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Integrated Phosphorus and Biofertilizer Management for Improving the Yield of Green Gram (*Vigna radiata* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Phosphorus fertilisation and microbial seed inoculation are used to improve green gram (*Vigna radiata* L.) productivity. A field experiment was conducted during the 2025 kharif season at Sri Ganganagar, Rajasthan, India, on sandy loam soil (pH 8.65; organic carbon 0.47%) to compare nine nutrient-management treatments in a randomised block design with three replications. The treatments comprised an untreated control and 20 or 40 kg P_2O_5 ha^{-1} applied alone or with phosphate-solubilising bacteria (PSB), *Rhizobium*, or both inoculants. Treatment T_9 (40 kg P_2O_5 ha^{-1} + PSB + *Rhizobium*) produced the highest numbers of pods per plant (22.47) and grains per pod (11.47), the highest test weight (34.97 g), and the highest grain yield (1,138 kg ha^{-1}) and straw yield (2,417 kg ha^{-1}). Its combined grain and straw yield was 3,555 kg ha^{-1}. Grain yield under T_9 was 518 kg ha^{-1} (83.5%) above the control and 40 kg ha^{-1} (3.6%) above T_7 (40 kg P_2O_5 ha^{-1} + *Rhizobium*). The differences between these

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treatments in pods per plant, grains per pod and test weight were smaller than the corresponding 5% critical differences. The results indicate that integrated phosphorus and microbial inoculant treatments can improve green gram yield under the field conditions studied.

Keywords: Green gram; phosphorus; phosphate-solubilising bacteria; Rhizobium; seed inoculation; grain yield; straw yield.

1. Introduction

Green gram (*Vigna radiata* L.) is a short-duration grain legume cultivated for food and fodder and valued for its role in diversified cropping systems. Its seed protein content is substantial: Wang *et al*. (2025) reported an average crude protein concentration of 25.91% among 400 mungbean accessions. Pulse cultivation is important to food and nutritional security in India (Das *et al*., 2016), while on-farm demonstrations illustrate the scope for improving green gram production through locally adapted agronomic management (Bhat *et al*., 2026).

Phosphorus is required for root development, energy metabolism, reproductive growth and the establishment of effective legume symbioses. Yet its availability may be constrained in soils where phosphorus is converted into less soluble forms (Sharma *et al*., 2013). Field studies in mungbean have shown responses to phosphorus application under contrasting tillage conditions and on sandy loam soil (Ghimirey *et al*., 2025). Phosphorus and sulphur nutrition also interact to influence growth, yield and seed composition (Oo *et al*., 2026). These findings support the evaluation of nutrient management under defined soil conditions rather than extrapolation from a single fertiliser rate or environment.

Phosphate-solubilising bacteria (PSB) can improve the availability of otherwise sparingly soluble phosphorus, while *Rhizobium* inoculation may promote symbiotic nitrogen fixation. In alkaline-calcareous soil, Khan *et al*. (2022) reported improvements in phosphorus acquisition, nodulation, nitrogen fixation and mungbean yield when PSB was combined with inorganic phosphorus. Bilal *et al*. (2021) also documented responses in mungbean performance to PSB and phosphorus. Related work evaluated phosphorus with molybdenum and *Rhizobium* under rainfed conditions (Siddiqui *et al*., 2024), whereas Ranjan *et al*. (2024) examined nutrient uptake under combined mineral nutrients, zinc and microbial inoculants.

Field evidence from Rajasthan demonstrated favourable green gram responses to phosphorus alongside PSB and *Rhizobium* (Tomar *et al*., 2024). In other environments, Sen *et al*. (2024) reported benefits of native PSB formulations in acidic red and lateritic soil, and Yousefi *et al*. (2025) identified genotype-dependent effects of microbial fertilisers on mungbean roots, nodulation and yield. Co-inoculation responses have also been reported in a mungbean–wheat sequence (Neha & Chandra, 2026), and combined microbial and fertiliser inputs improved mungbean performance in a separate field study (Awasthi *et al*., 2026). However, comparable nutrient combinations may perform differently under the alkaline sandy loam conditions of north-western Rajasthan. The present investigation compared two phosphorus rates applied alone and with PSB, *Rhizobium* or their combination in terms of the yield attributes and yield of green gram at Sri Ganganagar.

2. Materials and Methods

2.1 Experimental Site and Design

The field experiment was conducted during the kharif season of 2025 at the Agricultural Research Farm, Faculty of Agriculture, Tantia University, Sri Ganganagar, Rajasthan, India. The site has a hot semi-arid climate, and the experimental soil was sandy loam with a pH of 8.65 and an organic carbon content of 0.47%. Initial levels of available nitrogen, phosphorus and potassium in the soil were 125.44, 16.93 and 147.84 kg ha^{-1}, respectively. Soil pH was assessed following Piper (1966), organic carbon following Walkley and Black (1934), available nitrogen following Subbiah and Asija (1956), available phosphorus following Olsen *et al*. (1954), and available potassium following Jackson (1967).

Nine treatments were arranged in a randomised block design with three replications: T_1, untreated control; T_2, 20 kg P_2O_5 ha^{-1}; T_3, 40 kg P_2O_5 ha^{-1}; T_4, 20 kg P_2O_5 ha^{-1} + PSB; T_5, 40 kg P_2O_5 ha^{-1} + PSB; T_6, 20 kg P_2O_5 ha^{-1} + *Rhizobium*; T_7, 40 kg P_2O_5 ha^{-1} + *Rhizobium*; T_8, 20 kg P_2O_5 ha^{-1} + PSB + *Rhizobium*; and T_9, 40 kg P_2O_5 ha^{-1} + PSB + *Rhizobium*. Phosphorus was supplied through single superphosphate (SSP); PSB and *Rhizobium* were applied as seed inoculants in the corresponding treatments. Each plot measured 4 × 3 m, with inter-row and intra-row spacing of 30 cm and 10 cm, respectively. Irrigation, weed control and plant-protection practices were maintained uniformly among treatments.

2.2 Measurements and Data Analysis

Pods per plant, grains per pod and test weight (g) were recorded at harvest, together with grain and straw yields expressed in kg ha^{-1}. Combined grain and straw yield was calculated as the sum of the two yield components for each treatment. Treatment differences and changes relative to the control were calculated from the treatment means. Statistical comparisons followed randomised-block procedures (Panse & Sukhatme, 1967). For nine treatments and three replications, the residual error degrees of freedom were 16. For an error mean square (MSE), the standard error of a treatment mean is SEm = $\sqrt{(MSE/3)}$; the two-sided 5% critical difference is CD = $t_{0.975,16} \times \sqrt{2} \times$ SEm, where $t_{0.975,16} = 2.1199$.

3. Results and Discussion

3.1 Yield Attributes

The nutrient-management treatments were associated with a consistent increase in reproductive attributes from the untreated control towards the integrated high-phosphorus treatments. Pods per plant increased from 17.07 in T_1 to 22.47 in T_9, while grains per pod increased from 8.07 to 11.47. Test weight was 32.27 g in the control and 34.97 g in T_9. Treatment T_7 (40 kg P_2O_5 ha^{-1} + *Rhizobium*) was the next-highest treatment for pods per plant (21.87), grains per pod (11.07) and test weight (34.87 g). Table 1 summarises these treatment-wise observations.

Table 1. Effect of phosphorus and biofertilizer inoculation on green gram yield attributes

Treatment	Nutrient-management regime	Pods plant^{-1}	Grains pod^{-1}	Test weight (g)
T_1	Control	17.07	8.07	32.27
T_2	P20	18.07	8.40	32.50
T_3	P40	19.07	9.07	33.50
T_4	P20 + PSB	18.27	8.73	33.27
T_5	P40 + PSB	20.07	10.07	34.57
T_6	P20 + *Rhizobium*	19.67	9.60	34.50
T_7	P40 + *Rhizobium*	21.87	11.07	34.87
T_8	P20 + PSB + *Rhizobium*	21.00	10.47	34.63
T_9	P40 + PSB + *Rhizobium*	22.47	11.47	34.97
	SEm (±)	0.40	0.33	0.22
	CD (5%)	1.20	0.99	0.66

Note. P20 and P40 = 20 and 40 kg P_2O_5 ha^{-1}; PSB = phosphate-solubilizing bacteria; SEm = standard error of a treatment mean; CD = critical difference at the 5% level (16 error df)

The differences between T_9 and T_7 were 0.60 pods per plant, 0.40 grains per pod and 0.10 g in test weight. These differences were smaller than the corresponding 5% critical differences of 1.20, 0.99 and 0.66, respectively, indicating comparable values for the three yield attributes at the stated precision. The overall treatment pattern is consistent with findings from green gram field experiments involving phosphorus and inoculation (Hussain *et al*., 2010; Kumar & Yadav, 2018; Tomar *et al*., 2024). Kapat *et al*. (2024) reported improved green gram growth and yield following broader nutrient and organic amendments. Studies with related grain legumes also show responses to phosphorus and inoculants, including black gram (Gautam *et al*., 2022; Pallavi *et al*., 2022; Singh *et al*., 2008) and chickpea (Gupta & Sahu, 2012; Tagore *et al*., 2013). These comparative studies support the agronomic relevance of nutrient and microbial management while reflecting differences among crops and fertiliser combinations.

3.2 Grain, Straw and Combined Yield

Grain and straw yields followed the overall pattern observed for yield attributes. Treatment T_9 recorded 1,138 kg ha^{-1} of grain and 2,417 kg ha^{-1} of straw, compared with 620 and 1,558 kg ha^{-1}, respectively, in the untreated control. Thus, T_9 increased grain yield by 518 kg ha^{-1} (83.5%) and straw yield by 859 kg ha^{-1} (55.1%) relative to T_1. T_7 gave the second-highest grain yield (1,098 kg ha^{-1}) and straw yield (2,342 kg ha^{-1}), while T_8 produced 990 and 2,191 kg ha^{-1}, respectively. Table 2 presents all grain, straw and combined-yield treatment means.

Table 2. Effect of phosphorus and biofertilizer inoculation on green gram grain, straw and combined yield

Treatment	Nutrient-management regime	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Grain + straw (kg ha^{-1})
T_1	Control	620	1,558	2,178
T_2	P20	706	1,728	2,434
T_3	P40	810	1,898	2,708
T_4	P20 + PSB	783	1,813	2,596
T_5	P40 + PSB	910	2,058	2,968
T_6	P20 + *Rhizobium*	873	1,973	2,846
T_7	P40 + *Rhizobium*	1,098	2,342	3,440
T_8	P20 + PSB + *Rhizobium*	990	2,191	3,181
T_9	P40 + PSB + *Rhizobium*	1,138	2,417	3,555
	SEm (±)	3.41	10.76	—
	CD (5%)	10.22	32.26	—

Note. P20 and P40 = 20 and 40 kg P_2O_5 ha^{-1}; PSB = phosphate-solubilizing bacteria; SEm = standard error of a treatment mean; CD = critical difference at 5% (16 error df)

The response to the combined use of mineral phosphorus and inoculants is consistent with mungbean evidence that phosphorus availability and microbial inputs can influence root function and yield (Bilal *et al*., 2021; Khan *et al*., 2022). The field study by Tomar *et al*. (2024) similarly identified favourable performance when both inoculants were applied with phosphorus in Rajasthan. More recently, Awasthi *et al*. (2026) reported increased mungbean yield under integrated microbial and chemical fertiliser treatments, whereas Neha and Chandra (2026) identified a yield advantage from dual inoculation in a mungbean–wheat system.

The grain-yield difference between T_9 and T_7 was 40 kg ha^{-1}, exceeding the corresponding 5% critical difference of 10.22 kg ha^{-1}. Their straw-yield difference was 75 kg ha^{-1}, exceeding the critical difference of 32.26 kg ha^{-1}. These marginal differences were smaller than the respective responses from the untreated control to T_7. The use of SSP also means that phosphorus treatments supplied accompanying sulphur; phosphorus–sulphur responses have been documented in mungbean (Oo *et al*., 2026). The observed yield pattern is compatible with improved nutrient acquisition and microbial activity, mechanisms described in experimental studies (Khan *et al*., 2022; Sen *et al*., 2024; Yousefi *et al*., 2025). The treatment comparisons describe the performance of complete nutrient-management regimes.

4. Conclusion

Under the conditions of the 2025 kharif season on sandy loam soil at Sri Ganganagar, the treatment comprising 40 kg P_2O_5 ha^{-1} with PSB and *Rhizobium* (T_9) produced the highest observed values for reproductive attributes and the highest grain yield (1,138 kg ha^{-1}), straw yield (2,417 kg ha^{-1}) and combined grain and straw yield (3,555 kg ha^{-1}). Its grain yield exceeded the control by 83.5%. At the higher phosphorus rate, adding PSB to *Rhizobium* increased grain yield by 40 kg ha^{-1}, whereas pods per plant, grains per pod and test weight remained comparable between T_9 and T_7 at the 5% critical-difference threshold. These findings support integrated phosphorus and seed inoculation as an agronomically relevant management option under comparable field conditions.

5. Limitations of the Study

This experiment was conducted at one location during one growing season and compared nine practical nutrient-management regimes rather than a complete factorial set of phosphorus and inoculant treatments. Treatment-wise nodulation, plant nutrient uptake and changes in soil phosphorus availability were not reported, preventing direct evaluation of the mechanisms proposed to explain the yield response. Single superphosphate also supplies sulphur, which may contribute to responses assigned to phosphorus application. Multi-season, multi-location evaluation with complete inoculant characterisation and economic analysis would help establish the consistency and practical value of these treatment responses.

Declaration of AI Use

Generative AI tools assisted with manuscript drafting, language refinement and bibliographic presentation. The authors retain responsibility for the accuracy of the scientific content, original measurements, interpretation and conclusions.

Competing Interests

Authors have declared that no competing interests exist.

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