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Effect of *Rhizobium* and molybdenum inoculant on nodulation, growth and yield of green gram (*Vigna radiata* L.)

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Abstract
The present investigation entitled "Effect of *Rhizobium* and molybdenum inoculant on nodulation, growth and yield of green gram (*Vigna radiata* L.)" was carried out during *kharif* season 2024 at the Instructional Cum Research Farm, Barrister Thakur Chhedilal College of Agriculture and Research Station, Bilaspur (C.G.). The experiment was laid out in RBD with three replications. The treatments consisted of seven nutrient management practices *viz.*, Control with 100% PK (T_1), 100% RDF @ 25:50:25 kg N:P: K ha^{-1}(T_2), 100% PK+ *Rhizobium* @ 5g kg^{-1} seeds (T_3), 100% RDF+ Mo seed treatment @ 5g kg^{-1} seeds (T_4), 100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds (T_5), 100% PK+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds (T_6), 100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds (T_7).The results showed that growth parameters, *viz.*, plant population, plant height, number of branches, number of nodules, dry weight of nodules and yield attributes *viz.*, pod length, number of grains, number of pods, test weightwasfoundtobehigherundertreatmentT7-100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seedsstatisticallybeingatparwithT5-100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds and being significantly superior than all the other treatments. The yield parameters like grain yield and straw yield, recorded maximum yield under T7-100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds, this treatment was being statistically at par with T5-100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds and significantly superior than all the other treatments. The economic parameters like gross returns, net returns and B:C ratio was significantly superior under treatment T7-100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds. The highest gross return (132330.74₹ha^{-1}) and net return (101826.35₹ha^{-1}) were obtained under T7-100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds, followed by the treatment T5 -100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds and T4-100% RDF+ Mo seed treatment @ 5g kg^{-1} seeds. The highest benefit: cost ratio (3.33) recorded under the treatmentofT7-100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds. However, minimum gross return, net returns and benefit: cost ratio was obtained under control plot (T1).

Keywords: Green gram, nodulation, *Rhizobium*, molybdenum, benefit: cost ratio and yield

Introduction
Green gram (*Vigna radiata* L.), commonly known as mung bean, belongs to the family Leguminosae. It is a short-duration crop (65-90 days) cultivated on over 6 million hectares worldwide, primarily in warm regions. Mung bean is highly nutritious, providing protein (21-24 g), carbohydrates (56.72 g), fiber (4.11 g), fat (1.31 g), minerals (3.48 g) and energy (334 kcal) (Gopalan *et al.*, 2002; Dhakal *et al.*, 2015) [9, 7]. It also contains essential vitamins and minerals, including vitamin A (94 mg), vitamin C (8 mg), iron (7.3 mg), calcium (124 mg), magnesium (189 mg), phosphorus (367 mg), potassium (1246 mg), zinc (3 mg) and folate (549 mg), along with highly digestible, good-quality proteins (Mubarak, 2005) [15]. The grains are versatile and consumed in many forms such as vegetables, sprouts, dhal, roasted or fried beans, bean paste, and processed products like noodles, bread, cakes, jellies, and sweets (Asif *et al.*, 2013; Nair *et al.*, 2013) [2, 16]. Beyond its nutritional value, mung bean plays an important role in sustainable agriculture by reducing soil erosion and improving soil fertility through biological nitrogen fixation (Bansal, 2009) [4], thereby enhancing the productivity of succeeding crops (Jat *et al.*,

2012) [11]. Its roots form nodules that fix atmospheric nitrogen, while the vegetative parts, stalks, and husks serve as valuable fodder for livestock (Agboola & Fayemi, 1972) [1].

Rhizobium is a group of Gram-negative, aerobic, rod-shaped bacteria that are motile in their young stage, possessing bipolar, subpolar, or peritrichous flagella and are commonly found in soil. Inoculation of *Rhizobium* in legumes has been shown to enhance crop yield by 15-25%, protein content by 5-20% and nodulation by 30-50%. Globally, *Rhizobia* contribute an estimated 65-90 × 10^6 Mt of biological nitrogen fixation annually (Sufar *et al.*, 2024) [8]. These bacteria infect legume root nodules and convert atmospheric nitrogen (N_2) into ammonia (NH_4^+), which can be readily utilized by plants. Establishment of this symbiosis involves rhizosphere colonization (soil-root interface), root infection, progression through infection threads, and differentiation into nitrogen-fixing bacteroids (Wheatley *et al.*, 2020) [24]. The application of *Rhizobium* inoculants is a widely practiced agronomic strategy to supplement the nitrogen requirements of legumes, thereby reducing dependence on synthetic fertilizers (Rehman *et al.*, 2019) [17]. Artificial inoculation with effective strains is considered a cost-effective approach to secure optimal yields (Veer *et al.*, 2021) [22]. Excessive use of nitrogen fertilizers not only suppresses biological nitrogen fixation but also raises production costs. In contrast, *Rhizobium* inoculation enhances the availability of essential micronutrients such as molybdenum (Mo) and iron (Fe), thereby improving nodulation, nitrogen fixation efficiency, vegetative growth, crop maturity and ultimately yield (Veer *et al.*, 2022) [23].

Molybdenum (Mo) is an essential micronutrient required in very small quantities (0.1-1.0 ppm) for normal plant growth. Plants absorb it from the soil in the form of molybdate. Deficiency of Mo leads to stunted growth, pale or deformed leaves, poor development of buds and flowers, and restricted fruit setting (Mengel & Kirkby, 2001) [14]. Naturally low levels of Mo are common in certain regions, particularly in peat soils and highly weathered soils with poor nutrient content. Since Mo deficiency was first reported in tomato crops in 1939, similar symptoms have been observed in many other crops (Gupta, 1997) [10]. This micronutrient is vital for legumes, cereals, lettuce, tomato, cabbage, cauliflower, and citrus fruits, mainly because of its key role in nitrogen (N) metabolism and protein synthesis. During symbiotic nitrogen fixation, Mo functions as a cofactor of nitrogenase, catalyzing the reduction of atmospheric nitrogen (N_2) into ammonium (NH_4^+) ions (Mendel & Hänsch, 2002) [13]. It is also essential for nitrate reductase activity, which enables assimilation of nitrate from the soil. Consequently, plant nitrogen metabolism is strongly linked to soil Mo availability, particularly in legumes. A lack of Mo in legumes often results in excessive but ineffective nodulation, ultimately causing nitrogen deficiency (Marschner, 2011) [12]. Indian soils are generally low in Mo, with total content ranging from trace levels up to 12 mg kg^{-1} (Sakal, 2001) [18]. Around 11% of Indian soils are deficient in available Mo, compared to the optimal range of 1-1.5 ppm required for healthy plant growth. Therefore, external supplementation of Mo is crucial for improving crop performance and securing higher yields (Singh, 2001) [21].

Materials and Methods

The field experiment was conducted during the *kharif* season of 2024 at the Agriculture Research Cum Instructional Farm, Barrister Thakur Chhedilal College of Agriculture and Research, Bilaspur (C.G.). The experimental site is located at 22.09°N latitude and 82.15°E longitude, falling under India's Eastern Plateau and Hill Region (Agro-climatic Zone VII). Within Chhattisgarh, which is divided into three agro-climatic zones, Bilaspur lies in the plains zone. The experimental soil was sandy clay loam in texture, with a neutral pH (7.09). It was low in available nitrogen (237 kg ha^{-1}), medium in available phosphorus (14.32 kg ha^{-1}), and medium in available potassium (284.46 kg ha^{-1}). Data were recorded on plant population, plant height, number of branches, dry matter accumulation, nodule count, number of pods, pod length, grains per pod, test weight, grain yield, and stover yield of green gram at harvest, and subjected to statistical analysis. In addition, the economics of green gram cultivation in terms of gross return, net return, and benefit-cost ratio was worked out. The experimental data were statistically analyzed using the Analysis of Variance (ANOVA) technique.

Results and Discussion

The results indicate that plant population, plant height, number of branches, number of nodules, dry matter of nodules and dry matter accumulation of green gram were significantly affected by the different treatments across all observation intervals.

Growth parameters: The highest plant population was recorded in treatment T_7 (100% RDF + Rhizobium @ 5 g kg^{-1} seed + Mo seed treatment @ 5 g kg^{-1} seed) at both 30 DAS and harvest. Similarly, plant height and number of branches were also significantly superior under T7, which remained statistically at par with T_5 (100% RDF + Rhizobium @ 5 g kg^{-1} seed). In contrast, the lowest values for all these parameters were observed in the control treatment (T_1: 100% PK). These findings are in close agreement with the results reported by Siddique *et al.* (2024) [20] and Chaurasia *et al.* (2024) [6].

Nodulation: The maximum number of nodules and their dry weight were recorded in treatment T_7 (100% RDF + Rhizobium + molybdenum inoculation), which was statistically at par with T_5 (100% RDF + Rhizobium inoculation). In contrast, the lowest values for these traits were observed in T_1 (100% PK). The results clearly indicated that seed treatment with Rhizobium and molybdenum significantly enhanced root nodule development and weight, thereby promoting symbiotic nitrogen fixation. This improvement is likely to contribute to better growth and higher yield of green gram. Similar findings have also been reported by Samant (2017) [19].

Yield attributes: Yield attributes such as number of pods per plant, pod length (cm), number of seeds per pod, and test weight (g) were recorded significantly highest in treatment T_7 (100% RDF + Rhizobium @ 5 g kg^{-1} seed + Mo @ 5 g kg^{-1} seed), which was statistically at par with T_5 (100% RDF + Rhizobium @ 5 g kg^{-1} seed). In contrast, the lowest values for these parameters were observed in the control treatment (T_1: 100% PK). The results clearly demonstrate that the integration of Rhizobium and molybdenum with balanced fertilization markedly enhanced yield attributes. This emphasizes that the combined use of biofertilizers and micronutrients can effectively maximize the yield potential of green gram. These findings are consistent with the reports of Aslam *et al.* (2020) [3], Siddique *et al.* (2024) [20], and Chaudhari (2015) [5], who also highlighted the positive influence of biological and micronutrient inputs on improving seed yield traits in pulse crops.

Yield: Seed and stover yields of green gram were significantly affected by different nutrient and bio-inoculant treatments. The maximum seed yield **(**1497.25 kg ha⁻¹**)** and stover yield **(**2252.6 kg ha⁻¹**)** were obtained under T_7 (100% RDF + Rhizobium + Mo), which was statistically at par with T_5 (1402.14 and 2195.31 kg ha⁻¹) and T_4 (1282.31 and 1987.05 kg ha⁻¹). In contrast, the lowest seed yield (798.19 kg ha⁻¹**)** and stover yield (1314.15 kg ha⁻¹) were observed in the control treatment T_1 (100% PK only), which lacked nitrogen fertilization. Treatments involving Rhizobium inoculation (T_5 and T_3) consistently outperformed their non-inoculated counterparts (T_2 and T_1), confirming the beneficial role of biological nitrogen fixation. Molybdenum supplementation also played a positive role, as Mo-treated plots (T_6 and T_7) recorded higher yields compared to Rhizobium-only treatments, though the differences were statistically non-significant. The highest harvest index (39.94%) was recorded in T_7, followed by T_5 and T_6, whereas the lowest (37.77%) was found in T_1. These results suggest that the combined application of Rhizobium and molybdenum with balanced NPK fertilization not only enhanced yield attributes but also improved biomass partitioning efficiency in green gram.

Economics: The maximum cost of cultivation (₹ 30,504.39 ha⁻¹**)** was recorded in the treatment comprising 100% RDF with Rhizobium and molybdenum seed treatment, owing to the additional expenses of bio-inoculants and micronutrients. However, this treatment also produced the highest gross return (₹ 1,32,330.74 ha⁻¹)**,** net return (₹ 1,01,826.35 ha⁻¹), and the maximum benefit-cost (B:C) ratio (3.33), highlighting its superior profitability per unit investment. Treatments involving RDF with Rhizobium alone also proved economically beneficial, recording high gross and net returns with a B:C ratio of 2.10, which was statistically comparable to the combined inoculation treatment. In contrast, treatments that received only RDF or PK without bio-inoculants exhibited moderate to low profitability. The control treatment (100% PK) incurred the lowest cost of cultivation (₹ 27,795.66 ha⁻¹) but also recorded the lowest gross return (₹ 70,613.04 ha⁻¹)**,** net return (₹ 42,817.38 ha⁻¹), and B:C ratio (1.54). Overall, these findings clearly indicate that although integrated nutrient management with Rhizobium and molybdenum slightly increases cultivation costs, the substantial improvement in yield and economic returns far outweighs the additional investment, making it a highly efficient and profitable strategy.

Table 1: Effect of *Rhizobium* and molybdenum inoculation on plant population, plant height and number of branches of green gram (*Vigna radiata* L.)

Tr. No	Treatment details	Plant population(m⁻²)		Plant height				Number of branches			
		30 DAS	At Harvest	30 DAS	45 DAS	60 DAS	At Harvest	30 DAS	45 DAS	60 DAS	At Harvest
T_1	Control (100% PK)	30.86	27.97	25.04	37.53	40.83	42.86	2.26	3.11	6.32	6.57
T_2	100% RDF @ 25:50:25 kg N:P: K ha⁻¹	31.54	28.65	33.93	49.64	53.15	55.48	2.59	4.79	9.72	9.98
T_3	100% PK + *Rhizobium* @ 5g kg⁻¹ seeds	31.87	28.98	31.33	45.06	48.34	50.47	2.39	3.76	7.83	8.19
T_4	100% RDF + Mo seed treatment @ 5g kg⁻¹ seeds	33.04	30.15	35.23	51.95	55.56	57.98	2.63	5.12	10.16	10.65
T_5	100% RDF + *Rhizobium* @ 5g kg⁻¹ seeds	34.12	31.23	36.53	54.25	57.97	60.49	2.78	5.78	11.19	11.64
T_6	100% PK + *Rhizobium* @ 5g kg⁻¹ seeds + Mo seed treatment @ 5g kg⁻¹ seeds	33.37	30.48	32.63	47.33	50.73	52.96	2.42	4.09	8.48	8.88
T_7	100% RDF + *Rhizobium* @ 5g kg⁻¹ seeds + Mo seed treatment @ 5g kg⁻¹ seeds	34.26	31.37	36.87	55.98	59.68	62.27	2.81	5.93	11.43	11.88
	S. Em (±)	0.65	0.67	0.41	0.76	0.8	0.81	0.03	0.17	0.27	0.29
	CD (5%)	NS	NS	1.28	2.35	2.47	2.51	0.09	0.51	0.84	0.88

Table 2: Effect of *Rhizobium* and molybdenum inoculation on number of nodules and dry weight of nodules of green gram (*Vigna radiata* L.)

Tr. No	Treatment details	Number of nodules			Dry weight of nodules		
		30 DAS	45 DAS	60 DAS	30 DAS	45 DAS	60 DAS
T_1	Control (100% PK)	16.63	19.78	12.44	0.019	0.25	0.22
T_2	100% RDF @ 25:50:25 kg N:P: K ha⁻¹	26.95	32.26	27.38	0.03	0.4	0.36
T_3	100% PK + *Rhizobium* @ 5g kg⁻¹ seeds	34.08	43.36	35.76	0.038	0.49	0.42
T_4	100% RDF + Mo seed treatment @ 5g kg⁻¹ seeds	23.35	27.59	20.68	0.026	0.35	0.29
T_5	100% RDF + *Rhizobium* @ 5g kg⁻¹ seeds	43.54	51.81	50.6	0.05	0.63	0.54
T_6	100% PK + *Rhizobium* @ 5g kg⁻¹ seeds + Mo seed treatment @ 5g kg⁻¹ seeds	37.26	44.52	41.83	0.042	0.54	0.46
T_7	100% RDF + *Rhizobium* @ 5g kg⁻¹ seeds + Mo seed treatment @ 5g kg⁻¹ seeds	45.23	53.82	52.78	0.052	0.68	0.58
	S. Em (±)	2.02	2.23	2.25	0.001	0.02	0.02
	CD (5%)	6.24	6.89	6.92	0.003	0.07	0.06

Table 3: Effect of *Rhizobium* and molybdenum inoculation on Number of podsplant⁻¹, Pod length, Number of seeds pod⁻¹and Test weight of green gram (*Vigna radiata* L.)

Tr. No	Treatment details	Number of pods plant⁻¹	Pod length (cm)	Number of seeds pod⁻¹	Test weight (g)
T_1	Control (100% PK)	9.58	4.37	5.54	37.11
T_2	100% RDF @ 25:50:25 kg N:P: K ha⁻¹	13.32	8.34	9.98	37.98
T_3	100% PK+ *Rhizobium* @ 5g kg⁻¹ seeds	10.96	6.98	7.89	37.26
T_4	100% RDF+ Mo seed treatment @ 5g kg⁻¹ seeds	14.04	9.21	10.38	38.10
T_5	100% RDF+ *Rhizobium* @ 5g kg⁻¹ seeds	15.63	10.05	11.45	38.53

T_6	100% PK+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds	11.89	7.25	8.42	37.66
T_7	100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds	16.21	10.33	11.78	39.22
	S. Em (±)	0.43	0.24	0.33	2.36
	CD (5%)	1.34	0.75	1.02	NS

Table 4: Effect of *Rhizobium* and molybdenum inoculation on seed yield (kg ha^{-1}), stover yield (kg ha^{-1}) and harvest index (%) of green gram (*Vigna radiata* L.)

Tr. No	Treatment details	Seed yield (kg ha^{-1})	Stover yield (kg ha^{-1})	Harvest index (%)
T_1	Control (100% PK)	798.19	1314.15	37.77
T_2	100% RDF @ 25:50:25 kg N:P: K ha^{-1}	1201.65	1876.24	39.06
T_3	100% PK+ *Rhizobium* @ 5g kg^{-1} seeds	947.14	1534.32	38.19
T_4	100% RDF+ Mo seed treatment @ 5g kg^{-1} seeds	1282.31	1987.05	39.29
T_5	100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds	1402.14	2195.31	38.94
T_6	100% PK+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds	1048.24	1682.57	38.37
T_7	100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds	1497.25	2252.62	39.94
	S. Em (±)	42.28	51.49	1.14
	CD (5%)	130.29	158.67	NS

Table 5: Effect of *Rhizobium* and molybdenum inoculation on cost of cultivation, gross return, net return and B:C ratio of green gram (*Vigna radiata* L.)

Tr. No	Treatment details	Cost of cultivation	Gross return	Net return	Benefit-cost (B:C) ratio
T_1	Control (100% PK)	27795.66	70613.04	42817.38	1.54
T_2	100% RDF @ 25:50:25 kg N:P: K ha^{-1}	28459.39	106203.55	77744.16	2.73
T_3	100% PK+ *Rhizobium* @ 5g kg^{-1} seeds	28153.66	83765.06	55611.4	1.97
T_4	100% RDF+ Mo seed treatment @ 5g kg^{-1} seeds	30146.39	113317.26	83170.87	2.75
T_5	100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds	28817.39	123929.16	95111.77	3.30
T_6	100% PK+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds	29840.66	92690.81	62850.15	2.10
T_7	100% RDF+ *Rhizobium* @ 5g kg^{-1} seeds + Mo seed treatment @ 5g kg^{-1} seeds	30504.39	132330.74	101826.35	3.33

Conclusion
The pre-harvest parameters such as plant population, plant height, number of branches, number of nodules, and dry weight of nodules were recorded as highest under treatment (T_7) - 100% RDF + Rhizobium @ 5 g kg^{-1} seeds + Mo seed treatment @ 5 g kg^{-1} seeds, which was statistically on par with treatment (T_5) - 100% RDF + Rhizobium @ 5 g kg^{-1} seeds. Likewise, post-harvest attributes including number of pods per plant, pod length, seeds per pod, test weight, seed yield, stover yield, harvest index, as well as economic indicators such as cost of cultivation, gross return, net return, and benefit-cost ratio were also superior in T_7 and T_5 compared to the rest of the treatments. This highlights the consistent advantage of these treatments across growth, yield, and profitability parameters, making them highly effective for maximizing agricultural productivity under balanced fertilization. Overall, treatment T_7 (100% RDF + Rhizobium @ 5 g kg^{-1} seeds + Mo seed treatment @ 5 g kg^{-1} seeds) proved most effective, consistently outperforming other treatments in terms of crop growth, yield, and economics, thereby ensuring efficient resource utilization and enhanced agricultural output.

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