



Soil and Foliar Application of Molybdenum on Yield and Biochemical Quality of Black Gram (*Vigna mungo* L.) Grown in Fe Rich Acidic Soils of West Bengal, India

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Authors' contributions

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

Article Information

DOI: <https://doi.org/10.9734/ijpss/2026/v38i106370>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://pr.sdiarticle5.com/review-history/167489>

Original Research Article

Received: 12/08/2026

Accepted: 07/10/2026

Published: 09/10/2026

Abstract

West Bengal is characterised by a predominance of acidic soils, with more than 70% of the cultivated soils exhibiting acidic reactions and relatively high concentrations of Fe and Al. Under such soil conditions, molybdenum (Mo) availability is often restricted, which can adversely affect legume productivity. The yield of kharif black gram in the region remains considerably lower than the national average, partly owing to micronutrient limitations. Therefore, an experiment was conducted to evaluate the response of black gram variety PU-13 to different methods and levels of Mo application. The experiment was carried out at the Mondouri Farm of Bidhan Chandra Krishi Viswavidyalaya using an acidic, sandy loam soil with a light texture and relatively low fertility. The soil was characterised by appreciable levels of Fe, Mn and Al and inadequate Mo availability. Four rates of Mo were

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applied to the soil (0, 0.25, 0.5 and 0.75 kg ha⁻¹) in combination with two foliar concentrations, namely 0.1% (F1) and 0.2% (F2), to assess their effects on crop growth, yield components and nutrient uptake.

The results demonstrated that increasing the concentration of foliar-applied Mo enhanced the growth and yield-related characteristics of black gram. A similar positive response was observed when foliar application was combined with soil application of Mo. However, the beneficial effect was observed only up to the application of 0.25 kg Mo ha⁻¹ to the soil in combination with a 0.2% foliar spray. Beyond this treatment level, a decline in the measured growth and yield attributes was recorded. The maximum grain yield of 549 kg ha⁻¹ was obtained with the combined application of 0.25 kg Mo ha⁻¹ to the soil and a 0.2% Mo foliar spray. Molybdenum application also positively influenced the uptake of the major nutrients, particularly N, P and K. The greatest nutrient uptake was recorded under the S₃F₂ treatment combination. Post-harvest soil analysis further indicated an improvement in soil fertility status, with a positive NPK balance remaining in the soil after accounting for crop nutrient removal. Overall, the findings indicate that integrating soil and foliar application of Mo can improve the performance and nutrient utilisation of black gram cultivated under acidic, Fe-rich and low-fertility soil conditions. Among the treatments evaluated, the combined application of 0.25 kg Mo ha⁻¹ to the soil together with a 0.2% foliar spray proved to be the most effective treatment for maximising black gram productivity under the experimental conditions.

Keywords: *Vigna mungo* L.; molybdenum; acidic soil; foliar application; soil application; seed yield; chlorophyll; post-harvest soil fertility.

1. Introduction

Pulses constitute an essential component of the human diet, particularly for nutritionally vulnerable populations, owing to their importance as an affordable source of dietary protein and other nutrients. The Indian Council of Medical Research (ICMR) recommends approximately 50 g of pulses per person per day to meet nutritional requirements. In West Bengal, pulse crops are predominantly grown during the pre-rabi or pre-summer period by utilising the residual soil moisture available after rice harvest. In many rice fallows, however, pulse seeds are sown directly without adequate use of recommended agronomic practices. Consequently, black gram productivity in the state remains low, with productivity reported at around 465 kg ha⁻¹, substantially lower than the national average of 960 kg ha⁻¹ during 2015–16. Recent field evidence in black gram indicates that foliar inputs used together with recommended fertilisation can improve crop growth, grain yield and post-harvest soil nutrient status, supporting the relevance of foliar management in this crop (Charjan *et al.*, 2026).

A major constraint to pulse production in West Bengal is the predominance of acidic soils. Nearly 70% of the soils of the state are acidic and are generally characterised by appreciable concentrations of iron (Fe) and manganese (Mn). In addition, many of these soils possess low available nitrogen and widespread molybdenum (Mo) deficiency, resulting in poor soil fertility and restricted pulse productivity. The occurrence of Mo deficiency in acidic soils of India has also been documented by Singh *et al.* (2008) and Adhikari and Patel (2013). Molybdenum plays a critical role in plant nitrogen metabolism, particularly through its involvement in nitrate reductase activity (Smarrelli & Campbell, 1980). Under Mo-deficient conditions, the activity of this enzyme is reduced, thereby impairing nitrate assimilation and plant growth (Brar *et al.*, 2026). Liu *et al.* (2020) reported that reduced nitrate reductase activity can result in greater nitrate accumulation within plant tissues, accompanied by reductions in growth and yield. In legumes, the response to Mo can be dose-dependent, with adequate supply supporting N accumulation while excessive exposure may constrain N assimilation under some conditions (Yang & Wang, 2024).

Even relatively small additions of Mo may substantially improve crop performance when applied through soil, foliar or seed treatments (Choukri *et al.*, 2019). Wu *et al.* (2014) observed that Mo application can enhance biochemical and physiological processes in plants, ultimately contributing to improved crop productivity. Molybdenum is also closely associated with biological nitrogen fixation and therefore plays an important role in improving the effectiveness of *Rhizobium* under nutrient-deficient and acidic soil conditions (Li *et al.*, 2024). Since Mo deficiency is considered an important nutritional limitation in several pulse-growing regions, appropriate Mo management may provide an effective means of improving black gram productivity (Serawat *et al.*, 2018). Recent studies further show that foliar Mo-based nutrition can influence legume productivity: combined foliar phosphorus and Mo improved nodulation and yield in black gram, while foliar Co + Mo produced cultivar- and season-dependent responses in soybean (Shakya *et al.*, 2026; Delfim *et al.*, 2025). However, evidence remains limited on the comparative response of black gram to graded soil-applied Mo combined with foliar Mo concentrations under the acidic, Fe-rich, low-fertility soils evaluated in West Bengal, particularly for simultaneous effects on growth, yield, nutrient accumulation and post-harvest soil fertility.

Against this background, the present investigation was undertaken to assess the response of black gram to different levels and methods of Mo application, with particular emphasis on crop growth, yield attributes, nutrient accumulation, and changes in soil fertility under acidic, low-fertility soil conditions.

2. Materials and Methods

The experiment was conducted during the pre-kharif seasons of 2022–23 and 2023–24 at Mondouri Farm, Bidhan Chandra Krishi Viswavidyalaya. The study was designed to examine the influence of Mo fertilisation on the growth and productivity of black gram and its effect on soil fertility. A light-textured, acidic soil characterised by low fertility and inadequate availability of nitrogen and Mo was used for the pot experiment.

A completely randomised design (CRD) was followed with eight treatment combinations and three replications, resulting in a total of 24 pots. Each pot was filled with 5 kg of experimental soil. Molybdenum was supplied through sodium molybdate at four soil application rates, namely 0, 0.25, 0.5 and 0.75 kg ha⁻¹. In addition, foliar treatments were imposed at two concentrations, namely

0.1% and 0.2%, at 30 days after sowing (DAS). The treatments were applied in combination with the recommended fertiliser dose of 20:40:40 kg ha⁻¹ of NPK.

The entire quantity of phosphorus, half of the recommended nitrogen and potassium, along with the respective soil-applied Mo treatment, was incorporated as a basal application. The remaining half of the nitrogen and potassium was applied as a top dressing at 30 DAS. Six seeds of black gram variety PU-13 were initially sown in each pot. Following germination, the seedlings were thinned to maintain four healthy plants per pot. Foliar application of Mo was carried out at 30 DAS. The selected variety, PU-13, has an approximate crop duration of 80 days.

Crop observations included important vegetative and reproductive characteristics such as plant height, number of leaves, root length, pod length, number of pods plant⁻¹, number of seeds pod⁻¹, pod yield and seed yield. Chlorophyll *a* and *b* contents were also determined before and after Mo application. Nutrient concentrations in plant tissues and seeds were estimated to assess nutrient accumulation and uptake.

Chlorophyll pigments were extracted using acetone and quantified following the procedure of Arnon (1949). Plant and seed samples were analysed for their total nutrient contents according to the methodology described by Jackson (1973), and the resulting values were used to calculate nutrient uptake. Prior to the initiation of the experiment, the soil was characterised for its major physicochemical and fertility parameters (Subbiah & Asija, 1956), and the analytical results are presented in Table 1.

Table 1. Initial soil properties of experimental soil

Parameters	Value	Inference
pH (1:2.5)	5.8	Acidic
EC (dS/m)	0.08	Non saline
OC (g/kg)	5.00	Low
Clay (%)	13.8	—
Texture	Sandy loam	Light texture
Available N (kg/ha)	143.8	Low
Available P ₂ O ₅ (kg/ha)	10.2	Low
Available K ₂ O (kg/ha)	48.3	Low
Ex Ca (cmol (P ⁺)/kg)	7.2	—
Ex Mg (cmol (P ⁺)/kg)	3.5	—
DTPA Fe (ppm)	283	Very high
DTPA Mn (ppm)	63	High
Mo (ppm)	0.053	Low

3. Results and Discussion

The experimental soil was acidic and non-saline, with low organic carbon and a light-textured nature. It was characterised by low availability of major nutrients, including nitrogen, phosphorus and potassium, as well as low available Mo. In contrast, the soil contained comparatively high concentrations of Fe and Mn.

Plant height ranged from 26.41 to 33.22 across the different Mo treatments. The maximum height (33.22 cm) was recorded under S₁F₂, where 0.25 kg Mo ha⁻¹ was applied to the soil in combination with 0.2% foliar Mo. A similar effect was reported by Al Bashir *et al.* (2025) in cabbage. The number of leaves produced by black gram ranged from 11.31 to 14.61 across the different Mo treatments. The maximum number of leaves (14.61 plant⁻¹) was recorded under S₁F₁, where 0.25 kg Mo ha⁻¹ was applied to the soil in combination with 0.1% foliar Mo. Foliar application alone also improved leaf production, with the number of leaves increasing from 13.21 under 0.1% Mo spray to 14.01 under 0.2% Mo spray. A further improvement was recorded when soil application of Mo was combined with foliar treatment, with leaf number increasing from 14.41 to 14.61. These two treatments were statistically comparable.

Root development was also positively influenced by Mo nutrition. Root length varied between 11.31 and 15.81 cm among the treatments. The longest roots (15.81 cm) were produced by S₁F₂, corresponding to the combined application of 0.25 kg Mo ha⁻¹ to the soil and 0.2% Mo through foliar spray. The enhancement of root elongation under Mo nutrition may be associated with its influence on physiological processes involved in root development, including stimulation of abscisic acid (ABA) production. A similar relationship between Mo nutrition and root growth was reported by Imran *et al.* (2021).

Molybdenum application also produced a marked improvement in the reproductive characteristics of black gram. The maximum pod length of 8.39 cm was obtained under S₁F₂, in which 0.25 kg Mo ha⁻¹ was applied to the soil together with a 0.2% foliar Mo application. Thus, the combined mode of Mo nutrition was more effective in improving pod development than foliar application alone.

The number of pods produced per plant showed a distinct response to foliar Mo concentration. Foliar application of 0.1% Mo alone resulted in the lowest pod production, whereas increasing the foliar concentration to 0.2% significantly increased the number of pods to 5.92 plant⁻¹. This represented an increase of 30.67% compared with the 0.1% foliar treatment (S₀F₁). The maximum pod production, however, was achieved when foliar application was supplemented with soil-applied Mo. The S₁F₂ treatment produced the highest number of pods (9.42 plant⁻¹), demonstrating the beneficial effect of integrating soil and foliar Mo nutrition (Syafudin *et al.*, 2025).

Table 2. Growth attributing characters of Black gram

Treatments	Plant height(cm)	No of leaves per plant	Root length(cm)
S ₀ F ₁	26.41	13.21	11.91
S ₀ F ₂	27.66	14.01	14.11
S ₁ F ₁	28.76	14.41	14.71
S ₁ F ₂	33.22	14.61	15.81
S ₂ F ₁	29.46	12.11	14.21
S ₂ F ₂	29.87	11.31	13.31
S ₃ F ₁	30.84	13.11	11.41
S ₃ F ₂	32.12	13.71	11.31
SEM (±)	2.06	2.16	2.04
C.D. (0.05)	3.8	4.08	3.74

Table 3. Yield and yield attributing characters of black gram in response to Mo fertilization.

Treatments	Pod Length (cm)	No. of pods/plant	Number of flowers per plant	No of seeds /Pod	Pod yield (kg/ha)	Fruit setting (%)	Seed yield (kg/ha)	%Increase /Decrease
S ₀ F ₁	6.32	5.82	36	10.82	728.32	53	561.32	
S ₀ F ₂	7.7	5.92	38	11.62	744.32	56	579.32	3.9
S ₁ F ₁	7.8	8.52	37	12.12	754.32	60	618.32	12.35
S ₁ F ₂	8.39	9.42	42	12.62	781.32	59	650.32	19.29
S ₂ F ₁	8.09	9.22	37	12.52	818.32	54	627.32	14.30
S ₂ F ₂	8.05	9.12	38	12.12	821.32	56	623.32	13.43
S ₃ F ₁	7.32	7.92	36	12.02	826.32	54	622.32	13.22
S ₃ F ₂	6.35	7.52	39	12.02	801.32	55	621.32	13.06
SEM (±)	0.23	0.3	1.23	0.22	13.05	2.57	8.05	
C.D. (0.05)	0.58	0.81	2.87	0.56	42.05	9.23	25.05	

Table 4. Mean seed yield of black gram

Treatments	F ₁	F ₂	Mean	% increase
S ₀	561.32	579.53	570.32	
S ₁	618.24	650.32	634.43	12.62%
S ₂	627.57	623.65	625.53	11.24%
S ₃	622.65	621.82	621.82	10.24%
Mean	607.32	618.57	612.94	
% Increase		2.21		

Table 5. Effect of molybdenum fertilization on biochemical attributes of black gram

Treatments	Chlorophyll a (mg. g ⁻¹ fresh weight)		Chlorophyll b (mg. g ⁻¹ fresh weight)	
	Pre flowering	Pod development	Pre Flowering	Pod development
S ₀ F ₁	0.11	0.18	0.09	0.27
S ₀ F ₂	0.17	0.21	0.16	0.36
S ₁ F ₁	0.22	0.3	0.19	0.49
S ₁ F ₂	0.18	0.2	0.17	0.31
S ₂ F ₁	0.21	0.26	0.20	0.43
S ₂ F ₂	0.35	0.25	0.31	0.41
S ₃ F ₁	0.38	0.28	0.34	0.48
S ₃ F ₂	0.41	0.28	0.35	0.52
SEM (±)	0.05	0.03	0.03	0.03
C.D. (0.05)	0.13	0.06	0.05	0.05

The number of flowers showed considerable variation in response to different Mo fertilisation treatments, ranging from 36 to 42 per plant. The minimum number of flowers (36) was recorded with foliar application of Mo at 0.1% alone. Increasing the foliar concentration to 0.2% resulted in a modest increase to 42.

Pod yield of black gram showed considerable variation in response to different Mo fertilisation treatments, ranging from 728.32 to 826.32 kg ha⁻¹. The minimum pod yield (728.32 kg ha⁻¹) was recorded with foliar application of Mo at 0.1% alone. Increasing the foliar concentration to 0.2% resulted in a modest increase in pod yield to 744.32 kg ha⁻¹; however, this increment was not statistically significant. Incorporation of Mo into the soil in addition to foliar application resulted in a further improvement in pod production. Application of 0.25 kg Mo ha⁻¹ to the soil together with a 0.1% foliar spray increased pod yield to 754.32 kg ha⁻¹. Pod yield subsequently exhibited an increasing trend with progressive soil application of Mo. The maximum pod yield of 826.32 kg ha⁻¹ was obtained under S₃F₂, comprising 0.75 kg Mo ha⁻¹ through soil application along with 0.2% foliar spraying. The enhanced pod

production under Mo fertilisation may be related to improved nutrient availability and biological nitrogen fixation. Molybdenum is an essential component of enzymes associated with nitrogen metabolism and can enhance the efficiency of symbiotic nitrogen fixation, thereby supporting vegetative growth and reproductive development under Mo-deficient soil conditions. A similar positive influence of Mo application on pulse productivity has been reported by Velmurugan and Mahendran (2015) and Chatterjee and Bandyopadhyay (2017).

Fruit-setting percentage followed a similar trend. Across the treatments, it ranged from 53% to 60%. The minimum value (53%) was recorded with 0.1% foliar Mo application alone. Increasing the foliar concentration to 0.2% resulted in a significant increase to 60%.

Scatter plot analysis revealed varying degrees of association between seed yield and the four yield-attributing characters (Fig. 1). Plant height showed a relatively strong positive relationship with seed yield, with an R^2 value of 0.51, indicating that 51% of the variation in seed yield could be explained by variation in plant height. Fruit setting percentage also exhibited a positive association with seed yield, with an R^2 value of 0.42, suggesting that 42% of the variability in seed yield was associated with differences in fruit setting.

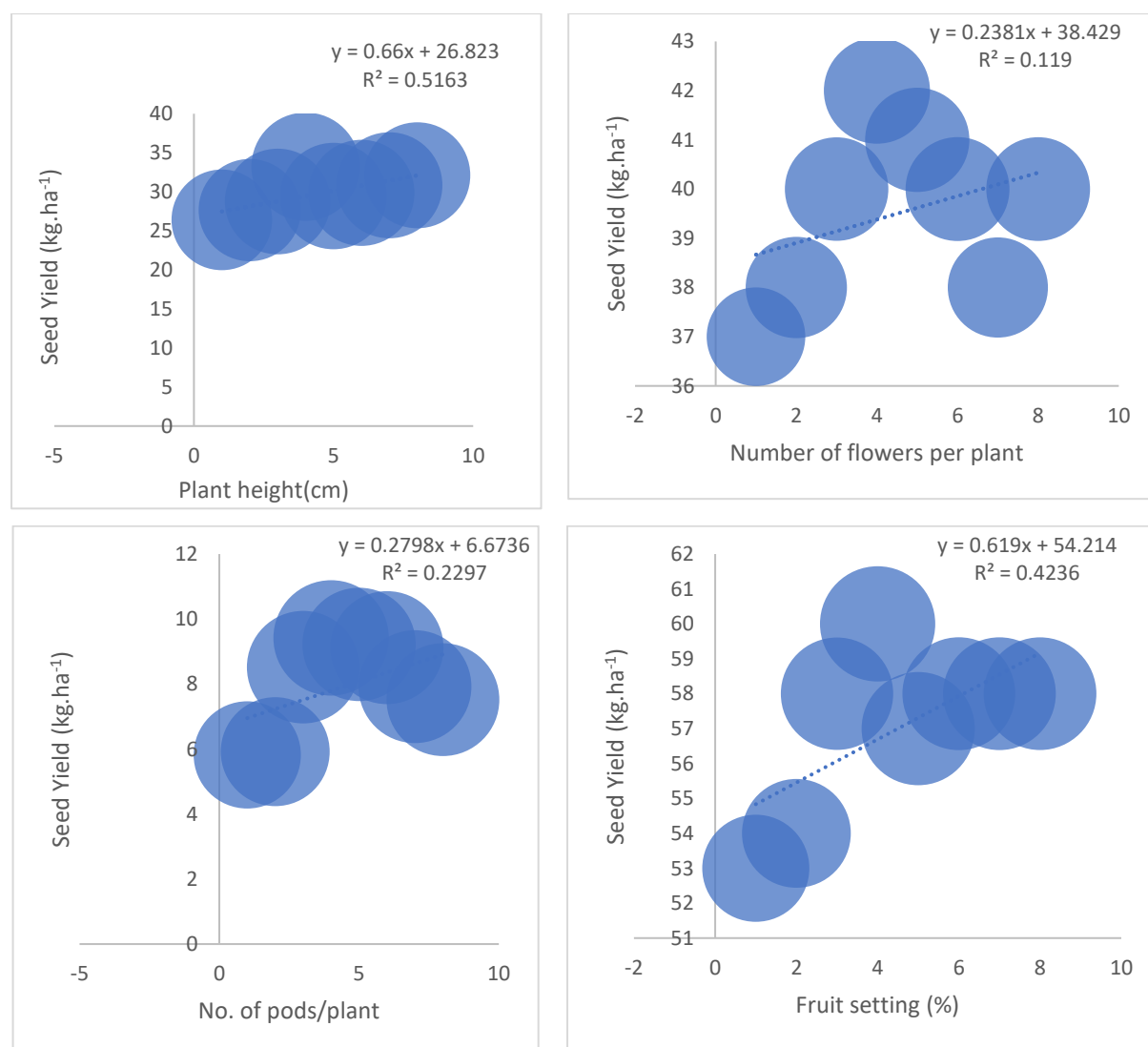


Fig. 1. Scatter plot between Seed yield and different yield attributing characters

In contrast, the number of pods per plant showed a comparatively weaker relationship with seed yield, with an R^2 value of 0.22, indicating that approximately 22% of the variation in seed yield was explained by this trait. The weakest association was observed for the number of flowers per plant, which recorded an R^2 value of 0.11, accounting for only 11% of the variation in seed yield. Overall, the scatter plot analysis indicated that plant height and fruit-setting percentage had relatively stronger associations with seed yield, whereas the relationships of the number of pods per plant and the number of flowers per plant with seed yield were comparatively weak.

The number of seeds per pod followed a similar trend. Across the treatments, seeds pod⁻¹ ranged from 10.82 to 12.62. The minimum value (10.82 seeds pod⁻¹) was recorded with 0.1% foliar Mo application alone. Increasing the foliar concentration to 0.2% resulted in a significant increase in seed number to 12.62 seeds pod⁻¹. Combining soil application with foliar Mo produced a further improvement, with the number of seeds per pod increasing by 15.29% over the 0.1% foliar treatment. The highest value of 12.62 seeds pod⁻¹ was recorded under S₁F₂, comprising 0.25 kg Mo ha⁻¹ as soil application together with 0.2% foliar Mo.

Seed yield also responded markedly to Mo nutrition and ranged from 561.32 to 650.32 kg ha⁻¹. The lowest seed yield was recorded with 0.1% foliar application of Mo alone, whereas the maximum yield of 650.32 kg ha⁻¹ was obtained under S₁F₂, i.e., 0.25 kg Mo ha⁻¹ applied to the soil in combination with 0.2% foliar Mo. Interestingly, further enhancement of the soil-applied Mo rate did not result in a corresponding increase in seed production. Rather, seed yield declined when the soil Mo dose was increased beyond 0.25 kg ha⁻¹, particularly at the higher application levels.

The mean seed yield obtained solely through foliar application of Mo was 570.32 kg ha⁻¹. Addition of 0.25 kg Mo ha⁻¹ to the soil increased the mean seed yield by 12.62%, irrespective of the foliar Mo concentration. A further increase in the soil-applied Mo rate resulted in a decline in mean seed yield, although the yield remained 11.7% higher than that obtained with foliar application alone. A comparable response was observed at the highest soil application rate of 0.75 kg Mo ha⁻¹. Increasing the foliar concentration from 0.1% to 0.2% resulted in only a 3.9% increase in seed yield at this Mo level.

The reduction in seed yield at higher Mo application rates may be associated with the adverse effects of both insufficient and excessive Mo nutrition on seed quality and development. An imbalance in Mo supply may affect biochemical constituents such as soluble sugars, starch, protein and nitrogen, as well as altering seed leaching characteristics and electrical conductivity. Excessive Mo availability may also result in the production of lighter and incompletely developed seeds with reduced vigour and germination capacity. Similar observations concerning the adverse effects of inappropriate Mo levels on seed quality have been reported by Gopal *et al.* (2016).

Because Mo is involved in important physiological and biochemical processes associated with chlorophyll formation and nitrogen metabolism, chlorophyll concentration was measured at two critical stages of crop development: the pre-flowering stage and the pod development stage. Chlorophyll a and chlorophyll b were estimated following the method of Arnon (1949).

The results indicated that chlorophyll *a* concentration generally increased from the pre-flowering stage to pod development, although the magnitude of response depended on the level and method of Mo application. At the pod development stage, chlorophyll *a* concentration ranged from 0.18 to 0.30 mg g⁻¹ fresh weight. The lowest concentration was recorded under the 0.1% foliar Mo treatment without soil application. The maximum chlorophyll *a* concentration (0.30 mg g⁻¹ fresh weight) was observed under S₁F₁, involving 0.25 kg Mo ha⁻¹ through soil application combined with 0.1% foliar spraying. This treatment remained statistically comparable with S₃F₁ and S₃F₂.

Chlorophyll *b* exhibited a different response pattern. Its concentration increased with the combined application of soil and foliar Mo compared with foliar application alone, and a progressive increase was also observed with increasing soil-applied Mo. The maximum chlorophyll *b* concentration (0.52 mg g⁻¹ fresh weight) was recorded under S₃F₂. At the pod development stage, chlorophyll *b* concentration remained lower than that of chlorophyll *a*. The improvement in chlorophyll concentration under Mo fertilisation may be attributed to improved nitrogen metabolism and enhanced physiological activity resulting from adequate Mo availability.

The data on initial and post-harvest soil available N, P and K as influenced by different treatments are presented in Table 6. The initial soil available N, P and K were 143.8, 10.20 and 48.30 kg ha⁻¹, respectively, across all treatments. Following crop harvest, available N increased under all treatments, ranging from 152.9 to 159.9 kg ha⁻¹. The highest available N (159.9 kg ha⁻¹) was recorded under S₁F₂, followed by S₂F₂ (158.9 kg ha⁻¹) and S₂F₁ (158.1 kg ha⁻¹), whereas the lowest value was observed under S₀F₁ (152.9 kg ha⁻¹).

Table 6. Effect of molybdenum fertilization on major nutrient content of post-harvest soil

Treatment	Initial N (kg ha ⁻¹)	Post-harvest N (kg ha ⁻¹)	ΔN (kg ha ⁻¹)	Initial P (kg ha ⁻¹)	Post-harvest P (kg ha ⁻¹)	ΔP (kg ha ⁻¹)	Initial K (kg ha ⁻¹)	Post-harvest K (kg ha ⁻¹)	ΔK (kg ha ⁻¹)
S ₀ F ₁	143.8	152.9	9.1	10.2	11.67	1.47	48.3	52.32	4.02
S ₀ F ₂	143.8	153.7	9.9	10.2	11.88	1.68	48.3	52.92	4.62
S ₁ F ₁	143.8	156.8	13	10.2	12.05	1.85	48.3	54.11	5.81
S ₁ F ₂	143.8	159.9	16.1	10.2	12.34	2.14	48.3	55.31	7.01
S ₂ F ₁	143.8	158.1	14.3	10.2	12.04	1.84	48.3	53.75	5.45
S ₂ F ₂	143.8	158.9	15.1	10.2	12.1	1.9	48.3	53.22	4.92
S ₃ F ₁	143.8	156.2	12.4	10.2	12.11	1.91	48.3	52.2	3.9
S ₃ F ₂	143.8	155.7	11.9	10.2	11.95	1.75	48.3	53.47	5.17
SEM (±)	-	1.18	-	-	0.14	-	-	0.62	-
C.D. (0.05)	-	3.52	-	-	0.42	-	-	1.85	-

Similarly, post-harvest available P increased from the initial value of 10.20 kg ha⁻¹ to 11.67–12.34 kg ha⁻¹ across the treatments. The maximum available P (12.34 kg ha⁻¹) was recorded with S₁F₂, while the minimum (11.67 kg ha⁻¹) was observed under S₀F₁. Available K also increased following harvest, with post-harvest values ranging from 52.20 to 55.31 kg ha⁻¹, compared with the initial value of 48.30 kg ha⁻¹. The highest available K (55.31 kg ha⁻¹) was recorded under S₁F₂, followed by S₁F₁ (54.11 kg ha⁻¹), while the lowest value was recorded under S₃F₁ (52.20 kg ha⁻¹).

Overall, S₁F₂ resulted in the highest post-harvest availability of N, P and K, indicating greater retention or accumulation of available nutrients in the soil under this treatment combination.

The enhanced uptake of N, P and K under Mo nutrition may be associated with improved root development, greater biomass production and more efficient nitrogen metabolism. Adequate Mo availability can also promote biological nitrogen fixation in legumes, thereby improving the nitrogen status of plants and supporting greater uptake and utilisation of other essential nutrients. The superior nutrient uptake recorded under S₁F₂ was consistent with the improvement observed in crop growth and yield components under the same treatment.

The experiment demonstrated a clear response of black gram to both soil and foliar Mo nutrition under acidic, low-fertility soil conditions. Although increasing Mo application improved several growth and yield-related parameters, the response was not uniformly proportional to the applied dose. The combined treatment of 0.25 kg Mo ha⁻¹ applied to the soil and a 0.2% Mo foliar spray (S₁F₂) consistently produced superior crop performance, particularly with respect to growth characteristics, yield components, seed yield and nutrient uptake.

The improvement in chlorophyll concentration and nutrient acquisition under Mo fertilisation further indicates the importance of adequate Mo availability for maintaining efficient physiological and nutritional functioning of black gram. Conversely, the decline in seed yield at higher soil Mo levels suggests that excessive Mo application may disturb the nutritional balance of the crop and adversely affect seed development.

Under the conditions of the present investigation, integrated Mo application consisting of 0.25 kg Mo ha⁻¹ to the soil together with a 0.2% Mo foliar spray applied twice appeared to provide an effective nutritional strategy for black gram grown on acidic, nutrient-deficient soils. Such an approach may be useful for improving crop productivity and nutrient utilisation where Mo deficiency is an important limitation to pulse production.

4. Conclusion

Under the acidic, Fe-rich and low-fertility soil conditions evaluated in this pot experiment, black gram (*Vigna mungo* L.) responded to both soil and foliar molybdenum (Mo) application. The S₁F₂ combination—0.25 kg Mo ha⁻¹ applied to the soil with 0.2% foliar Mo—produced the highest seed yield (650.32 kg ha⁻¹) and favourable values for several growth and yield attributes. Increasing the soil Mo rate above 0.25 kg ha⁻¹ did not further improve seed yield, indicating that the crop response was not proportional to increasing Mo supply. The same treatment was associated with the highest post-harvest available N, P and K values among the treatments evaluated. Chlorophyll responses varied across treatment combinations, indicating that biochemical responses were not identical to yield responses. Overall, the results support a moderate, integrated soil-and-foliar Mo strategy for improving black gram performance under the specific soil and pot conditions of this study. Field-scale validation is required before the treatment can be recommended more broadly across acidic soils of West Bengal.

5. Limitations

This study was conducted as a pot experiment at a single location using one black gram variety (PU-13), four soil-applied molybdenum rates and two foliar concentrations. Consequently, the observed responses may not represent the variability expected under field conditions, across contrasting acidic soils or among different cultivars. The manuscript also reports a single stated foliar application timing, limiting assessment of timing effects. Multi-location field studies using additional cultivars and application schedules would be needed to evaluate the wider applicability of the treatment response.

Acknowledgement

The authors sincerely acknowledge the support and facilities provided by Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal, for conducting the field and laboratory investigations. The authors are also grateful to the staff and technical personnel of Mondouri Farm for their assistance and cooperation during the course of the experiment.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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