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Effect of Zinc Management Practices on Productivity and Quality of Mung Bean (*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

Zinc management may influence the productivity and seed mineral content of mung bean, although the comparative performance of individual and combined application methods requires evaluation under specific field conditions. A field experiment was conducted during the kharif season of 2025–26 at the Agricultural Research Farm, Faculty of Agriculture, Tantia University, Sri Ganganagar, Rajasthan, India, to evaluate zinc management practices in mung bean. The experiment was laid out in a randomised block design with seven treatments and three replications. The treatments comprised a control; soil application of $ZnSO_4$ at 25 kg ha^{-1}; seed priming with 0.5% $ZnSO_4$; foliar application of 0.5% $ZnSO_4$; soil application + seed priming; soil application + foliar application; and soil application + seed priming + foliar application. The experimental soil was sandy loam, with low levels of organic carbon (0.46%) and available nitrogen (220 kg ha^{-1}), medium in available phosphorus (14.21 kg ha^{-1}) and potassium (214.55 kg ha−1),

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with a neutral reaction (pH 7.11). The combined application of $ZnSO_4$ through soil, seed priming and foliar spray produced the highest plant height, branches plant^{-1}, pods plant^{-1}, seeds pod^{-1}, test weight, grain yield, stover yield, biological yield, harvest index and seed zinc content. Grain yield increased from 9.48 q ha^{-1} in the control to 13.28 q ha^{-1} under the combined treatment. The same treatment recorded the highest gross return (₹122,920 ha^{-1}), net return (₹95,385 ha^{-1}) and benefit:cost ratio (3.46). The results indicate that integrated zinc management through soil application, seed priming and foliar application can improve mung bean productivity, grain zinc concentration and economic returns under the conditions of the experiment.

Keywords: Vigna radiata; zinc sulphate; seed priming; foliar zinc application; agronomic biofortification; grain yield; seed zinc concentration; harvest index.

1. Introduction

Mung bean is an important short-duration pulse crop valued for its protein, mineral content and adaptability. Zinc is essential for enzyme activity, protein synthesis, membrane integrity and several physiological processes in plants. Inadequate zinc availability may restrict crop growth, yield formation and grain nutritional quality. Agronomic zinc management through soil application, seed priming and foliar spray offers practical approaches for improving zinc availability and its accumulation in edible plant parts. The present investigation was therefore undertaken to study the effect of different zinc management practices on growth, yield attributes, yield, seed zinc content and economics of mung bean.

Zinc availability at the soil–root interface influences plant nutrient acquisition, and zinc participates in numerous biochemical and physiological functions linked to crop growth (Broadley *et al*., 2007; Cakmak, 2008; Cakmak *et al*., 2017). Agronomic biofortification seeks to increase the mineral concentration of edible tissues through nutrient management; its effectiveness can vary with soil characteristics, crop genotype and application method (Bhardwaj *et al*., 2022; White & Broadley, 2009). Earlier agronomic discussions of zinc nutrition and crop biofortification provide further context (Lindsay, 1972; Prasad *et al*., 2014).

The agricultural-production context for improving short-duration pulse crops has also been documented (Ministry of Agriculture and Farmers Welfare, 2025). In mung bean, field studies have reported improvements in growth and yield following zinc application to soil, foliage or seed, but the relative response to each approach is not uniform across experimental conditions (Haider *et al*., 2019; Haider *et al*., 2020; Hussain *et al*., 2021; Kaur & Sharma, 2025). Mung bean studies further indicate that micronutrient application can modify grain mineral concentration as well as yield (Dhaliwal *et al*., 2023; Farooq *et al*., 2025). Recent field trials provide additional evidence that the effects of zinc management on mung bean depend on treatment composition and application timing. Yadav *et al*. (2026) investigated zinc rates combined with thiourea and reported differences in mung bean growth, yield and economic outcomes, whereas Rashid *et al*. (2024) compared basal and differently timed foliar zinc treatments. Studies evaluating foliar zinc with other nutrients (Jassal *et al*., 2026) and under contrasting irrigation regimes (Asif *et al*., 2026) also reported responses in grain yield and zinc content; however, these treatment arrangements are not identical to the combined soil, seed-priming and foliar applications examined here.

Evidence from rice indicates that seed priming with zinc-containing solutions can influence germination and early seedling growth (Oo *et al*., 2026), although responses in rice should not be assumed to apply directly to mung bean. Nevertheless, differences in crop variety, nutrient combinations, treatment timing and growing conditions across the available studies leave uncertainty about the relative performance of individual and combined ZnSO4 application routes for mung bean under the soil and seasonal conditions investigated in the present study. The objective of the present study was to compare soil application, seed priming, foliar application and their combinations for growth, yield attributes, grain and stover yields, seed zinc content and economic returns of mung bean cultivar MH-421 under the specified field conditions.

2. Materials and Methods

The experiment was conducted at the Crop Research Farm, Department of Agronomy, Tantia University, Sri Ganganagar, Rajasthan (28.4° N, 72.2° E; 178 m above mean sea level) during the kharif season of 2025–26. The cultivar used was MH-421. The experiment was arranged in a randomised block design with seven treatments and three replications. The gross plot size was 3 m × 3 m and the net plot size was 2.5 m × 2.5 m. The seed rate was 15 kg ha^{-1} and the row spacing was 30 cm. The recommended fertilizer dose was 20:40:20 kg ha^{-1} N:P2O5:K2O. The seven treatments are detailed in Table 1.

Table 1. Treatment details for the zinc management practices evaluated in mung bean

Treatment	Description
T1	Control (No Fertilizer)
T2	ZnSO4 soil application @ 25 kg ha−1
T3	ZnSO4 seed priming @ 0.5%
T4	ZnSO4 foliar application @ 0.5%
T5	Soil application + seed priming
T6	Soil application + foliar application
T7	Soil application + seed priming + foliar application

Zinc sulphate containing 21% Zn was used. For seed priming, seeds were soaked in 0.5% ZnSO4 solution for six hours, rinsed and shade-dried. Foliar application of 0.5% ZnSO4 was carried out at 30 and 45 days after sowing. Observations on plant height and branches plant−1 were recorded at 30 and 45 DAS and at harvest. Pods plant−1, seeds pod−1, test weight, grain yield, stover yield,

biological yield, harvest index and seed zinc content were recorded. Seed zinc was estimated after di-acid digestion using an atomic absorption spectrophotometer. Data were analysed using analysis of variance for a randomised block design, and treatment means were compared using the critical difference at the 5% significance level.

3. Results

The reported treatment differences are interpreted within the randomised-block analysis framework, for which established procedures for agricultural experiments are described by Gomez and Gomez (1984).

3.1 Growth and Yield Attributes

Zinc management significantly influenced plant height at 45 DAS and at harvest, whereas differences at 30 DAS were non-significant. The maximum plant height at 45 DAS (41.31 cm) and harvest (66.85 cm) was recorded under T7, followed by T6 (40.62 cm and 64.33 cm, respectively). The control recorded the minimum plant height at 45 DAS (33.73 cm) and harvest (52.12 cm). Branches plant^{-1} at harvest were highest under T7 (7.42), followed by T6 (7.14), while the control recorded 5.79 branches plant^{-1}.

The treatment pattern was also reflected in the number of pods per plant, seeds per pod and test weight: T7 recorded 50.60 pods per plant, 12.14 seeds per pod and 44.93 g, compared with 36.11, 8.67 and 32.06 g, respectively, in the control (Table 2). Previous mung bean experiments likewise reported improvements in branching or yield-associated traits after zinc supplementation, although the most effective application route differed among experiments (Haider *et al*., 2020; Hussain *et al*., 2021; Kaur & Sharma, 2025).

Table 2. Effect of zinc management practices on plant growth and yield attributes of mung bean

Treatment	Plant height at harvest (cm)	Branches plant^{-1} at harvest	Pods plant^{-1}	Seeds pod^{-1}	Test weight (g)
T1 Control	52.12	5.79	36.11	8.67	32.06
T2 Soil	60.27	6.69	44.25	10.62	39.29
T3 Priming	56.67	6.29	40.65	9.75	36.09
T4 Foliar	57.91	6.43	41.50	9.96	36.85
T5 Soil + priming	62.76	6.97	46.25	11.10	41.07
T6 Soil + foliar	64.33	7.14	47.33	11.36	42.03
T7 Soil + priming + foliar	66.85	7.42	50.60	12.14	44.93
SEm (±)	1.21	0.13	0.88	0.27	1.02
CD	3.73	0.41	2.70	0.85	3.15

3.2 Yield, Harvest Index and Seed Zinc Content

The combined application of $ZnSO_4$ through soil, seed priming and foliar spray recorded the highest grain yield (13.28 q ha^{-1}), stover yield (32.36 q ha^{-1}) and biological yield (45.64 q ha^{-1}). These values were statistically at par with soil application + foliar application. The control produced the lowest grain yield (9.48 q ha^{-1}), stover yield (24.18 q ha^{-1}) and biological yield (33.65 q ha^{-1}). Harvest index was highest under T7 (29.10%) and lowest under the control (28.16%). Seed zinc content was maximum under T7 (41.53 ppm), followed by T6 (38.85 ppm), while the control recorded 29.64 ppm.

Numerically, T7 exceeded the control by 3.80 q ha^{-1} in grain yield and 11.89 ppm in seed zinc concentration (Table 3). Similar associations between improved zinc nutrition, higher mung bean productivity and enrichment of harvested grain have been reported under soil, foliar and combined application strategies (Dhaliwal *et al*., 2023; Farooq *et al*., 2025; Haider *et al*., 2020). However, the reported statistical equivalence of T7 and T6 for grain, stover and biological yields does not support a claim of a significant yield advantage of the three-route treatment over soil plus foliar application.

The increase in grain zinc concentration is relevant to agronomic biofortification, but mineral concentration alone does not demonstrate increased dietary zinc absorption, which may also depend on seed composition and processing (Bhardwaj *et al*., 2022; White & Broadley, 2009). In contrast to the numerical advantage of combined delivery in the present field experiment, Farooq *et al.* (2025) identified foliar supplementation as particularly effective in their experimental system; differences among studies may reflect the zinc source, genotype, growing environment and treatment schedule (Farooq *et al*., 2025; Hussain *et al*., 2021).

Table 3. Effect of zinc management practices on grain, stover and biological yields, harvest index and seed zinc content of mung bean

Treatment	Grain yield (q ha^{-1})	Stover yield (q ha^{-1})	Biological yield (q ha^{-1})	Harvest index (%)	Seed Zn (ppm)
T1 Control	9.48	24.18	33.65	28.16	29.64
T2 Soil	11.61	28.75	40.36	28.77	36.32
T3 Priming	10.67	26.71	37.38	28.54	31.56
T4 Foliar	10.89	27.07	37.96	28.69	34.97
T5 Soil + priming	12.14	29.79	41.93	28.95	37.96
T6 Soil + foliar	12.42	30.39	42.82	29.01	38.85
T7 Soil + priming + foliar	13.28	32.36	45.64	29.10	41.53
SEm (±)	0.35	0.87	1.23	0.01	1.11
CD	1.09	2.69	3.78	0.02	3.41

3.3 Economics

The cost of cultivation was highest under T7 (₹27,535 ha^{-1}) and lowest under the control (₹24,425 ha^{-1}). T7 recorded the highest gross return (₹122,920 ha^{-1}), net return (₹95,385 ha−1) and benefit:cost ratio (3.46). The corresponding values under the control were ₹87,930 ha^{-1}, ₹63,505 ha^{-1} and 2.60, respectively.

The additional cost of T7 relative to the control was ₹3,110 ha^{-1}, while the corresponding increase in reported net return was ₹31,880 ha^{-1} (Table 4). This comparison indicates an economic benefit under the crop prices and input costs used in the present analysis, but treatment rankings should be interpreted alongside the statistical similarity between T7 and T6 for several yield measures. In another mung bean investigation, Haider *et al*. (2020) reported the highest marginal net benefits from soil plus foliar zinc application, illustrating that the maximum grain zinc response and the best economic option need not coincide.

The profitability of zinc interventions depends on the cost and timing of treatment as well as the realised harvest response. Dhaliwal *et al*. (2023) also assessed economic outcomes alongside yield and grain micronutrient composition in mung bean, whereas Kaur and Sharma (2025) examined crop productivity and energy efficiency under soil and foliar zinc management. Accordingly, the financial advantage observed here should be evaluated across seasons and input-price conditions before broad recommendations are made.

Table 4. Effect of zinc management practices on cultivation cost, gross and net returns, and benefit:cost ratio of mung bean

Treatment	Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	B:C ratio
T1 Control	24425	87930	63505	2.60
T2 Soil	26050	107572	81522	3.13
T3 Priming	24585	98880	74295	3.02
T4 Foliar	25750	100924	75174	2.92
T5 Soil + priming	26210	112384	86174	3.29
T6 Soil + foliar	27375	115004	87629	3.20
T7 Soil + priming + foliar	27535	122920	95385	3.46
SEm (±)	-	3274	3274	0.13
CD	-	10087	10087	0.39

4. Discussion

The superior performance of integrated zinc management may be attributed to the complementary effects of soil application, seed priming and foliar nutrition. Soil application improves zinc availability in the root zone, seed priming supports early establishment and foliar application supplies zinc during active vegetative and reproductive growth. Improved plant growth and branching likely enhanced the formation of pods and seeds, while better assimilate production and translocation contributed to increased test weight and yield. The higher seed zinc concentration under integrated management indicates improved agronomic biofortification. Although the integrated treatment involved a higher cultivation cost, the increases in grain and stover yields resulted in higher gross and net returns.

The response is biologically plausible because zinc is associated with enzyme function and the maintenance of metabolic processes required for plant development; nevertheless, the present experiment did not measure enzyme activity, photosynthetic capacity or zinc fluxes and therefore cannot directly establish these mechanisms (Bhardwaj *et al*., 2022; Broadley *et al*., 2007; Cakmak *et al*., 2017). Differences in rhizosphere zinc mobilisation may further influence the availability of applied zinc, as discussed by Hafeez *et al*. (2013), but microbial mobilisation was not quantified in this trial.

The relative effectiveness of application routes merits comparison with other mung bean studies. Haider *et al*. (2020) found that responses to zinc osmopriming, soil placement and foliar supplementation varied with site and genotype, while Kaur and Sharma (2025) recorded benefits from soil plus foliar zinc. Hussain *et al*. (2021) reported favourable growth and yield with basal zinc application under their conditions, and Farooq *et al*. (2025) highlighted foliar application for improving zinc and iron biofortification. These results suggest that integrated delivery is one viable approach rather than evidence of a universally superior prescription.

The rise in seed zinc content from 29.64 ppm in the control to 41.53 ppm under T7 is consistent with agronomic enrichment of the harvested grain, in agreement with the broader biofortification literature and mung bean-specific studies (Dhaliwal *et al*., 2023; Farooq *et al*., 2025; White & Broadley, 2009). Nevertheless, the outcome reflects one variety, field location and experimental season, and neither zinc bioavailability to consumers nor changes in grain antinutritional constituents were measured.

5. Conclusion

Under the conditions of the present field experiment, zinc application through soil, seed priming and foliar spray was associated with improvements in mung bean growth, yield attributes, grain yield and seed zinc content compared with the untreated control. The combined treatment (T7), comprising soil application of $ZnSO_4$ at 25 kg ha^{-1}, seed priming with 0.5% $ZnSO_4$ and foliar application of 0.5% $ZnSO_4$ at 30 and 45 days after sowing, recorded a grain yield of 13.28 q ha^{-1} and a seed zinc concentration of 41.53 ppm. These values exceeded the corresponding control values of 9.48 q ha^{-1} and 29.64 ppm. T7 also achieved the highest reported net return (₹95,385 ha^{-1}) and benefit ratio (3.46). Nevertheless, its grain, stover and biological yields were statistically

comparable to those obtained with soil plus foliar zinc application (T6), indicating that the additional seed-priming step did not produce a statistically distinguishable yield advantage for these measurements. Therefore, the findings support integrated zinc management as a potential approach under the tested conditions, but broader recommendations require confirmation across seasons, sites and cultivars.

6. Limitations

This study was conducted during one experimental season at a single site using mung bean cultivar MH-421, which limits the generalisability of the findings to other soils, seasons and genotypes. The three replications and single treatment schedule do not establish the consistency of responses under varying field conditions. The economic comparisons reflect the input costs and crop prices considered in the study. Multi-location and multi-season trials, alongside additional grain-quality measurements, are needed to evaluate the robustness of the results.

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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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