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Soybean Rhizospheric and Growth Response Induced by Graded Phosphorus and Molybdenum Application in Acid *Alfisols*

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Abstract

A field experiment was conducted during *kharif* 2021 at CSKHPKV - Experimental farm, Palampur to assess the influence of graded phosphorus (0, 30, 60 and 90 kg P ha^{-1}) and molybdenum (0, 1.0 and 2.0 kg Mo ha^{-1}) on soybean performance under acid soil conditions. Application of 90 kg P and 2.0 kg Mo ha^{-1} recorded the maximum improvement in root attributes (dry weight, volume and mass density), nodulation and growth traits including plant height, branch and leaf number and test weight, ultimately enhancing yield. Significant P × Mo interactions were observed for plant height, branching, root volume and nodulation traits (number of nodules and nodule dry weight), however, their combined influence registered non-significant impact on soybean productivity. Overall, the sole application of 90 kg P and 2.0 kg Mo ha^{-1} was identified as the most effective rates for enhancing soybean growth and productivity under acidic soils.

Keywords: Acidic, Growth, Molybdenum, Phosphorus, Productivity

Sustainable crop production demands a balanced supply of macro and micronutrients as nutrient imbalances significantly restrict early plant growth. Although, intensive cropping coupled with heavy use of NPK fertilizers has enhanced yields, but it has simultaneously accelerated depletion of micronutrients, leading to a gradual decline in soil fertility and productivity. Such issues are particularly critical in legumes like soybean (*Glycine max* L.), a major oilseed crop which is reliant on symbiotic nitrogen (N) fixation. Furthermore, in India, nearly 28% of the geographical area is impacted by soil acidity, which severely limits productive and sustainable agriculture (Mandal *et al.* 2019). Despite India ranking fifth globally in soybean production, productivity remains low primarily due to edaphic constraints. Reduction in yield under acidic soil conditions is due to reduced nutrient availability; root mass, and nutrient uptake (Sharma & Sharma 2016). In acid soils, restricted phosphorus (P) availability and inherent molybdenum (Mo) deficiency are major barriers to efficient root development and biological nitrogen (N) fixation. A substantial fraction of applied P becomes immobilized through fixation by Fe and Al oxides, reducing its plant availability (Sarkar *et al.* 2024) and only ≤20% of applied P is utilized during the first year (Chakraborty *et al.* 2024) resulting in stunted growth, poor nutrient uptake and reduced biomass. Furthermore, Indian soils are beset with a higher degree of variability in crop response to different levels of phosphatic fertilizers in different agro-climatic zones due to wide variations in fixation of applied fertilizer owing to variations in soil pH, organic matter, clay content, microbial immobilization, method and dose of fertilization.

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Mo deficiency further exacerbates limitations in productivity of legumes, globally around 15% of cultivated soils are Mo deficient, ranking Mo as the third most limiting micronutrient after B and Zn (Graham 2008). Under pH < 5.5, Mo adsorption to sesquioxides increases sharply, reducing its availability (Rana *et al.* 2025). Since, Mo is required in small quantities, application of this nutrient at optimum concentration would increase root elongation with greater root proliferation and nodulation. The efficiency of biological N fixation is severely limited by Mo deficiency. Consequently, Mo-deficient soybean exhibits reduced height, impaired root development, poor nodulation and growth (Tiwari *et al.* 2018). Further, the sole impact of P and Mo in legume physiology is well recognized, but their combined impact on root development, nodulation and growth characteristics under acid soil conditions remains insufficiently explored particularly under field conditions. Therefore, the present investigation aimed to determine appropriate application rates of both P and Mo to improve soybean performance and support sustainable productivity under such constrained soil conditions.

MATERIALS AND METHODS

Experimental Site

The study was undertaken at Experimental Farm, Department of Soil Science, CSKHPKV, Palampur, H.P at an elevation of 1290 m (32°06′ N, 76°03′ E), falling within the mid-hill wet temperate zone (Zone II) of the north western Himalaya. The study area features moderate summers and harsh winters.

Climate and Weather

An average rainfall of 1882 mm, accompanied by mean temperatures of 31.1° C (maximum) and 10.5° C (minimum), with weekly relative humidity varying between 60 and 94.03% were recorded during the cropping period.

Soil Characteristics

The experimental field was underlain by silty clay loam soil and an acidic pH of 5.32. Initially, the soil's available nutrient contents (NPK and Mo) were 307, 16.3 and 119 kg ha^{-1} and 0.160 mg kg^{-1}, respectively.

Experimental Details

The investigation was performed on soybean during *kharif* 2021, testing four levels of phosphorus (0, 30, 60 and 90 kg P ha^{-1}) and three of molybdenum (0, 1 and 2 kg Mo ha^{-1}) with twelve treatment combinations, arranged in a completely randomized block design. Crop was sown on 18th June, 2021, with 20 kg N and 40 kg K_2O ha^{-1} applied at sowing *via* urea and MOP while, P and Mo were applied as per the treatments using SSP and sodium molybdate, respectively. Standard cultural practices were adhered to throughout the crop's growth.

Field Studies

Plant height and branch count $plant^{-1}$ was recorded at 60 DAS and at harvest from five randomly tagged plants $plot^{-1}$, and expressed on mean basis. Leaf number was similarly recorded at 60 DAS. Days to 50% flowering were determined visually for each plot. Test weight was calculated by weighing 100 dried seeds from each plot and multiplying by 10. For root traits, five plants p ha^{-1} plot were sampled at 50 DAS. Roots were excavated up to 0.30 m depth, washed, dried, weighed and submerged in a graduated cylinder to determine root volume via water displacement. Root mass density was computed as the ratio of root biomass to root volume. For nodulation, washed roots were blotted to remove moisture, nodules were counted and both fresh and oven dried weights (at 70° C) were recorded and averaged per treatment.

Statistical Analysis

The data were analysed following the technique of analysis of variance for randomized block design as outlined by Gomez and Gomez (1984) using Microsoft excel.

RESULTS AND DISCUSSION

Growth and Yield Determinants

Plant Height and Number of Branches Plant-1

At 60 DAS and at harvest, application of 90 kg P ha^{-1} witnessed significantly taller plants and maximum number of branches $plant^{-1}$ compared to unfertilized plots (Table 1). The height registered quantum jumps of about 22 and 29 % while, branch count by 32 and 28 % at these two respective stages over their

Table 1. Soybean growth and yield determining traits in response to P and Mo rates

Treatment	Plant Height (cm)		Number of Branches Plant^{-1}		No. of Leaves Plant^{-1}	Days to 50 % Flowering	Test Weight (g)
	60 DAS	Harvest	60 DAS	Harvest	60 DAS		
P levels							
P_0	69.1	76.5	3.52	4.41	18.4	54	173
P_{30}	75.4	80.4	3.84	4.75	20.2	52	176
P_{60}	78.8	85.5	4.41	5.34	21.8	51	177
P_{90}	84.2	98.6	4.66	5.63	23.1	50	180
CD ($p \leq 0.05$)	3.3	3.9	0.18	0.09	0.7	0.9	2.8
Mo levels							
Mo_0	74.2	79.0	4.02	4.87	19.8	53	174
Mo_1	76.9	85.6	4.07	5.05	20.9	51	177
Mo_2	80.0	91.2	4.23	5.18	21.9	51	180
CD ($p \leq 0.05$)	2.8	3.3	0.15	0.08	0.6	0.8	2.4

Table 2. Interactive effect of P and Mo on plant height (cm) and number of branches plant^{-1} at harvest

Treatment	P levels							
	Plant height (cm)				Number of branches plant^{-1}			
Mo levels	P_0	P_{30}	P_{60}	P_{90}	P_0	P_{30}	P_{60}	P_{90}
Mo_0	70.8	79.0	82.2	84.1	4.25	4.56	5.26	5.41
Mo_1	77.6	79.6	82.9	103	4.34	4.83	5.36	5.66
Mo_2	81.3	82.7	91.5	109	4.65	4.86	5.39	5.83
CD ($p \leq 0.05$)	7.0				0.15			

control treatments. This response in height might be a consequence of extensive root system anchored by P that might have enhanced its absorption, promoted greater cell division and elongation in shoots (Khan *et al*. 2023). While, improvement in branch count might be the outcome of role of P in stimulating cell division, meristem activity and axillary bud initiation, with enhanced cytokinin production further promoting lateral branch formation by activating axillary buds (Sultani *et al*. 2022). Furthermore, Pranav *et al*., (2024) reported tallest height and maximum branch count in soybean with 90 kg P ha^{-1} which however showed statistical comparability with 60 and 30 kg P ha^{-1}. In contrast, Rabbani *et al*., (2023) reported maximum height and branching in soybean with appliance of 36 kg P ha^{-1} under non-calcareous soils.

Across Mo levels, at 60 DAS, the highest height was achieved with 2.0 kg Mo ha^{-1}, followed by 1.0 kg which lied in statistically parity with control treatment. On the contrary, branch count at 60 DAS documented a consistent increase up to 2.0 kg Mo ha^{-1}. By harvest, appliance of 2.0 kg Mo ha_^{1} resulted an increase in height and branch count by about 15 and 6 %, respectively relative to their omitted treatments. The enhancement in plant height and branching might have likely resulted from key role of Mo in N metabolism, further improving N fixation, nitrate assimilation, protein synthesis, cytokinin production and cell division, thus driving stem elongation and transformation of axillary buds into branches (Li *et al.* 2023; Jamali *et al.* 2023). In contrast to our study, Ahmad *et al*. (2022) reported tallest plants with appliance of 90 kg P and 1.5 kg Mo ha^{-1} in mungbean grown under silt loam soils. The interaction between both nutrients significantly influenced the height and branch count, but only at harvest (Table 2). Conjoint use of 90 kg P ha^{-1} and 2.0 kg Mo ha^{-1} recorded significantly taller plants and

branch count followed by 90 kg P ha^{-1} and 1.0 kg Mo ha^{-1} and the least in unfertilized plots.

Number of Leaves $Plant^{-1}$, Days to 50% Flowering and Test Weight

The graded fertilization with P and Mo witnessed noteworthy improvements in these parameters (Table 1). Leaf count $plant^{-1}$ at 60 DAS increased progressively with highest doses of both nutrients, peaking at 90 kg P and 2.0 kg Mo ha^{-1}. P might have probably enhanced nutrient uptake and photosynthesis, stimulating meristematic activity in apical and intercalary buds (Tehria *et al.* 2014), consistent with prior work done by Singh and Pareek (2003). Mo might have further promoted leaf initiation and development through its role in N metabolism, chlorophyll synthesis and amino acid production (Sikka *et al.* 2022). Earliest flowering incurred with 90 kg P ha^{-1}, while delayed in unfertilized plots. P might have accelerated floral transition *via* ATP-mediated metabolic activity and vegetative growth (Khaswa *et al.* 2014) (Table 1). Likewise, 2.0 kg Mo ha^{-1} induced earlier flowering, statistically alike to 1.0 kg, whereas delayed flowering occurred without Mo, likely due to improved N status and cytokinin mediated floral regulation (Banerjee *et al.* 2021). Test weight significantly increased with 90 kg P and 2.0 kg Mo ha^{-1}. The weights at 60 and 30 kg P ha^{-1} were statistically alike and analogous trend followed with 2.0 and 1.0 kg Mo ha^{-1}. These enhancements might be owing to P-driven energy metabolism and Mo-induced improvements in nitrogen assimilation and seed development (Singh *et al.* 2014; Adesoji *et al.* 2009).

Root Characteristics

Root Dry Weight, Root Volume and Root Mass Density

A significant and marked increase in root dry weight and volume was evident with graded fertilization with P upto 90 kg ha^{-1} (Table 3). However, root mass density at 90 kg P lied in statistical parity with 60 kg P ha^{-1} and lowest under unfertilized plots. Likewise, Mo applications exponentially increased the root dry weight and volume up to 2 kg Mo ha^{-1}. On the contrary, root mass density did not exhibit any significant influence with any of the applied Mo doses. The interaction between P and Mo levels significantly influenced the root volume at 50 DAS (Table 4). The maximum volume was attained with 90 kg P and 2.0 kg Mo ha^{-1}, followed by 90 kg P and 1.0 kg Mo, while the control registered the least. In the absence of P, root volume increased significantly with Mo application only up to 1.0 kg Mo ha^{-1}. Conversely, at 90 kg P ha^{-1}, an exponential increase was evident with rising Mo levels. As, P fuels root growth, while Mo enhances N fixation, metabolism and hormonal regulation, jointly enhancing root biomass, volume and root mass density (Huang *et al.* 2023). Furthermore, there are very limited studies assessing the impact of P and Mo on soybean root characteristics.

Table 3. Rhizospheric root characteristics in response to graded P and Mo applications

Treatment	Root Dry Weight (g)	Root Volume (cm^3)	Root Mass Density (g cm^{-3})	No. of Nodules $Plant^{-1}$	Nodule Dry Weight (mg $plant^{-1}$)
P levels					
P_0	1.18	5.75	0.20	57.3	0.33
P_{30}	1.77	8.06	0.22	64.2	0.51
P_{60}	2.36	9.48	0.25	71.6	0.58
P_{90}	2.54	10.35	0.25	79.0	0.62
CD ($p \leq 0.05$)	0.06	0.11	0.01	3.0	0.02
Mo levels					
Mo_0	1.85	8.06	0.23	61.9	0.45
Mo_1	1.99	8.48	0.23	68.7	0.49
Mo_2	2.04	8.68	0.23	73.5	0.58
CD ($p \leq 0.05$)	0.05	0.09	NS	2.6	0.01

Table 4. Interaction effect of P and Mo levels on root volume (cm^3), number of nodules $plant^{-1}$ and nodule dry weight (mg $plant^{-1}$) at 50 DAS

Treatment	P levels											
Mo Levelss	Root Volume (cm^3)				Number of Nodules $Plant^{-1}$				Nodule Dry Weight (mg $plant^{-1}$)			
Mo	P_0	P_{30}	P_{60}	P_{90}	P_0	P_{30}	P_{60}	P_{90}	P_0	P_{30}	P_{60}	P_{90}
Mo_0	5.51	7.36	9.30	10.0	51.0	61.8	61.5	73.4	0.25	0.42	0.54	0.60
Mo_1	5.81	8.25	9.49	10.4	59.1	62.8	75.3	77.5	0.33	0.50	0.56	0.64
Mo_2	5.93	8.55	9.65	10.6	61.8	68.1	78.0	86.1	0.40	0.61	0.62	0.69
CD ($p \leq 0.05$)	0.19				5.2				0.03			

Number of Nodules $Plant^{-1}$ and Nodule Dry Weight

The nodule number and dry weight increased consistently with rising P levels, from 0 to 90 kg P ha^{-1} (Table 3). Increases of about 38 and 88 % were reported in the respective traits with 90 kg P ha^{-1} over their respective control treatments. Ahmad *et al.* (2022) have also reported maximum nodule count with appliance of 90 kg P ha^{-1} and 1.5 kg Mo ha^{-1} in mungbean. An analogous pattern followed for the Mo doses as well. Application at 2.0 kg Mo ha^{-1} demonstrated improvements of about 19 and 29 % in nodule number and weight, respectively over its no supplementation. The phosphorus × molybdenum interaction significantly influenced nodule number and dry weight (Table 4). The highest nodulation and nodule dry weight incurred with conjoint use of 90 kg P ha^{-1} and 2.0 kg Mo ha^{-1}, followed by 90 kg P and 1.0 kg Mo ha^{-1} and the minimum in control plots. Together, P might have ensured energy supply while Mo enabled effective N fixation, resulting in numerous, larger and heavier nodules with higher dry weight (Huang *et al.* 2023).

Soybean Productivity

Grain yield was boosted significantly and consistently with the rising doses of both P and Mo (Figure 1), but their interaction exhibited statistical equivalence. The yield response followed the trend 90 > 60 > 30 kg P ha^{-1} and 2.0> 1.0 > 0 kg Mo ha^{-1}. Omitting P fertilization declined yield by about 61 % over the highest tested dose, while corresponding drop with skipping Mo was around 18 % relative to the highest examined dose. In acid *Alfisols*, graded additions of P might have overcomed its sorption by sequioxides and enhanced energy metabolism and reproductive development.

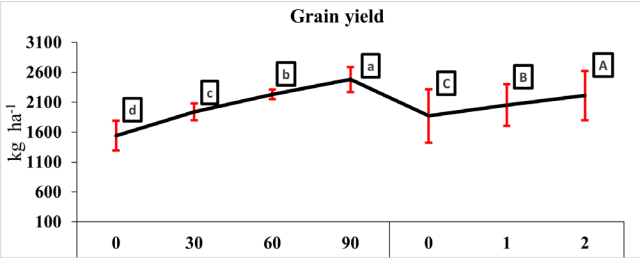


Figure 1. Soybean productivity in response to graded application of P and Mo. Bars labelled with different letters indicate significant differences (p value≤ 0.05) within group as per Duncan's new multiple range test. Error bars represent standard errors of each treatment

In a study Sikka *et al.* (2022) observed significant improvement in soybean grain yield up to 40 kg P ha^{-1}, while higher rates up to 80 kg P ha^{-1} did not reflect any further improvement. While, external application of Mo under inherently deficient conditions might have served as a cofactor for nitrogenase and nitrate reductase, thus boosting biological N fixation and assimilation. Functioning complementarily, both P and Mo improved the growth characteristics and thus caused a significant improvement in soybean productivity. These results are in close conformity with the findings of Spandana (2016). In contrast to our results, Patel *et al.* (2024) reported synergistic effect of combined use of 40 kg P ha^{-1} and 0.5 kg Mo ha^{-1} on the seed yield of green gram cultivated in light textured soils.

CONCLUSIONS

Combined application of 90 kg P and 2 kg Mo ha^{-1} significantly improved soybean growth and productivity in acid soils, indicating complementary relationship between the two nutrients. The results reinforced the importance of integrating Mo with P

fertilization to improve the root growth and ultimately nodulation. However, since the investigation was confined to a single location and crop season, broader validation across diverse soils and cropping systems is required to refine the application thresholds. Overall, the study provides ground base to incorporate Mo into routine nutrient management to boost productivity in acidic agroecosystems.

Conflict of Interest: The authors declare that they have no conflict of interest.

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