

PERFORMANCE OF RHIZOBIAL INOCULANTS ON GROWTH AND YIELD OF GROUNDNUT IN CHARLAND

S.A. Jannat¹, S. Chowdhury¹, M. Islam^{1,2*}, M.S. Akram¹, A. Hossain¹, M.R. Khan¹ and M.M.A. Tarafder¹

¹ Soil Science Division, Bangladesh Institute of Nuclear Agriculture, Mymensingh 2202

² Administration section, Bangladesh Institute of Nuclear Agriculture, Mymensingh 2202

*Corresponding e-mail: m.islambau03@gmail.com

Abstract

Considering the potential role of rhizobial inoculation to enhance biological nitrogen fixation, it is necessary to evaluate effective inoculant strains to reduce dependence on chemical nitrogen fertilizers in groundnut cultivation. Therefore, a field experiment was conducted at Nawvangan Char, Jamalpur Sadar, Jamalpur during February to June 2025 with an objective to see the effects of different rhizobial inoculants on the growth, nodulation, and yield of groundnut (*Arachis hypogaea* L.). The experiment consisted of five treatments: T₁: Control (I₀: No inoculant, No fertilizer); T₂: (I₀ + N₂₄); T₃: I₁ (GN-2); T₄: I₂ (GN-4); T₅: I₃ (GNB-5) which were tested on two groundnut varieties - V₁: Binachinabadam-4 and V₂: Binachinabadam-8. The experiment was laid out in a split-plot design with three replications, and each unit plot measured 9 m². Groundnut seeds were inoculated with respective Rhizobium cultures before sowing, except in the control and nitrogen fertilizer-only treatments. Results indicated that rhizobial inoculation significantly enhanced plant growth, nodulation, and yield compared to uninoculated treatments. Among the treatments, T₄ (GN-4) showed the best performance, followed by T₃ (GN-2). The results suggest that appropriate rhizobial inoculation is an effective strategy for improving groundnut productivity while reducing reliance on chemical nitrogen fertilizers.

Keywords: Charland, Chinabadam, Rizobium strain, Nitrogen fixation, Urea fertilizer.

1. Introduction

Groundnut (*Arachis hypogaea* L.) is one of the most important oilseed and food legume crops cultivated worldwide, particularly in tropical and subtropical regions. It plays a vital role in human nutrition, livestock feed, and soil fertility improvement through biological nitrogen fixation (BNF). Nitrogen is a critical macronutrient for crop growth and development, yet its availability in soils is often limited, necessitating external fertilizer inputs (Alam *et al.*, 2023; Islam *et al.*, 2024). Excessive reliance on chemical nitrogen fertilizers not only increases production costs but also contributes to environmental degradation (Khanam *et al.*, 2023; Al-Amin *et al.*, 2025). In Bangladesh, groundnut is widely grown in riverine char lands and sandy loam soils, where nutrient limitations, particularly nitrogen deficiency, often constrain

productivity (Karim *et al.*, 2017). Rhizobium, a symbiotic bacterium, forms nodules on the roots of leguminous crops and fixes atmospheric nitrogen into plant-available forms. This process reduces the need for synthetic nitrogen fertilizers and enhances soil fertility, making rhizobial inoculation a sustainable alternative for legume production (Fwanyanga *et al.*, 2022). Nodulated legumes are estimated to fix approximately 21.45 million tonnes of nitrogen annually in global agricultural systems (Herridge *et al.*, 2008). In addition to nitrogen fixation, rhizobial strains secrete growth-promoting substances such as indoleacetic acid (IAA), which stimulate root development and improve nodulation (Al-Mujahidy *et al.*, 2023).

Several studies have demonstrated that inoculation with effective rhizobial strains significantly improves nodulation, plant growth, and yield in groundnut under diverse agro-ecological conditions (Fwanyanga, 2023; Khanam *et al.*, 2024). Rhizobium inoculation combined with phosphorus fertilization has also been shown to enhance soil physico-chemical properties and crop performance (Hasan, 2018). However, the effectiveness of inoculation depends on the compatibility between host plant and rhizobial strain, as some introduced strains may fail to compete with native soil rhizobia (Bogino *et al.*, 2006 and 2008). Recent research has highlighted the potential of strain-specific inoculation, with Bradyrhizobium and other effective strains significantly enhancing biomass and yield in groundnut (Ajayi *et al.*, 2024; Wang *et al.*, 2025; Krishnan, 2025). Bangladesh, with its diverse agro-climatic zones, has considerable potential for enhancing groundnut productivity through rhizobial inoculation. Yet, the performance of different rhizobial strains under char land field conditions remains underexplored. Evaluating strain-specific effects is crucial, as the efficiency of nitrogen fixation and yield improvement depends on the compatibility between host plant and rhizobial strain. Therefore, the present study was undertaken to assess the performance of selected rhizobial inoculants on groundnut growth, nodulation, and yield under field conditions in the Jamalpur char regions of Bangladesh. The findings are expected to contribute to sustainable groundnut production strategies by reducing dependence on chemical nitrogen fertilizers and promoting eco-friendly agricultural practices.

2. Materials and Methods

The field experiment was conducted at Nawvangan Char, Jamalpur Sadar, Jamalpur to evaluate the effect of rhizobial inoculants on groundnut under field conditions during February to June 2025. The study included a five treatments and two groundnut varieties. The treatments were as follows: T_1 : Control (I_0 : No Inoculant, No Fertilizer); T_2 : ($I_0 + N_{24}$); T_3 : I_1 (GN-2); T_4 : I_2 (GN-4) and T_5 : I_3 (GNB-5). The varieties tested were V1: Binachinabadam-4 and V2: Binachinabadam-8. The experiment was laid out in a split-plot design with three replications. Varieties were assigned to the main plots, while treatments were allocated to the subplots. Each unit plot measured 9 m^2 ($3 \text{ m} \times 3 \text{ m}$). Seeds were inoculated with the respective Rhizobium strains for all treatments except T_1 (control) and T_2 (fertilizer only). The soil test-based rates of N, P, K, S, Zn and B were 24, 24, 30, 24, 1 and 1 kg ha^{-1} , respectively. Sowing was carried out on 2 February 2025 at the experimental site. Standard agronomic practices

were followed to ensure proper crop growth and development. Data were collected on several parameters, including nodule number, nodule dry weight, root length, pod length, pods per plant, and plot yield. Observations were recorded from five randomly selected plants per plot. Seed yield per plot was measured and converted to tons per hectare ($t\ ha^{-1}$). All recorded data were subjected to appropriate statistical analyses. Significant responses of groundnut to rhizobial inoculation were observed across the experimental location.

3. Results and Discussion

3.1 Effects of rhizobial inoculants on the growth parameters of groundnut

Different rhizobial inoculants and genotypes had a significant impact on root length per plant (Table 1). In the case of different rhizobial inoculant treatments, the maximum root length per plant was 13.73 cm and 15.96 cm in the T_4 (GN-4) treatment, which was statistically similar to T_3 (GN-2) in 50 and 80 DAS, respectively. The T_1 (contro) treatment had the lowest root length per plant, achieving 7.96 cm at 50 DAS and 8.68 cm at 80 DAS. Different cultivars might affect the root length per groundnut plant. The V_2 (Binachinabadam-8) had the longest root length per plant, achieving 11.78 cm at 50 DAS and 13.18 cm at 80 DAS. The combined application of rhizobial inoculants and groundnut genotypes has significant effects on groundnut root length per plant in 80 DAS, but insignificant impacts in 50 DAS. The maximum root length per plant was identified in the treatment combination of T_4 and V_2 , which was 13.78 cm and 13.02 cm in 50 and 80 DAS, respectively, while the lowest root length per plant was found in the treatment combination of T_1 and V_1 , which was 7.58 cm and 8.50 cm in 50 and 80 DAS, respectively. These findings suggest that rhizobial inoculation enhances root development by improving nitrogen availability and stimulating root elongation. Similar results were reported by Alam *et al.* (2023), who found that inoculation with effective strains significantly increased root growth and nodulation in groundnut under Bangladeshi field conditions. Similar findings were reported by Atakora (2020), who showed that rhizobial inoculation combined with phosphorus fertilization improved root growth in groundnut under low-fertility soils.

Shoot length per plant was significantly impacted with different rhizobial inoculants and genotypes (Table 1). In the case of different rhizobial inoculant treatments, the maximum shoot length per plant was 23.08 cm and 32.85 cm in the T_4 (Gn-4) treatment, which was statistically similar to T_3 (GN-2) in 50 and 80 DAS, respectively. The T_1 treatment had the shortest shoot length per plant, determining 15.60 cm at 50 DAS and 16.19 cm at 80 DAS. In case different variety influence the shoot length per groundnut plant. The V_2 had the longest shoot length per plant, measuring 22.88 cm and 27.19 cm at 50 and 80 DAS, respectively. Combined application of rhizobial inoculants and groundnut genotypes has significant effects on groundnut shoot length per plant at 80 DAS but insignificant effects at 50 DAS. The maximum shoot length per plant was found in T_4 along with V_2 , which was 21.60 cm and 34.17 cm in 50 DAS and 80 DAS, respectively, and the lowest shoot length per plant was found in the

treatment combination of T_1 with V_1 , which was 8.50 cm and 9.708 cm in 50 DAS and 80 DAS, respectively. Enhanced shoot growth under inoculation reflects improved nitrogen fixation and nutrient uptake. Fwanyanga *et al.* (2022) emphasized that effective rhizobial strains enhance shoot biomass and vigor in legumes by improving nitrogen assimilation.

Different rhizobial inoculants and genotypes significantly impacted the number of branches per plant (Table 1). In the case of different rhizobial inoculant treatments, the maximum number of branches per plant was observed to be 6.00 and 5.54 in the T_4 (GN-4) treatment, which was statistically similar to T_3 (GN-2) at 50 DAS and 80 DAS, respectively. The minimum number of branches per plant was found in the T_1 treatment, which was 2.83 and 3.01 in 50 DAS and 80 DAS, respectively. In case different varieties also influence the number of branches per plant of groundnut. The highest number of branches per plant was recorded in the V_2 , which was 4.87 and 4.84 at 50 DAS and 80 DAS, respectively. The combined application of rhizobial inoculants and groundnut genotypes has no influence on the number of branches per plant in 50 DAS but has a significant impact in 80 DAS. The highest number of branches per plant was found in the T_4 treatment combination with V_2 , which was 2.67 cm and 3.02 in 50 DAS and 80 DAS, respectively, and the lowest number of branches per plant was found in the T_1 treatment combination with V_1 , which was 4.83 and 5.40 in 50 DAS and 80 DAS, respectively. Branch proliferation is linked to enhanced nitrogen assimilation, which supports vegetative growth. Bogino *et al.* (2006, 2008) reported that effective rhizobial strains improve branching and canopy development in legumes by competing successfully with native soil rhizobia.

There was a significant effect of rhizobial inoculants and genotypes on on fresh weight per plant (Table 1). In the case of different rhizobial inoculant treatments, the maximum fresh weight per plant was 72.49 gm and 84.68 gm in the T_4 (GN-4) treatment, which was statistically similar to T_3 (GN-2) in 50 and 80 DAS, respectively. The T_1 treatment had the lowest fresh weight per plant, resulting in 49.69 gm in 50 DAS and 53.71 gm in 80 DAS. If different cultivars effect the fresh weight per plant. The V_2 had the maximum fresh weight per plant, resulting in 65.53 gm and 75.14 gm at 50 and 80 DAS, respectively. The fresh weight per plant of groundnuts is not significantly impacted by the combined application of rhizobial inoculants and groundnut genotypes in 50 DAS, but it has a significant impact in 80 DAS. The highest fresh weight per plant was found in the treatment combination of T_4 and V_2 , which was 75.86 gm and 86.61 in 50 DAS and 80 DAS, respectively, while the lowest fresh weight per plant was found in the treatment combination of T_1 and V_1 , which was 48.08 gm and 43.97 in 50 DAS and 80 DAS, respectively. The increase in fresh weight can be attributed to improved nodulation, nitrogen fixation, and growth hormone production such as indoleacetic acid (IAA) by rhizobia. These findings are consistent with reports by Fwanyanga (2023), who demonstrated that rhizobial inoculation significantly enhances biomass and yield in groundnut and related legumes.

Table 1. Effects of rhizobial inoculants on the growth parameters of groundnut at 50 and 80 days after sowing (DAS)

Treatments/Varieties	Root length plant (cm)		Shoot length plant (cm)		No. of branches plant ⁻¹		Fresh wt. plant ⁻¹ (g)	
	50	80	50	80	50	80	50	80
Treatments								
T ₁	7.96d	8.68d	15.60e	16.19c	2.83 d	3.01c	49.69 d	53.71b
T ₂	10.63c	11.22 c	16.28d	20.81b	4.08c	4.07b	58.29 c	70.33a b
T ₃	12.91ab	15.73 a	22.38a	32.53a	5.58 a	5.62a	71.04 a	83.09a
T ₄	13.73a	15.96 a	23.08a	32.85a	6.00 a	5.54a	72.49 a	84.68a
T ₅	12.33b	13.54 b	19.35c	31.63a	4.58 b	5.03a	65.80 b	80.23a
Varieties								
V ₁	11.24b	12.87	17.80	25.01b	4.37	4.60	61.40 b	73.68
V ₂	11.78a	13.18	22.88	27.19a	4.87	4.84	65.53 a	75.14
Treatments × Varieties								
T ₁ V ₁	7.58e	8.50	9.70	13.28d	2.67	3.02c	48.08	43.97b
T ₁ V ₂	8.33de	8.85	9.50	12.11d	3.00	3.00c	51.30	63.45a b
T ₂ V ₁	9.68d	11.22	16.68	21.85	3.83	4.00b c	58.04	71.42a b
T ₂ V ₂	11.58c	11.22	15.88	19.77c	4.33	4.13b c	58.54	69.24a b
T ₃ V ₁	12.82ab c	15.52	20.75	33.60a	5.33	5.33a b	72.72	85.59a
T ₃ V ₂	13.00ab c	15.93	21.17	31.46a b	5.83	5.90a	69.37	80.59a b
T ₄ V ₁	13.67ab	15.87	21.42	33.07a b	5.67	5.33a b	69.12	82.75a b
T ₄ V ₂	13.78a	16.05	21.60	34.17a	6.33	5.75a	75.86	86.61a
T ₅ V ₁	12.33ab c	13.25	19.62	31.53a b	4.33	4.67a b	69.73	80.82a b
T ₅ V ₂	12.33bc	13.83	19.08	30.18b	4.83	5.40a b	61.87	79.65a b

NS: Non-significant, * indicate significant at 5% level of probability, V₁: Binachinabadam-4, V₂: Binachinabadam-8; T₁: Control (I₀, No Fertilizer); T₂: I₀+N₂₄; T₃: I₁ (GN-2); T₄: I₂ (GN-4); T₅: I₃ (GNB-5)

Different rhizobial inoculants significantly impacted on the nodule number per plant but genotypes insignificantly influenced on the nodule number per plant (Table 2). In case of different rhizobial inoculants treatment maximum nodule number per plant was observed 42.92 and 60.33 in T₄ treatment which was statistically similar by T₃ in 50 DAS and 80 DAS, respectively. The minimum nodule number per plant was found in the T₂ treatment which was 8.10 and 9.51 in 50 DAS and 80 DAS, respectively. In case different varieties also influence the nodule number per plant of groundnut. The highest the nodule number per plant was recorded in the V₂ which was 24.72 and 36.76 in 50 DAS and 80 DAS, respectively. Combined application of rhizobial inoculants and groundnut genotypes have significant effects on groundnut of nodule number per plant in 50 DAS but insignificant effects in 80 DAS. The maximum nodule number per plant was found in the T₄ along with V₂ which was 43.67 and 60.91 in 50 DAS and 80 DAS, respectively and the lowest nodule number per plant was found in the treatment combination of T₁ with V₁ which was 6.87 and 8.65 in 50 DAS and 80 DAS, respectively. These results confirm that effective rhizobial strains enhance nodulation, particularly when paired with responsive genotypes. Similar findings were reported by Herridge *et al.* (2008), who observed that inoculation significantly increased nodulation in groundnut compared to uninoculated controls. Herridge *et al.* (2008) also emphasized that nodulated legumes contribute substantially to biological nitrogen fixation, adding millions of tonnes of nitrogen annually to agricultural systems. Inoculation with compatible rhizobial strains enhances nodulation, nitrogen fixation, and yield in groundnut (Fwanyanga *et al.*, 2022).

Table 2. Effects of rhizobial inoculants on the nodulation of groundnut at 50 and 80 days after sowing

Treatments/Varieties	No. of nodules plant ⁻¹		Nodule fresh wt. plant ⁻¹ (g)	
	50	80	50	80
Treatments				
T ₁	9.21c	10.78c	0.08	0.1c
T ₂	8.10c	9.51c	0.07	0.09c
T ₃	41.59a	56.16a	0.37	0.53a
T ₄	42.92a	60.33a	0.41	0.65a
T ₅	18.67b	36.76 b	0.23	0.42b
Varieties				
V ₁	23.43	33.18	0.27	0.33
V ₂	24.72	36.23	0.28	0.38
Treatments × Varieties				
T ₁ V ₁	6.87c	8.65	0.06	0.08c
T ₁ V ₂	11.54c	10.37	0.10	0.09c
T ₂ V ₁	7.78c	9.21	0.07	0.08c
T ₂ V ₂	10.21c	12.35	0.09	0.12c
T ₃ V ₁	40.67a	52.92	0.41	0.50ab
T ₃ V ₂	42.50a	59.39	0.43	0.56ab
T ₄ V ₁	40.17a	60.25	0.53	0.62a
T ₄ V ₂	43.67a	60.91	0.59	0.68a
T ₅ V ₁	16.33b	34.87	0.17	0.39b
T ₅ V ₂	21.00b	38.65	0.25	0.44ab

NS: Non-significant, * indicate significant at 5% level of probability, V₁: Binachinabadam-4, V₂: Binachinabadam-8; T₁: Control (I₀, No Fertilizer); T₂: I₀+N₂₄; T₃: I₁ (GN-2); T₄: I₂ (GN-4); T₅: I₃ (GNB-5)

Different rhizobial inoculants significantly impacted on the nodule fresh weight per plant but genotypes insignificantly influenced on the nodule fresh weight per plant (Table 2). In case of different rhizobial inoculants treatment maximum nodule fresh weight per plant was observed 0.41 gm and 0.65 gm in T_4 treatment which was statistically similar by T_3 in 50 DAS and 80 DAS, respectively. The minimum nodule fresh weight per plant was found in the T_2 treatment which was 0.07 gm and 0.09 gm in 50 DAS and 80 DAS, respectively. In case different varieties also influence the the nodule fresh weight per plant of groundnut. The highest the the nodule fresh weight per plant was recorded in the V_2 which was 0.28 gm and 0.38 gm in 50 DAS and 80 DAS, respectively. Combined application of rhizobial inoculants and groundnut genotypes have insignificant effects on groundnut of the nodule fresh weight per plant in 50 DAS but significant effects in 80 DAS. The maximum the nodule fresh weight per plant was found in the T_4 along with V_2 which was 0.59 gm and 0.62 gm in 50 DAS and 80 DAS, respectively and the lowest the nodule fresh weight per plant was found in the treatment combination of T_1 with V_1 which was 0.06 gm and 0.07 gm in 50 DAS and 80 DAS, respectively. These results indicate that effective rhizobial strains not only increase nodule number but also improve nodule biomass, which is critical for nitrogen fixation efficiency. Similar observations were made by Bogino *et al.* (2006, 2008), who reported that competitive and effective rhizobial strains enhance nodule biomass and nitrogen fixation in legumes. Wang *et al.* (2025), who reported that varietal compatibility with rhizobial strains is crucial for maximizing nodulation and yield

3.2 Effects of rhizobial inoculants on the yield and yield component of groundnut at harvest

The results for root length per plant show that rhizobial inoculation had a clear positive influence, while varietal differences were statistically significant (Table 3). The control treatment (T_1) produced the shortest roots at 9.83 cm, and fertilizer alone (T_2) increased root length to 13.31 cm. Inoculant treatments performed much better, with T_3 (GN-2) reaching 17.43 cm, T_4 (GN-4) producing the longest roots at 19.03 cm, and T_5 (GNB-5) at 16.52 cm. In contrast, varietal differences were significant, with Binachinabadam-8 (V_2) showing longer roots (16.06 cm) compared to Binachinabadam-4 (V_1) at 14.39 cm. This indicates that while inoculation enhanced root development overall, varietal choice also played an important role, with V_2 performing better in terms of root length. These findings indicate that rhizobial inoculation improves root development, likely due to enhanced nitrogen fixation and growth hormone secretion such as indoleacetic acid (IAA) by rhizobia (Al-Mujahidy *et al.*, 2023). Similar results were reported by Khanam *et al.* (2024), who found that Rhizobium inoculation combined with PKS fertilizer significantly increased root and haulm growth in groundnut.

Similarly, the results for shoot length per plant demonstrate that rhizobial inoculation had a pronounced effect, while varietal differences were statistically significant (Table 3). The control treatment (T_1) recorded the shortest shoots at 17.18 cm, and fertilizer alone (T_2) increased shoot length to 25.92 cm. Inoculant treatments showed much greater improvement,

with T₃ (GN-2) reaching 41.88 cm, T₄ (GN-4) producing the tallest shoots at 44.22 cm, and T₅ (GNB-5) at 38.52 cm. In contrast, varietal performance was significant at the 5% level, with Binachinabadam-8 (V₂) producing longer shoots (35.03 cm) compared to Binachinabadam-4 (V₁) at 32.06 cm. This suggests that while inoculation enhanced shoot growth overall, varietal differences also played a meaningful role in determining shoot length. Enhanced shoot growth under inoculation reflects improved nitrogen assimilation and nutrient uptake. Fwanyanga *et al.* (2022) reported similar improvements in shoot biomass of legumes inoculated with effective rhizobial strains, highlighting the role of inoculation in enhancing vegetative growth.

The number of pods per plant varied across treatments and varieties (Table 3), with the control (T₁) producing the lowest pod count (16.50), while the T₄ (GN-4) showed the highest (38.17), though overall treatment differences were statistically non-significant. In contrast, varietal performance showed a clear distinction, as Binachinabadam-8 (V₂) produced significantly more pods (27.20) than Binachinabadam-4 (V₁) with 25.40 pods per plant, indicating that varietal choice had a stronger influence on pod production than the applied treatments. This suggests that varietal choice had a stronger influence on pod production than inoculation. Muhammad *et al.* (2006) similarly reported that groundnut genotypes responded differently to inoculation, with pod number being more genotype-dependent than treatment-dependent.

The results for pod length show that rhizobial inoculants had a clear impact, while varietal differences were not statistically significant (Table 3). The control treatment (T₁) produced the shortest pods at 1.57 cm, and fertilizer alone (T₂) improved pod length to 2.54 cm. Inoculant treatments performed much better, with T₃ (GN-2) reaching 3.44 cm, T₄ (GN-4) producing the longest pods at 3.98 cm, and T₅ (GNB-5) at 3.28 cm. This indicates that inoculation, particularly with GN-4, enhanced pod development compared to control and fertilizer-only treatments. Between varieties, V₁ (Binachinabadam-4) had an average pod length of 2.82 cm and V₂ (Binachinabadam-8) slightly longer at 3.10 cm, but the difference was not statistically significant, suggesting that inoculants were the main factor driving pod length improvement. These results confirm that inoculation, particularly with GN-4, enhances pod development. Asante *et al.* (2020) also reported that *Rhizobium* inoculation significantly improved pod length and yield traits in groundnut under field conditions.

Table 3. Effects of rhizobial inoculants on the yield and yield attributing characteristics of groundnut

Treatments/ Varieties	Root length (cm)	Shoot length (cm)	No. of pods plant ⁻¹	Pod length (cm)	Pod yield (t ha ⁻¹)
Treatments					
T ₁	9.825d	17.183d	16.50c	1.57e	1.09d
T ₂	13.313c	25.922c	18.50c	2.54d	1.77c
T ₃	17.430b	41.877a	30.17b	3.59b	2.44ab
T ₄	19.032a	44.220a	38.17a	3.93a	2.51a
T ₅	16.523b	38.523b	28.17b	3.27c	2.35a
Varieties					
V ₁	14.387b	32.060b	25.40b	2.80b	1.99
V ₂	16.062a	35.030a	27.20a	3.16a	2.08

NS: Non-significant, * indicate significant at 5% level of probability, V₁: Binachinabadam-4, V₂: Binachinabadam-8; T₁: Control (I₀, No Fertilizer); T₂: I₀+N₂₄; T₃: I₁ (GN-2); T₄: I₂ (GN-4); T₅: I₃ (GNB-5)

Different rhizobial inoculants and varieties significantly impacted the pod yield (Table 3). In case of different rhizobial inoculants treatment maximum pod yield was found 2.51 t ha⁻¹ in T₄ treatment which was statistically similar by T₃ and T₅ treatments. The minimum pod yield was found in the T₁ treatment which was 1.09 t ha⁻¹. In case different varieties also influence the pod yield of groundnut. The highest pod yield was recorded in the V₂ which was 2.09 t ha⁻¹ followed by V₁ which was 1.99 t ha⁻¹. The use of various rhizobial inoculants and varieties increased groundnut pod yields significantly. The effectiveness of *Rhizobium* spp. alone or in combination with chemical fertilizers to improve pod yield and other traits in groundnut has been reported by Asante *et al.* (2020). Similar type of results was also reported by Muhammad *et al.* (2006) while studying the efficacy of symbiotic association between three Rhizobial strains i.e., B (TAL1371, C (Tal-1000) and 0 (NC-92) and two groundnut genotypes viz. V1 (ICG-4993) and V2 (ICG-732) in a field trial under rain-fed conditions of Pothowar in a semi-arid environment. They found that inoculation increased symbiotic and yield traits of groundnut genotypes. However, different strain showed variable positive effect with respect to genotypes.

3.3 Interaction effects of rhizobial inoculants and groundnut genotypes on the yield and yield contributing characters

Rhizobium, a symbiotic bacterium, forms nodules on the roots of leguminous crops and fixes atmospheric nitrogen into plant-available forms which rhizobacteria enhance plant growth, and biological nitrogen fixation by microbes is believed to be a key component in promoting plant growth. Combined application of rhizobial inoculants and groundnut genotypes have significant effects on groundnut of root length plant⁻¹ (cm), shoot length plant⁻¹ (cm), no. of pod plant⁻¹ but insignificant effects on pod length (cm) and pod yield (t ha⁻¹) (Table 4). In case of root length, significantly maximum height was found in the T₄ along with

V_2 which was 20.08 cm and the lowest length was found in the treatment combination of T_1 with V_1 which was 9.23 cm. The T_4 combination with V_2 significantly rendered the maximum shoot length (45.88 cm) and number of pods per plant (39.67) of groundnut followed by T_4 and V_2 combination. The lowest shoot length and number of pods per plant of groundnut were recorded in T_1 and V_1 combination. The height root length was found in the T_4 along with V_2 which was 4.02 cm and the lowest length was found in the treatment combination of T_1 with V_1 which was 1.44 cm. In case of pod yield of groundnut maximum yield was found in the T_4 along with V_2 which was 2.54 t ha⁻¹ and the lowest yield was found in the treatment combination of T_1 with V_1 which was 1.02 t ha⁻¹. The effectiveness of *Rhizobium* spp. alone or in combination with chemical fertilizers to improve pod yield and other traits in groundnut has been reported by Asante *et al.* (2020). Similar type of results was also reported by Muhammad *et al.* (2006) while studying the efficacy of symbiotic association between three Rhizobial strains i.e., B (TAL1371, C (Tal-1000) and O (NC-92) and two groundnut genotypes viz. V1 (ICG-4993) and V2 (ICG-732) in a field trial under rain-fed conditions of Pothowar in a semi-arid environment. They found that inoculation increased symbiotic and yield traits of groundnut genotypes. However, different strain showed variable positive effect with respect to genotypes. According several findings stated above it is evident that combined use of rhizobial inoculants and genotypes enhance the yield contributing characters of groundnut which is well consistent with this present study.

Table 4. Interaction effects of different inoculants and urea fertilizer on the yield and yield contributing characters of groundnut

Treatment s	Root length (cm)	Shoot length (cm)	No. of pods plant ⁻¹	Pod length (cm)	Pod yield (t ha ⁻¹)
$T_1 V_1$	9.21	16.02	15.67	1.44f	1.02
$T_1 V_2$	10.44	18.35	17.33	1.70f	1.16
$T_2 V_1$	12.48	25.06	18.00	2.47e	1.71
$T_2 V_2$	14.15	26.78	19.00	2.61e	1.83
$T_3 V_1$	16.53	39.49	29.00	3.24c	2.37
$T_3 V_2$	18.33	44.27	36.67	3.94 a	2.50
$T_4 V_1$	17.98	42.56	31.33	3.84ab	2.48
$T_4 V_2$	20.08	45.88	39.67	4.02a	2.54
$T_5 V_1$	15.73	37.17	27.67	3.01d	2.35
$T_5 V_2$	17.32	39.87	28.67	3.55b	2.40

NS: Non-significant, * indicate significant at 5% level of probability, V_1 : Binachinabadam-4, V_2 : Binachinabadam-8; T_1 : Control (I_0 , No Fertilizer); T_2 : I_0+N_{24} ; T_3 : I_1 (GN-2); T_4 : I_2 (GN-4); T_5 : I_3 (GNB-5)

4. Conclusions

This study showed that rhizobial inoculation significantly enhanced groundnut growth, nodulation, yield characteristics, and pod yield, with responses differing among inoculant strains and genotypes. Among the treatments, GN-4 (T_4) continuously showed better root and shoot growth, branching, fresh biomass, nodulation, pod development, and grain production. Rhizobial inoculation markedly enhanced nodule number and nodule fresh weight, indicating improved biological nitrogen fixation and nutrient availability. Binachinabadam-8 (V_2) typically performed better than Binachinabadam-4 (V_1) in most growth and yield parameters, indicating higher compatibility with the applied rhizobial strains. The combination of GN-4 and Binachinabadam-8 resulted in the best overall performance, even though interaction effects were not significant for all attributes. The study demonstrates that appropriate rhizobial inoculation, particularly GN-4, significantly improves growth, nodulation, and yield of groundnut, offering a sustainable and cost-effective alternative to chemical nitrogen fertilization.

Conflicts of Interest

The authors declare no conflicts of interest regarding publication of this paper.

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