

Synergistic Role of Phosphorus and Zinc in Maximizing Carbon Sequestration in Green Gram (*Vigna radiata* L.)

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ABSTRACT

A field experiment was conducted at MM(DU) Mullana, during *kharif* season of 2024, to investigate the effect of phosphorus (P) and foliar zinc (Zn) application on carbon sequestration potential, growth and yield of green gram. Experiment was laid in split-plot design with three replications. Phosphorus was applied in main plots with four levels i.e. control, 75, 100 and 125% RDP, while foliar zinc was applied in sub-plots with three levels i.e. control, 1.0 and 1.5%. Growth parameters such as plant height, branches/plant, dry matter accumulation and seed yield were significantly improved with the application of 125% RDP to the tune of 68.3 cm, 6.0 branches per plant, 3.09, 16.46 g/plant, and 1089 kg/ha, respectively. Application of 1.5% zinc in the form of foliar spray also resulted in remarkable enhancement in these growth parameters and yield attributes compared to control. On the basis of interaction effect of both the factors on yield, application of 100% recommended dose of phosphorus along with 1.0% foliar spray of zinc was recommended as the most effective and economical method to enhance carbon sequestration as well as productivity in green gram. This combined nutrient management approach resulted in statistically at par seed yield with higher dosages of phosphorus and zinc and hence it was a viable path to sustain pulse productivity while making a contribution towards agroecosystem carbon reduction plans.

Key words: Phosphorus, zinc, carbon sequestration, green gram, yield

INTRODUCTION

Agricultural ecosystems are crucial sinks for atmospheric carbon dioxide (CO₂) through carbon sequestration, which contributes to mitigating global climate change while enhancing soil fertility and crop production (Ray *et al.*, 2025). Legume crops such as green gram (*Vigna radiata* L.) are part of sustainable agroecosystems due to their potential to fix nitrogen, short growth duration, and tolerance to a wide range of agroclimatic zones (Kumar *et al.*, 2023). Although the role of green gram in ecosystem carbon cycling has been well recognized, underlying nutrient-mediated mechanisms controlling its potential for carbon storage and fixation remain poorly elucidated.

Phosphorus (P) and zinc (Zn) are essential macronutrient and micronutrient, respectively, involved in fundamental physiological and

biochemical functions that control plant development and photosynthetic carbon assimilation (Islam *et al.*, 2025). Phosphorus is the cornerstone of energy transfer via adenosine triphosphate (ATP) and nucleic acid synthesis, with roots, nodulation, and carbohydrate metabolism being affected (Khan *et al.*, 2023; Liu *et al.*, 2025). Zinc acts as a catalytic cofactor in numerous enzymatic activities including carbonic anhydrase activity that is crucial for CO₂ hydration and assimilation, and regulating auxin biosynthesis that controls vegetative growth and biomass accumulation (Sethi *et al.*, 2025; Zinzala *et al.*, 2026). Interactive interaction of these nutrients can potentially enhance the effectiveness of carbon assimilation, biomass accumulation, and following carbon sequestration in above and below-ground plant organs.

This study evaluated the phosphorus and foliar zinc application synergistic impact on the

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morphological, physiological and yield attributes of green gram with special focus on quantifying carbon content in plant biomass and field sequestration potential of carbon. Through depiction of the nutrient dynamic that contributed to carbon fixation, this study aimed at steering integrated nutrient management programs towards the improvement of carbon sequestration in pulse-based cropping systems and facilitating climate change mitigation.

MATERIALS AND METHODS

The study was conducted during *kharif* 2024 at Students' Research Farm, Faculty of Agriculture, Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala, Haryana. The geographical coordinates of experimental site are 30° 17'0" N latitude and 77° 3'0" E longitude and altitude is 264 meter above mean sea level. The average rainfall of the region is approximately 700 mm annually. The soil of the experimental field consisted of 54% sand, 35% silt and 11% clay content making soil texture as sandy loam. Soil was also found to be low in organic carbon (0.30%) and available nitrogen (169.34 kg/ha), while it was medium in available P₂O₅ (13.43 kg/ha) and available K₂O (208.59 kg/ha). The experiment was laid out in split plot design. Main plots included four levels of phosphorus viz. M₁-Control, M₂-75% recommended dose of phosphorus (RDP), M₃-100% RDP and M₄-125% RDP, while sub-plots encompassed of three levels of foliar zinc viz. S₁-Control, S₂-1.0% foliar zinc and S₃-1.5% foliar zinc. The recommended dose of fertilizer as 20-40-0 kg N-P-K which was applied as per treatment requirements as basal dose before sowing. Nitrogen and phosphorus were applied using urea and single super phosphate, while

zinc sulphate was used for foliar spray of zinc. Variety MH-1142 was used for sowing in the experiment and sowing was done on 19th July 2024 using 20 kg/ha seed rate at a row spacing of 30 cm. The data of growth parameters like plant height, number of branches/plant and leaf area index were recorded from five tagged plants selected randomly from each plot while, the dry matter accumulation/plant, was recorded from five plants selected randomly in the second outermost row in each plot. Growth parameter observations were recorded periodically at 20, 40, 60 DAS and at harvest. The seed yield (kg/ha) was determined by weighing seeds from each net plot, while the biological yield (kg/ha) was determined by weighing bundle weight from each net plot at harvest.

RESULTS AND DISCUSSION

Height of green gram plant increased progressively with crop development and was directly affected by phosphorus and zinc application (Table 1). Among phosphorus rates, none of the treatment imparted any significant effect on plant height at 20 DAS. However, significantly higher plant height at later phase of growth of 48.6, 62.7 and 68.3 cm at 40, 60 DAS, and at harvest was recorded with the application of 125% RDP (M₄) which was statistically at par with 100% RDP (M₃). Such linear rise with increasing levels of phosphorus was an indication of increased root growth and nutrient uptake, culminating in higher vegetative vigour and carbon assimilation capacity. Zinc application also had a significant impact on plant height at harvest. 1.5% Zn (S₃) resulted in significantly higher plant height (64.9 cm), which was statistically at par with 1.0% Zn (S₂; 62.0 cm) which were statistically superior to control (S₁; 58.1 cm). The spectacular increase in plant

Table 1. Effect of phosphorus and zinc fertilization on plant height (cm) of green gram

Treatment	20 DAS	40 DAS	60 DAS	At harvest
Main plot (Phosphorus)				
Control (M ₁)	17.9	41.2	51.1	51.6
75% RDP (M ₂)	16.6	43.9	57.5	61.0
100% RDP (M ₃)	18.4	48.0	61.8	65.8
125% RDP (M ₄)	18.0	48.6	62.7	68.3
LSD (P=0.05)	NS	4.1	4.4	5.0
Sub plot (Foliar zinc)				
Control (S ₁)	17.9	44.9	56.4	58.1
1.0% foliar zinc (S ₂)	17.3	45.9	57.8	62.0
1.5% foliar zinc (S ₃)	17.9	45.5	60.7	64.9
LSD (P=0.05)	NS	NS	NS	4.3
Interaction LSD (P=0.05)				
M × S	NS	NS	NS	NS

NS-Not Significant.

height with increases in phosphorus and zinc levels can be caused by their inherent functions in physiological and metabolic processes of the plant. Phosphorus stimulates root development and energy transfer by ATP synthesis that increases profuse vegetative growth and storage of nutrients. Zinc nutrition was also noteworthy in increasing dry matter content. Zinc-requiring enzymes like carbonic anhydrase regulate intercellular CO₂ conversion to bicarbonate with a profound influence on photosynthetic rate and dry matter accumulation. Increased biomass in 1.0% and 1.5% Zn treatments supports the role of zinc for enhanced carbon fixation efficiency and tissue growth. Increased total dry matter outcome directly is linear to an expanded fixed pool carbon, hence contributing to plant input to atmospheric carbon sequestration. Similar results with higher phosphorus and zinc fertilization were also observed by Masih *et al.* (2020).

Dry matter accumulation (DMA) increased progressively from 20 DAS to harvest and was highly affected by phosphorus and zinc content (Table 2). At 20 DAS, DMA varied from 0.61 to 0.64 g/plant but none of the treatments had any significant effect. However, in case of phosphorus, significantly higher DMA was recorded in 125% RDP (M₄) (4.58, 13.70 and 16.46 g/plant) at 40, 60 DAS and at harvest, respectively, which was statistically at par with 100% RDP (M₃). At harvest, the respective plant's corresponding carbon content of each (45% of biomass) varied from 4.91 g C/plant (M₁) to 7.41 g C/plant (M₄). M₃ and M₄ treatments exhibited greater carbon sequestration than M₁ and M₂ but statistically were identical to one another. Under zinc application, the same trend existed with DMA as well. At maturity, S₃ (1.5% Zn) contained

14.87 g/plant, closely followed by S₂ (1.0% Zn; 14.61 g/plant), both statistically equal but much higher than S₁ (13.74 g/plant). The accompanying plant carbon content was between 6.18 and 6.69 g C/plant. Proper phosphorus and zinc availability appeared to maximize photosynthetic carbon fixation and assimilate accumulation, further increasing the sequestration potential of the crop. Dry matter linear increase with incremental phosphorus concentrations up to 125% RDP reflects a desirable carbon assimilation niche for enhanced root growth, nodulation and energy transfer. Phosphorus promotes carbohydrate metabolism and CO₂ fixation by the Calvin cycle with enhanced biomass yield. Zinc nutrition also contributed significantly towards dry matter accumulation. Zinc-dependent carbonic anhydrase controls intercellular CO₂ conversion to bicarbonate, directly affecting photosynthetic rate and dry matter. Higher biomass at 1.0 and 1.5% Zn treatments is witness to zinc's role in the efficiency of carbon fixation and tissue development. Similar results were also observed by Dhinakaran *et al.* (2021)

Crop age-increased number of branches per plant was significantly influenced by phosphorus and zinc concentrations (Table 3). At 20 DAS, treatment values were not significant; however, 40 DAS onwards, M₄ (5.6, 5.8 and 6.0 branches/plant) and M₃ (5.4, 5.8 and 5.8 branches/plant) significantly performed better than M₂ and M₁. Among zinc treatments, branches/plant was not affected statistically by foliar zinc application at any growth stage. Early growth and development of the plants for obtaining a required morphological shape before foliar application of zinc might be attributed to non-significant

Table 2. Effect of phosphorus and zinc fertilization on dry matter accumulation (g/plant) of green gram

Treatment	20 DAS	40 DAS	60 DAS	At harvest
Main plot (Phosphorus)				
Control (M ₁)	0.62	3.98	9.63	10.92
75% RDP (M ₂)	0.61	4.19	11.14	14.17
100% RDP (M ₃)	0.64	4.52	13.22	16.07
125% RDP (M ₄)	0.63	4.58	13.70	16.46
LSD (P=0.05)	NS	0.38	0.91	0.85
Sub plot (Foliar zinc)				
Control (S ₁)	0.62	4.08	11.36	13.74
1.0% foliar zinc (S ₂)	0.62	4.44	12.09	14.61
1.5% foliar zinc (S ₃)	0.63	4.43	12.32	14.87
LSD (P=0.05)	NS	NS	NS	0.74
Interaction LSD (P=0.05)				
M × S	NS	NS	NS	NS

NS–Not Significant.

results. High branch numbers per plant with high levels of phosphorus indicate increased meristematic activity and supply of assimilates. Phosphorus promotes cell division and nutrient remobilization from roots to shoots, 100 and 125% RDP treatments provided increased branches, indicative of increased photosynthetic surface area and canopy development. This structural development increases light capture and CO₂ fixation, leading to increased carbohydrate synthesis and dry matter accumulation. Similar results with higher phosphorus and zinc fertilization were also observed by Masih *et al.* (2020).

Phosphorus treatment produced highest seed yield, varying from 6.5 q/ha (M₁) to 10.9 q/ha (M₄), with M₃ (10.8 q/ha) and M₄ not significantly different but superior to that of M₂ (8.7 q/ha) and control (M₁). The biological yield of the treatments also matched, varying from 22.4 q/ha (M₁) to 39.0 q/ha (M₄), wherein M₃ (38.2 q/ha) and M₄ were statistically equivalent but significantly greater than the lower phosphorus grades (Table 4). Respective carbon sequestration by plants was equivalent to 1008.0-1755.0 kg C/ha or 3696-6435 kg CO₂/ha. Similar results were also observed by Kumawat *et al.* (2022). On the other hand, seed yield raised from 8.47 q/ha (S₁) to 9.69 q/ha (S₃) by the use of zinc, with S₂ (9.44 q/ha) and S₃ statistically equal but significantly greater than S₁. Biological yield also raised from 29.85 q/ha (S₁) to 34.20 q/ha (S₃), with S₂ (33.59 q/ha) and S₃ statistically equal but both greater than control. Respective carbon sequestration by plants varied from 1343.2 to 1539.0 kg C/ha or 4925-5643 kg CO₂/ha. Interaction effect of phosphorus and zinc further indicated that application of 100% recommended dose of phosphorus with 1.0% foliar zinc spray was

statistically similar to higher phosphorus and zinc fertilizer treatments under consideration of seed and biological yield.

Augmentation of stover and seed yield under elevated phosphorus and zinc levels are strong indications of increased assimilate production and partitioning (Table 5). Whereas the seed component is carbon sequestered in the product harvested, stover is organic return of carbon to the soil and consequently increases soil carbon sequestration directly. The dramatic increase in seed and stover yields at higher rates of phosphorus and zinc indicates the synergistic interaction among the nutrients in elevating assimilate yield and partitioning. Phosphorus increases root nodulation, nitrogen fixation and energy metabolism that results in increased reproductive efficiency. Optimum seed production at 100 and 125% RDP is attributed to improved translocation of photosynthate into reproductive as well as vegetative sinks, which

Table 4. Effect of phosphorus and zinc fertilization on yield of green gram

Treatment	Seed yield (q/ha)	Biological yield (q/ha)	Harvest index (%)
Main plot (Phosphorus)			
Control (M ₁)	6.5	22.4	28.9
75% RDP (M ₂)	8.7	30.6	28.4
100% RDP (M ₃)	10.8	38.2	28.2
125% RDP (M ₄)	10.9	39.0	28.0
LSD (P=0.05)	0.47	1.74	NS
Sub plot (Foliar zinc)			
Control (S ₁)	8.47	29.85	28.38
1.0% foliar zinc (S ₂)	9.44	33.59	28.21
1.5% foliar zinc (S ₃)	9.69	34.20	28.56
LSD (P=0.05)	0.41	1.51	NS
Interaction LSD (P=0.05)			
M x S	0.82	3.02	NS

NS-Not Significant.

Table 3. Effect of phosphorus and zinc fertilization on number of branches/plant of green gram

Treatment	20 DAS	40 DAS	60 DAS	At harvest
Main plot (Phosphorus)				
Control (M ₁)	2.9	4.5	5.0	5.3
75% RDP (M ₂)	3.2	4.9	5.2	5.6
100% RDP (M ₃)	3.2	5.4	5.8	5.8
125% RDP (M ₄)	3.4	5.6	5.8	6.0
LSD (P=0.05)	NS	0.4	0.4	0.3
Sub plot (Foliar zinc)				
Control (S ₁)	3.1	4.9	5.2	5.5
1.0% foliar zinc (S ₂)	3.2	5.1	5.6	5.7
1.5% foliar zinc (S ₃)	3.2	5.3	5.6	5.8
LSD (P=0.05)	NS	NS	NS	NS
Interaction LSD (P=0.05)				
M x S	NS	NS	NS	NS

NS-Not Significant.

Table 5. Interactive effect of phosphorus and zinc on seed and stover yield

	Seed yield (q/ha)					Biological yield (q/ha)				
	M ₁	M ₂	M ₃	M ₄	Total	M ₁	M ₂	M ₃	M ₄	Total
S ₁	6.07	8.54	9.58	9.70	8.47	21.59	30.09	33.76	33.95	29.85
S ₂	6.44	8.66	11.23	11.42	9.44	22.18	30.68	40.12	41.36	33.59
S ₃	6.84	8.90	11.48	11.55	9.69	23.34	31.13	40.78	41.55	34.20
Total	6.45	8.70	10.76	10.89	LSD=0.82	22.37	30.63	38.22	38.95	LSD=3.02

is facilitated by the right amount of phosphorus-induced ATP supply. Zinc plays a role in the formation of pollen, enzyme activity and grain filling leading to increased seed set and yield. However, it was also observed that none of the treatments imparted any significant effect on harvest index suggesting similar rate of change in seed and stover yield of the treatments. Similar results with higher phosphorus and zinc fertilization were also observed by Masih *et al.* (2020).

CONCLUSION

The study confidently demonstrated that the collective use of phosphorus and zinc had a remarkable synergistic effect on growth, biomass production and carbon sequestration in green gram. Higher phosphorus content (up to 125% RDP) and foliar zinc (1.0-1.5%) enhanced photosynthetic efficiency, resulting in enhanced growth parameters and yield attributes, thus augmenting carbon fixation potential. Interestingly, blending 100% RDP with 1.0% foliar zinc resulted in statistically similar yield and carbon sequestration so that of the higher fertilizer rates, and offered a resource-conserving and economically sustainable nutrient management option. This blended approach provided a viable avenue to increase green gram productivity while mitigating climate change through carbon sequestration in agroecosystems.

REFERENCES

- Dhinakaran, M., Indirani, R., Pandian, P. S., Gurusamy, A. and Kannan, P. (2021). Effect of organic fortified zinc on growth and yield of green gram [*Vigna radiata* (L). Wilczek] in Typic Chromustert. *J. Appl. Nat. Sci.* **13**: 1166-1171.
- Islam, M. M., Li, L., He, J., Naznin, A., Huda, S., Ahemd, T., Tissue, D. and Chen, Z. H. (2025). Decoding plant metabolomic response to potassium and nutrient stresses in controlled environments. *Physiol. Plant.* **177**: e70547.
- Khan, F., Siddique, A. B., Shabala, S., Zhou, M. and Zhao, C. (2023). Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. *Plants* **12**: 2861. <https://doi.org/10.3390/plants12152861>.
- Kumar, S., Gopinath, K. A., Sheoran, S., Meena, R. S., Srinivasarao, C., Bedwal, S., Jangir, C. K., Mrunalini, K., Jat, R. and Praharaj, C. S. (2023). Pulse-based cropping systems for soil health restoration, resources conservation, and nutritional and environmental security in rainfed agroecosystems. *Front. Microbiol.* **13**: 1041124. <https://doi.org/10.3389/fmicb.2022.1041124>.
- Kumawat R., Ram B., Singh P., Tetarwal J. P., Yadav R. K., Gupta A. K. and Bijarnia A. (2022). Response of summer mungbean (*Vigna radiata*) to phosphorus levels, biophos liquid biofertilizer and growth-regulator. *Ind. J. Agron.* **67**: 170-174.
- Liu, H., Gao, X., Fan, W. and Fu, X. (2025). Optimizing carbon and nitrogen metabolism in plants: From fundamental principles to practical applications. *J. Int. Plant Bio.* **67**: 1447-1466. <https://doi.org/10.1111/jipb.13919>.
- Masih, A., Dawson, J. and Singh, R.E. (2020). Effect of levels of phosphorus and zinc on growth and yield of green gram (*Vigna radiata* L.). *Int. J. Cur. Microbiol. App. Sci.* **9**: 3106-3112.
- Ray, S., Adhikary, R., Masina, S., Divya, S. and Sameer, S. (2025). Carbon sequestration and its effect on soil quality and crop productivity. *Trop. Agric.* **102**: 424-440.
- Sethi, G., Behera, K. K., Sayyed, R., Adarsh, V., Sipra, B. S., Singh, L., Alamro, A. A. and Behera, M. (2025). Enhancing soil health and crop productivity: The role of zinc-solubilizing bacteria in sustainable agriculture. *Plant Growth Regulation* **105**: 601-617.
- Zinzala, V. J., Patel, J. V., Tripathi, S. Patel, K. G., Naik, J. R., Singh, N., Varshney, N. and Amamkuzhiyil, D. (2026) Optimizing boron and zinc supplementation for cane growth and its residual effect on the ratoon crop. *Sci. Rep.* **16**. <https://doi.org/10.1038/s41598-025-29338-y>.