Nigerian savanna. However, this contrasts with Akpalu *et al.* (2014), who reported that rhizobia inoculation did not significantly affect grain yield.

Furthermore, they recorded an increase in grain yield following P addition, which contrasts with our findings, as P addition did not increase grain yield. Results from the study locations show consistently high values for all measured yield parameters at Dinki. This signifies that this

location responded best to inoculation with introduced rhizobia. Of all the locations, Dinki had the lowest MPN, which may explain the observed result.

Table 2: Effect of treatment and location on yield of soybean

Treatments	100 Seed (g)	Above ground biomass (Kg ha⁻¹)	Grain weight (Kg ha⁻¹)
IRJ2180A	13.31ab	14513bcd	4392.50bc
NAK 128	13.31ab	19097a	5273.50ab
USDA 110	13.3ab	16909abcd	5256.70ab
NAK 82	13.19ab	15645abcd	4187.90bc
RANI 22	13.19ab	18667ab	4758.00bc
USDA 532c	12.96ab	18397ab	6302.00a
RACA 6	12.7bc	18017abc	5062.20abc
Control	11.99c	13754cd	3879.80bc
Control + P	12.87ab	12936d	3584.60c
Nitrogen	13.63a	17698abc	5045.10abc
SE±	0.252	1337	476.71
LOS	*	*	**
Location			
DINKI	13.80a	23896a	6942.70a
MAHUTA	12.92b	15811b	5431.0b
RAFIN GORA	12.47c	9983c	2182.30c
SE±	0.139	732.305	261.107
LOS	***	***	***
Treatment x location	NS	NS	NS

Means followed by the same letter (s) in a column are not significantly different at 5% level of probability using Duncan Multiple Range Test (DMRT). NS: Not significant; SE = Standard error; LOS = Level of significance

CONCLUSION

This study demonstrates that rhizobia inoculation can significantly enhance soybean nodulation, nitrogen fixation, biomass accumulation, and grain yield in the Northern Guinea Savanna of Nigeria. Selected strains, particularly NAK 128 and USDA 532c, showed strong potential to substitute or complement mineral nitrogen fertilizers by achieving comparable or superior performance. However, inoculation effectiveness was strongly influenced by location, highlighting the importance of environmental and soil factors in determining symbiotic efficiency. The superior performance observed at Dinki underscores the role of favourable soil conditions in enhancing inoculant success. Conversely, reduced responses in Rafin Gora indicate that site-specific constraints can limit inoculation benefits. These findings emphasize that while rhizobia inoculation is a viable and sustainable strategy for improving soybean productivity, its success depends on careful matching of inoculant strains to local environmental conditions. Future efforts should focus on developing location-specific inoculant recommendations, improving soil fertility management (particularly phosphorus supplementation), and understanding interactions between introduced and native rhizobia populations. Integrating effective rhizobia inoculation into soybean production systems offers a cost-effective and environmentally sustainable pathway to enhance biological nitrogen fixation, reduce reliance on synthetic fertilizers, and improve agricultural productivity in the savanna agro-ecosystems of sub-Saharan Africa.

ACKNOWLEDGEMENTS

We thank the Bill & Melinda Gates Foundation for funding this research through N2Africa: Putting Nitrogen fixation to work for smallholder farmers in Africa (www.N2Africa.org), a grant to Wageningen University implemented in 11 countries in sub-Saharan Africa, including Nigeria.

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