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OPTIMIZING NODULATION AND POD YIELD IN FRENCH BEAN THROUGH STRATEGIC MOLYBDENUM SUPPLEMENTATION

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Abstract

A field experiment was conducted to evaluate the effect of molybdenum (Mo) on the nodulation, growth and yield performance of French bean (*Phaseolus vulgaris* L.). Mo supplementation significantly enhanced nodule formation, size and dry matter accumulation, which in turn improved biological nitrogen fixation. This physiological improvement was further supported by an increase in photosynthetic pigment content, indicating higher photosynthetic efficiency. Consequently, Mo treated plants exhibited superior growth characteristics, including increased plant height (45.53 cm), a greater number of branches (5.33 per plant), higher nodule count (25.20 per plant), and greater dry matter accumulation (3.99 g per plant). Improved nodulation with Mo application positively influenced photosynthetic pigments, growth and yield attributes, ultimately leading to higher pod productivity. Among the different Mo treatments, the most effective method involved soil drenching of Mo at the root zone followed by foliar applications. This combination significantly enhanced nodulation, growth and yield-related attributes. The findings underscore the importance of Mo application, particularly through a combined soil drench and foliar spray strategy in improving the growth and productivity of French bean.

Introduction

French bean (*Phaseolus vulgaris* L.), commonly referred to as kidney bean, bush bean, snap bean, haricot bean and rajma, is a widely cultivated legume crop known for its dual purpose use as both a pulse and vegetable. It belongs to the family *Leguminosae*, grown for its immature tender pods, dry and green grains, as well as for its foliage, which can be used as fodder and green manure (Kakon *et al*. 2016). The crop has a relatively short growing season, matures within 65 to 110 days after emergence. French bean is nutritionally rich, providing a good source of energy, complex carbohydrates, protein, dietary fiber, and essential vitamins and minerals including calcium, iron, magnesium, phosphorus, potassium, zinc, and folic acid. Owing to its nutritional profile and affordability, it is often termed the poor man's protein. In addition to its nutritional value, French bean contributes to soil fertility through biological nitrogen fixation, enhancing soil health and sustainability in cropping systems. In India, the crop is cultivated over an area of 14.65 million hectares, contributing to 22.1% of global production, with an annual output of approximately 6.12 million tons. Globally, French bean is grown on 35.92 million hectares with a total production of 27.72 million metric tons (Faostat 2023), indicating its significant role in global food security.

Despite its agronomic and nutritional importance, French bean production remains constrained by suboptimal nutrient management, particularly among resource limited farmers. Unlike many other pulse crops, French bean forms determinate type root nodules and typically

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requires less nitrogen. However, effective nitrogen fixation still depends on the presence of *Rhizobium* bacteria in the root nodules and essential micronutrients especially molybdenum (Mo). Mo is a vital micronutrient that plays a key role in nitrogen metabolism, serving as a structural component of the enzymes nitrogenase and nitrate reductase, which mediate redox reactions in root cells (Steiner and Zoz 2015). Deficiency of Mo can severely impair nitrogen fixation and crop productivity, given its importance Mo must be considered alongside primary and secondary nutrients in crop nutrition planning (Oliveira *et al.* 2022). Therefore, the present study was undertaken to evaluate the effect of a micronutrient formulation enriched with Mo on the morphological traits, nodulation, yield and yield components of French bean. The aim was to determine the most effective application method of Mo for maximizing crop productivity under field conditions.

Materials and Methods

The field experiment was conducted at the experimental site of the National Horticultural Research and Development Foundation (NHRDF), Regional Research Station, Nashik, Maharashtra. The geographical coordinates of the site are 20°N latitude and 73°57′E longitude, with an altitude of approximately 492 meters above mean sea level. The soil of the experimental plot was neutral in reaction (pH 7.3), with an organic carbon (0.85%), available nitrogen (430 kg/ ha), phosphorus (68.67 kg/ha) and potassium (784.0 kg/ha). The calcium carbonate content (4.80%) and the available calcium (640.0 ppm).

The French bean cultivar 'Falguni', which is bushy in growth habit and characterized by slender, dark green pods with a smooth texture, was used in the study. Sowing was carried out on first fortnight of September, with a spacing of 0.80 m between rows and 0.25 m between plants. The experiment followed a randomized block design (RBD) with six treatment combinations and three replications. Each plot measured 3.8 m × 3.6 m. The recommended dose of fertilizers (RDF) was uniformly applied across all plots using urea, single super phosphate and muriate of potash. The molybdenum-rich micronutrient mixture used in the experiment contained 4% Mo, 2% B, 5% Zn, 5% Fe, 5% Mn, 2% Cu, 5% S, and 5% K. The six treatment combinations were as follows: T1- Soil application of Mo @ 625 g/ha at sowing; T2- Soil drench of Mo @ 500 g/ha at the root zone at 25 and 50 days after sowing (DAS); T3- Soil drench of Mo @ 500 g/ha at the root zone at 20 DAS, followed by foliar applications @ 1 g/l of water at 30 and 45 DAS; T4- Foliar application of Mo @ 1 g/l of water at 30 DAS; T5- Foliar applications of Mo @ 1 g/l of water at 30 and 45 DAS; T6- Control (no Mo). The crop was harvested over eight pickings, with the first harvest conducted at 45 DAS. Observations were recorded on phenological traits, physiological parameters, and yield attributes throughout the crop growth period. Data collected were statistically analysed using the analysis of variance technique. The significance of differences among treatment means was tested using a general R Shiny-based statistical analysis platform.

Results and Discussion

The application of molybdenum (Mo) significantly influenced the physiological and phenological characteristics of French bean, with all the treatment combinations showing marked improvement over the untreated control ($p < 0.05$). The application of Mo markedly enhanced branching, leaf area and the biomass of the shoot and root (Table 1). At the vegetative stage, the highest plant height (14.47 cm) was observed in the treatment receiving soil application of Mo @ 625 g/ha (T1) at sowing followed closely by the treatment which involved soil drench of Mo @ 500 g/ha at the root zone at 20 DAS, followed by foliar applications @ 1 g/l of water at 30 and 45 DAS (T3), however, during the pod formation stage the same treatment of Mo recorded the maximum plant height, indicating sustained growth and vigour due to the combined mode of Mo

application. Mo treatments led to a notable increase in leaf area at vegetative and pod formation stages compared. This improvement is attributed to enhanced nitrogen availability, facilitated by Mo role in improving nitrogen uptake, solubilisation of native phosphorus, and stimulation of beneficial microbial activity responsible for secondary metabolite production. These processes collectively contributed to more robust plant growth. The increase in growth parameters can be explained by Mo function as a structural component of the nitrogenase enzyme, which is critical for biological nitrogen fixation in root nodules (Valenciano *et al.* 2011). Notably, Mo application produced early and sustained benefits, influencing the crop's development throughout its life cycle. Mo addition also had a significant effect on nodulation, among the treatments, soil drench of Mo @ 500 g/ha at the root zone at 20 DAS, followed by foliar applications @ 1 g/l of water at 30 and 45 DAS (T3) resulted in the highest number of nodules (25.67/plant) and fresh (1.01 g/nodule), and dry (0.33 g/ nodule) nodule weights (Table 2). This enhancement in nodulation is primarily due to Mo role in promoting root nodule development and function, which directly improves nitrogen assimilation (Ahmadreza *et al.* 2019). Mo is essential for nitrogenase enzyme activity, and its external application has been shown to increase enzyme function, leading to greater nitrogen fixation and nodule mass. Additionally, Mo application increased total shoot nitrogen by sustaining nitrate reductase activity for a longer period, thereby extending the efficiency of nitrogen metabolism. One of the primary outcomes of Mo application is the enlargement of nodules and delay in their senescence, which prolongs the period of active nitrogen fixation (Vieira and Cordoso 1998). Moreover, Mo treated plants exhibited significantly higher levels of photosynthetic pigments, including chlorophyll a, chlorophyll b, carotenoids and total chlorophyll content compare to control (Fig. 1). Among the treatments, the highest chlorophyll a (0.957 mg/g FW) and carotenoid content (0.480 mg/g FW) were recorded in soil drench of Mo @ 500 g/ha at the root zone at 20 DAS, followed by foliar applications @ 1 g/l of water at 30 and 45 DAS (T3), followed by (0.913 mg/g and 0.453 mg/g) soil drench of Mo @ 500 g/ha at the root zone at 25 and 50 DAS (T2), while the lowest (0.833 mg/g and 0.390 mg/g) were observed in the control (T6). Similarly, chlorophyll b content ranged from 0.207 to 0.267 mg/g FW, with soil drench of Mo @ 500 g/ha at the root zone at 25 and 50 DAS (T2) showing the higher value. Overall, treatments T1 and T3 were most effective, demonstrating that molybdenum application, particularly through soil and foliar modes, enhances photosynthetic pigment synthesis, nitrogen assimilation and photosynthetic efficiency. This indicates improved photosynthetic capacity, contributed to enhanced plant vigour and yield potential. These findings are consistent with earlier studies of Rana *et al.* (2020) and Muñoz-Márquez *et al.* (2022), who also reported similar improvements in chlorophyll content with Mo application.

Table 1. Effects of soil drenching and foliar application of molybdenum on growth and phenological characteristics of French bean.

Treatments	Plant height (cm)		Leaf area (cm^2)		Days to 1st flower initiation	Days to 50% flower	Branches /plant	Length of pod (cm)
	30 DAS	70 DAS	30 DAS	70 DAS				
T1	14.47^{a}	38.33^{a}	15.61^{a}	57.33^{b}	45.0^{c}	48.0^{c}	5.83^{bc}	13.03^{b}
T2	10.67^{bc}	39.78^{a}	12.72^{bc}	59.33^{b}	47.33^{bc}	50.67^{bc}	6.50^{b}	13.67^{a}
T3	12.07^{b}	42.06^{a}	15.76^{a}	64.67^{a}	46.33^{bc}	49.33^{cd}	7.50^{a}	13.87^{a}
T4	11.53^{bc}	40.63^{a}	13.33^{b}	57.33^{b}	48.0^{b}	51.67^{b}	5.77^{cd}	13.58^{a}
T5	10.47^{bc}	41.94^{a}	14.15^{ab}	58.33^{b}	45.67^{bc}	49.33^{cd}	5.27^{cd}	12.80^{b}
T6	9.20^{c}	37.00^{a}	11.31^{c}	50.33^{c}	51.33^{a}	54.67^{a}	5.13^{d}	13.60^{a}
S. Em ±	0.75	1.38	0.64	1.43	0.84	0.51	0.22	0.02
CD at 5%	2.38	NS	2.01	4.50	NS	1.62	0.68	0.05
CV %	11.46	5.97	8.01	4.27	3.08	1.76	6.20	3.13

Means sharing same letter/s are not significantly different, NS indicates Non-significant.

Table 2. Effects of soil drenching and foliar application of molybdenum on nodule biomass, yield components, and pod yield of French bean.

Treatments	20 pods weight (g)	No. of nodules/plant	Nodules FW (g)	Nodules DW (g)	No. of pods/ plant	Shelf life	Pod yield (q/ha)
T1	75.44[a]	23.0[b]	0.92[b]	0.28[b]	34.78[ab]	6.44[a]	68.07[ab]
T2	78.78[a]	23.02[b]	0.91[b]	0.28[b]	33.44[bc]	6.67[a]	68.93[ab]
T3	81.78[a]	25.67[a]	1.01[a]	0.33[a]	37.22[a]	6.78[a]	73.01[a]
T4	75.56[a]	21.22[b]	0.91[b]	0.28[b]	32.45[bc]	6.56[a]	62.13[bc]
T5	76.78[a]	21.81[b]	0.88[b]	0.27[b]	32.44[bc]	6.67[a]	65.44[abc]
T6	66.00[b]	16.82[c]	0.77[c]	0.25[c]	30.89[c]	6.0 [b]	58.14[c]
S. Em ±	0.01	0.12	2.71	0.74	0.91	0.12	2.50
CD at 5%	0.02	0.37	8.54	2.34	2.88	0.36	7.86
CV %	4.56	1.51	6.20	5.87	4.71	3.05	6.55

Means sharing same letter/s are not significantly different, NS indicates Non-significant.

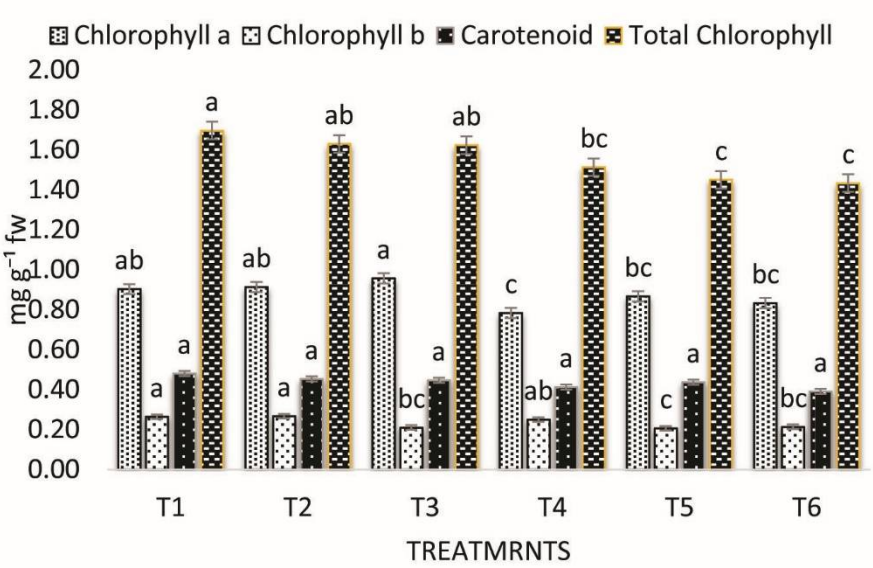

Fig. 1. Effects of soil drenching and foliar application of molybdenum on photosynthetic pigments of French bean.

In addition to the recommended nitrogen, the application of Mo, significantly influenced the yield and yield components of French bean. Mo plays a crucial role in facilitating biological nitrogen fixation, which enhances nitrogen availability and subsequently improves photosynthetic efficiency and assimilate production. These assimilates are translocated to the reproductive organs, thereby positively impacting yield. Like the biomass accumulation, pod yield exhibited a strong response to Mo application, particularly under treatment soil drench of Mo @ 500 g/ha at the root zone at 20 DAS, followed by foliar applications @ 1 g/l of water at 30 and 45 DAS (T3), which recorded the highest yield (73.01 q/ha) performance among all treatments, and the same treatment produced maximum number of pods per plant (37.22/plant), along with superior pod length (13.87 cm) (Table 1) and 20 pods weight (871.78 g) (Table 2). This clearly reflects the beneficial impact of Mo applied through combined soil and foliar methods. The increased number of pods per plant under Mo treated plots can be attributed to improved early vegetative growth, characterized by enhanced leaf area, greater dry matter accumulation, and a more developed root system. These

factors led to an increased number of branches, including more pod bearing branches, ultimately contributing to higher productivity. These findings are in agreement with those of Singh *et al.* (2020), Zhou et al. (2023) and Rana et al. (2025), who also reported improved yield parameters and pod quality following molybdenum supplementation in leguminous crops.

The correlation analysis revealed significant and positive relationships among various physiological parameters and yield attributes in French bean as influenced by Mo supplementation. Mo application, particularly at soil drench of Mo @ 500 g/ha at the root zone at 20 DAS, followed by foliar applications @ 1 g/l of water at 30 and 45 DAS (T3) was most effective in enhancing growth parameters such as shoot biomass, leaf area, and root nodulation, which in turn translated into increased pod yield. A strong positive correlation was observed between leaf area and the number of root nodules, suggesting that increased nodulation enhanced nitrogen fixation, thereby improving overall plant growth and productivity (Fig. 2). These results reinforce the role of Mo as a critical micronutrient in the nitrogen assimilation process, owing to its role as a cofactor for key enzymes like nitrogenase and nitrate reductase. The findings are consistent with earlier reports by Manivannan *et al*. (2001), who documented increased crop yield following the application of Mo alone or in combination with other micronutrients such as boron. The present results emphasize the agronomic importance of Mo supplementation in French bean cultivation, highlighting its potential to improve both vegetative growth and yield outcomes. However, it is important to note that higher rates of Mo application did not further enhance growth and, in some cases, showed signs of growth inhibition. This is in line with previous studies which reported that excessive Mo levels can become phytotoxic, leading to reduced dry matter accumulation and stunted plant growth. Thus, while moderate Mo supplementation is beneficial, careful management of application rates is essential to avoid adverse effects on plant health.

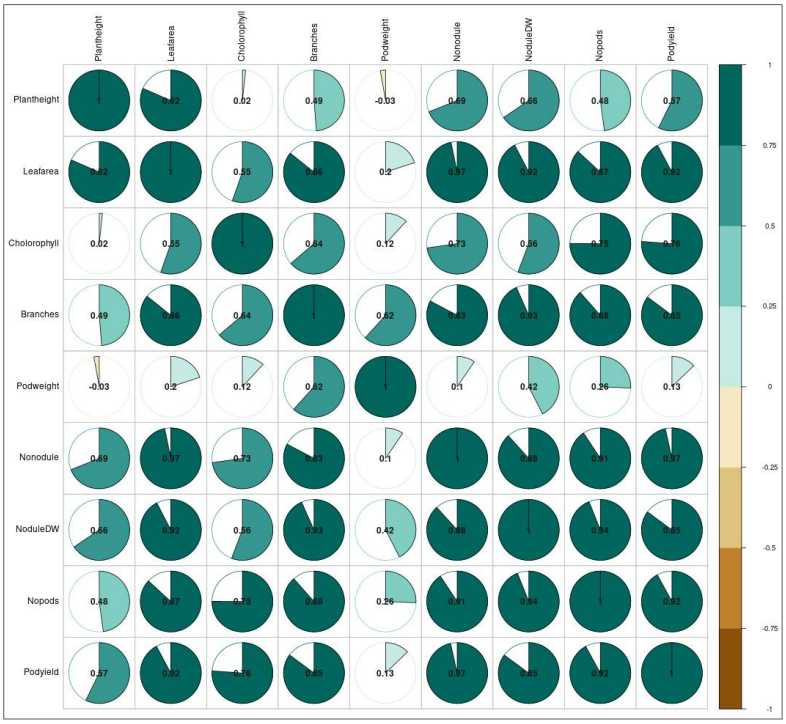

Fig. 2. Correlation between yield, phenological traits, and chlorophyll content in French bean. Significant at $p \leq 0.05$.

The present study demonstrates that Mo supplementation particularly through soil drenching at 500 g/ha at 20 days after sowing (DAS), followed by foliar sprays at 30 and 45 DAS, significantly improved growth, nodulation, nitrogen uptake, and pod yield of French bean. Overall, this study highlights the critical role of molybdenum in optimizing the physiological efficiency and yield potential of French bean.

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