



ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2025): 4.97
IJAFA 2025; 7(10): 473-479
www.agriculturaljournals.com
Received: 18-09-2025
Accepted: 22-10-2025

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Optimizing zinc seed priming to enhance growth and yield of Mungbean (*Vigna radiata*) under laboratory and field conditions

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DOI: <https://www.doi.org/10.33545/2664844X.2025.v7.i10g.911>

Abstract

Seed quality and uniform crop establishment are major challenges in Mungbean (*Vigna radiata*) production, often limiting yield potential. This study evaluated the effects of different zinc-based seed priming treatments on seed germination, seedling vigour, and agronomic performance under both *in vitro* and field conditions. Treatments included ZnSO₄ at various concentrations (300, 450, and 600 ppm), ZnO (900 ppm), zinc polyphosphate (750 ppm), hydropriming, and an untreated control. Results revealed that priming with ZnSO₄ at 450 ppm significantly enhanced germination percentage, reduced hard seed incidence, improved root and shoot growth, and increased vigour indices compared to other treatments and control. Field trials confirmed the superiority of this treatment in promoting early emergence, accelerated flowering, greater plant height, increased branching, pod set, seed number per pod, earlier maturity, and ultimately higher yield and seed weight. Excessive zinc concentrations showed diminished benefits, emphasizing the importance of optimizing zinc levels for seed priming. The findings highlight zinc seed priming as a potent, practical strategy for improving Mungbean crop establishment and productivity, particularly in zinc-deficient soils.

Keywords: Crop yield, field performance, micronutrient biofortification, mungbean, seed germination, seed priming, seedling vigour, zinc deficiency, zinc sulfate, vigour index

Introduction

Mungbean (*Vigna radiata*) is a nutritionally significant legume crop widely cultivated for its high protein content, short duration, and role in sustainable agriculture through nitrogen fixation. Despite its importance, Mungbean production is often limited by poor seed quality, low and uneven germination, and vulnerability to abiotic stresses during early growth stages, which ultimately impact crop establishment and yield potential. Improving seed performance is, therefore, critical for ensuring reliable stand establishment and enhanced productivity. Seed priming a pre-sowing treatment involving controlled seed hydration has emerged as an efficient, cost-effective approach to advance seed metabolic processes, enabling faster germination and more vigorous seedlings. Among various priming agents, zinc has drawn particular interest due to its crucial involvement in numerous physiological and biochemical functions such as enzyme activation, hormone regulation, protein synthesis, and antioxidant defense. Zinc deficiency is widespread in many soils, affecting both crop yield and nutritional quality, thus making zinc-based seed priming a dual-benefit strategy to improve seed vigor and address micronutrient limitations. Studying the effects of different zinc seed priming treatments is necessary to optimize protocols tailored for Mungbean, a crop of great socioeconomic importance in many regions, to maximize germination efficiency, seedling growth, and ultimately, field performance and yield stability under diverse environmental conditions. This research contributes to filling knowledge gaps on appropriate zinc dosages and formulations for seed priming, providing practical recommendations to enhance Mungbean cultivation sustainably.

Methodology

Seed Material and Treatments: Certified seeds of Mungbean (*Vigna radiata*) were subjected to various seed priming treatments involving soaking in zinc-based solutions for 4

hours followed by drying to original moisture content. Treatments included ZnSO₄ at 300 ppm (T₂), 450 ppm (T₃), and 600 ppm (T₄), ZnO at 900 ppm (T₆), Zinc polyphosphate seed coating at 750 ppm (T₅), hydropriming (T₁), and untreated control (T₀). Seed priming protocols are well established to enhance seed physiological performance by stimulating metabolic pathways critical for germination and early growth (Farooq *et al.*, 2005; Cakmak, 2008) [10, 7].

Experimental Design

Laboratory studies assessing germination and seedling quality parameters were conducted using a Completely Randomized Design (CRD), while field experiments were arranged in a Randomized Block Design (RBD) with three replications to minimize experimental error and environmental variability (Gomez and Gomez, 1984; Steel *et al.*, 1997) [13, 22].

Data Transformation and Statistical Analysis

Percentage data (e.g., germination, emergence) and count data (e.g., number of branches, pods) were subjected to arcsine and square root transformation, respectively, to stabilize variance and meet assumptions of parametric analysis (Gomez and Gomez, 1984) [13]. Analysis of variance (ANOVA) was performed, and treatment means were separated using Duncan's Multiple Range Test (DMRT) to determine statistically significant differences among treatments (Duncan, 1955; Gomez and Gomez, 1984) [8, 13].

In vitro and Field Evaluations

Seed germination percentage, hard seed content, root and shoot lengths, vigour indices, and seedling dry weight were evaluated under controlled laboratory conditions following ISTA guidelines (ISTA, 2019) [16]. Field trials measured key agronomic traits including field emergence, days to 50% flowering, plant height, number of branches and pods per plant, seed count per pod, days to maturity, and yield components (Shivay *et al.*, 2007; Imran *et al.*, 2015) [21, 15].

Result and Discussion

In vitro Conditions

The results of different seed priming treatments on Mungbean under *in vitro* conditions are presented in Table 1

and depicted in Figure 1 and Figure 2. A significant variation was observed among the treatments for all seed quality parameters studied.

Seed germination (%)

Treatment T₃ (95.33%) recorded significantly higher germination percentage than all other treatments. Treatments T₆ (93.27%) and T₂ (92.80%) were at par with each other and next in effectiveness, while T₀ (86.67%) and T₁ (87.33%) remained significantly inferior. The marked increase in germination with Zn priming can be attributed to zinc's role as a cofactor for an array of enzymes that govern vital metabolic processes during early germination, especially carbohydrate and protein metabolism. Zinc-dependent enzymes such as alcohol dehydrogenase and carbonic anhydrase become rapidly activated upon seed imbibition, resulting in efficient mobilization of stored food reserves and hastened metabolic reactivation (Cakmak, 2008; Waqas *et al.*, 2019) [7, 24]. Additionally, zinc can stabilize membrane structures and regulate hormone balance most notably by supporting optimal auxin biosynthesis which collectively promote rapid and uniform germination even under suboptimal conditions (Farooq *et al.*, 2012; Hafeez *et al.*, 2013) [12, 14]. These results confirm and extend earlier findings that zinc priming confers a physiological advantage for early seedling establishment.

Hard Seed (%)

The lowest hard seed content was recorded in T₃ (3.33%), which was significantly superior to all other treatments. T₆ (4.33%) and T₂ (5.67%) followed and were at par. The highest hard seed percentages were observed in T₀ (8.00%) and T₁ (7.33%). This decline in hard seed percentage indicates improved seed coat permeability and water uptake due to Zn priming. Zinc ions likely activate hydrolytic enzymes and promote alterations in seed coat structure, facilitating radicle protrusion and dormancy breaking (Shahzad *et al.*, 2013) [20]. Controlled production of reactive oxygen species during Zn priming may also function as signaling molecules to regulate dormancy release genes. The pronounced reduction compared with hydropriming and control highlights zinc's unique biochemical role in dormancy alleviation (Basra *et al.*, 2003; Farooq *et al.*, 2007) [3, 10].

Table 1: Effect of different seed priming treatments on Mungbean under *in vitro* conditions

Treatment No.	Treatment Name	Seed germination (%) [#]	Hard Seed (%) [#]	Root length (cm)	Shoot length (cm)	Vigour index I	Vigour index II	Seedling dry weight (g)
T ₀	Absolute Control (No priming)	86.67 (68.59) ^d	8.00 (16.41) ^a	10.67 ^d	13.87 ^d	2126.33 ^e	20.22 ^e	0.23 ^d
T ₁	Hydropriming for 4 hrs and drying back to original moisture content.	87.33 (69.15) ^d	7.33 (15.66) ^a	11.80 ^c	15.20 ^c	2357.93 ^d	21.84 ^{de}	0.24 ^{cd}
T ₂	Seed priming with ZnSO ₄ 300 ppm Zn ²⁺ for 4 hrs and drying back to original moisture content.	92.80 (74.44) ^b	5.67 (13.76) ^{ab}	12.97 ^{bc}	16.00 ^{bc}	2691.17 ^{bc}	24.75 ^{bc}	0.27 ^{bc}
T ₃	Seed priming with ZnSO ₄ 450 ppm Zn ²⁺ for 4 hrs and drying back to original moisture content.	95.33 (77.54) ^a	3.33 (10.50) ^c	14.87 ^a	18.17 ^a	3149.10 ^a	29.87 ^a	0.31 ^a
T ₄	Seed priming with ZnSO ₄ 600 ppm Zn ²⁺ for 4 hrs and drying back to original moisture content.	91.37 (72.96) ^{bc}	6.00 (14.15) ^{ab}	12.93 ^{bc}	15.87 ^{bc}	2631.53 ^c	23.46 ^{cd}	0.26 ^{cd}
T ₅	Seed coating with Zinc Polyphosphate 750 ppm Zn ²⁺ for 4 hrs and drying back to original moisture content.	89.00 (70.64) ^{cd}	6.67 (14.95) ^a	12.23 ^c	15.53 ^{bc}	2471.10 ^d	22.55 ^{cde}	0.25 ^{cd}
T ₆	Seed priming with ZnO 900 ppm Zn ²⁺ for 4 hrs and drying back to original moisture content.	93.27 (75.05) ^{ab}	4.33 (12.00) ^{bc}	13.47 ^b	16.40 ^b	2786.23 ^b	26.11 ^b	0.28 ^b
S.E.(m) ±		0.44	0.40	0.26	0.24	33.39	0.57	0.005
CD at 1%		2.20	1.74	1.11	1.01	140.56	2.39	0.025

[#] = Values in parenthesis are arcsine transformed.

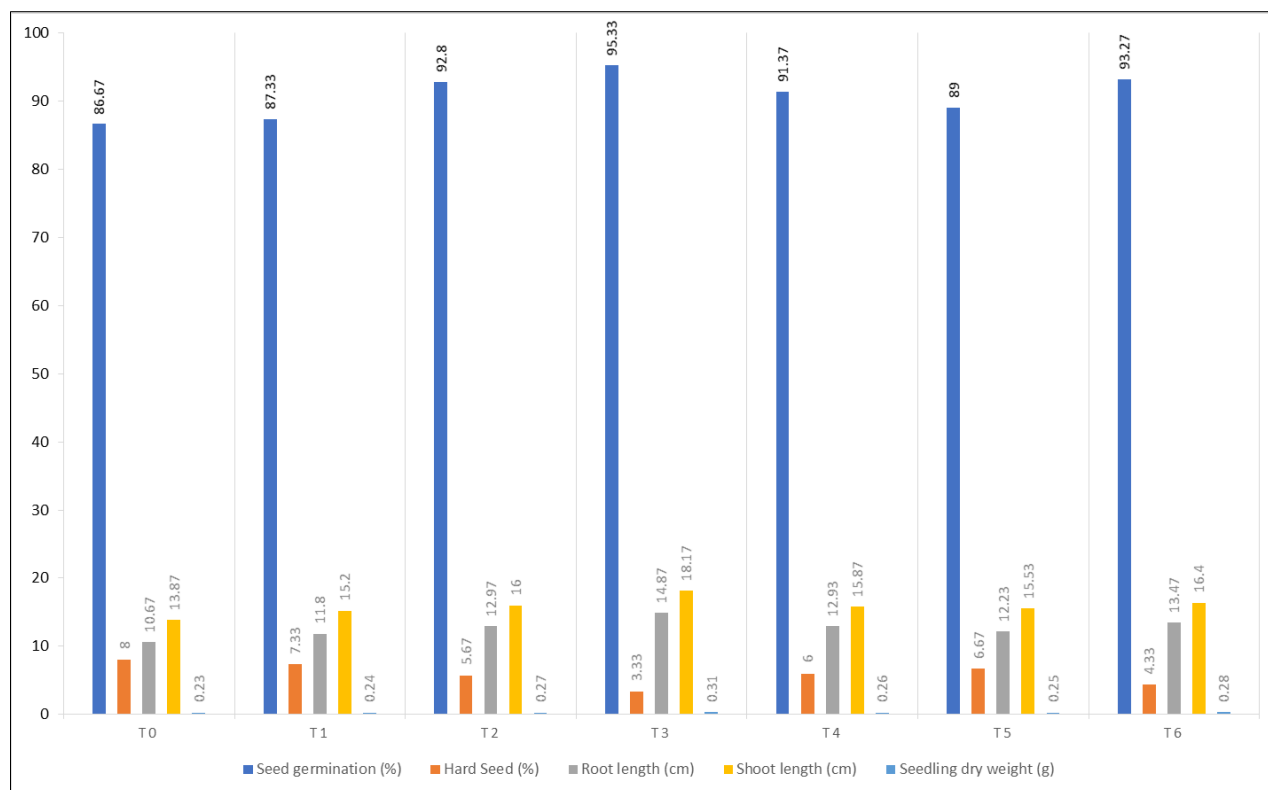


Fig 1: Effect of different seed priming treatments on various growth parameters of Mungbean under *in vitro* conditions

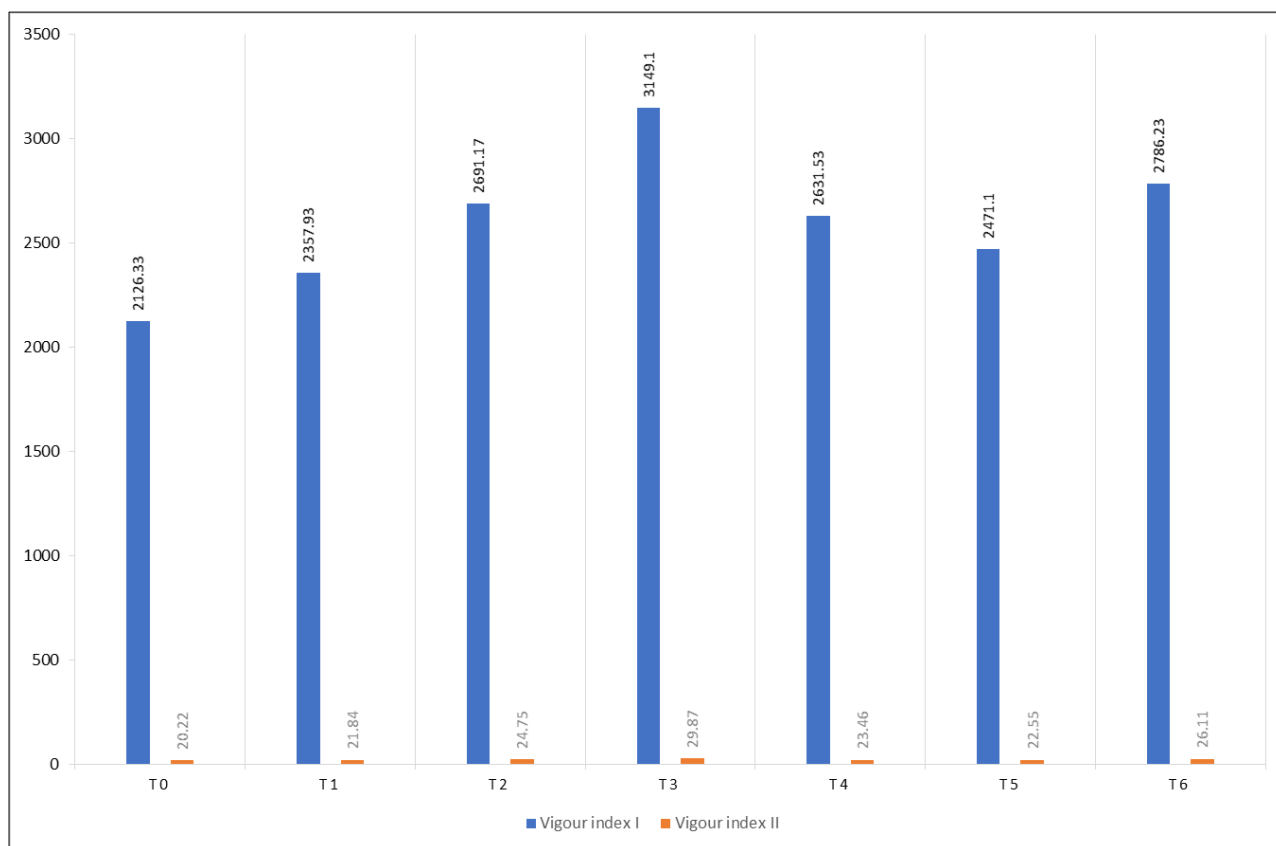


Fig 2: Effect of different seed priming treatments on Vigour index I and Vigour index II of Mungbean under *in vitro* conditions

Root length (cm)

Root length was maximized in T₃ (14.87 cm), significantly superior to all other treatments. T₆ (13.47 cm) and T₂ (12.97 cm) were at par and next effective, while T₀ (10.67 cm) and T₁ (11.80 cm) had the shortest roots. Zinc's pivotal role in enhancing root growth is linked to its stimulation of indole-

3-acetic acid synthesis, which promotes cell division and elongation in root meristems (Brown *et al.*, 1993; Marschner, 2012) ^[5, 17]. Zinc also stabilizes nucleic acids and proteins during rapid cell proliferation, enabling more vigorous root development that facilitates improved nutrient and water uptake (Imran *et al.*, 2015; Alloway, 2009) ^[15, 1].

Reduced root length in T₄ (12.93 cm) and T₅ (12.23 cm) indicates possible inhibitory effects at higher zinc concentrations, likely due to ionic toxicity or oxidative stress (Fageria *et al.*, 2002) [9].

Shoot length (cm)

Shoot length showed similar trends, with T₃ (18.17 cm) significantly superior to all other treatments. T₆ (16.40 cm) and T₂ (16.00 cm) were statistically at par and next best, while T₀ (13.87 cm) exhibited the shortest shoots. Zinc positively influences chlorophyll biosynthesis, photosynthesis, and protein metabolism, all of which are essential for shoot elongation and vigour (Cakmak, 2000) [6]. However, T₄ (15.87 cm) and T₅ (15.53 cm) showed a relative decline, possibly reflecting oxidative damage and nutrient imbalance caused by excessive zinc doses (Broadley *et al.*, 2007) [4]. These results affirm the importance of adequate and balanced zinc application for optimal shoot growth (Rehman *et al.*, 2015) [18].

Vigour index I

Treatment T₃ (3149.1) recorded the highest vigour index I, significantly outperforming all others. Treatments T₆ (2786.2) and T₂ (2691.2) were at par and second best, while T₀ (2126.3) recorded the lowest value. The integrated outcome of enhanced germination and seedling length under zinc priming accounts for this improvement. Zinc-mediated protection of membranes, enzymatic activation, and rapid mobilization of seed reserves contribute to stronger, more vigorous seedlings (Farooq *et al.*, 2005) [10]. Similar patterns have been observed in cereals and legumes, reinforcing zinc's beneficial role in seedling vigour (Basra *et al.*, 2005; Umar *et al.*, 2018) [3, 23].

Vigour index II

Correspondingly, vigour index II was maximal in T₃ (29.87), significantly higher than all other treatments. T₆ (26.11) and T₂ (24.75) were at par and next in rank, while T₀ (20.22) was the lowest. This parameter reflects both germination success and seedling dry mass accumulation, highlighting zinc's promotion of physiological quality and biomass partitioning (Marschner, 2012; Shivay *et al.*, 2007) [17, 21]. Zinc priming facilitates protein synthesis and antioxidant defense, which underpin these improvements observed widely in field and controlled studies (Rengel,

2015) [19].

Seedling dry weight (g)

Seedling dry weight was significantly greater in T₃ (0.31 g) than all other treatments, with T₆ (0.28 g) and T₂ (0.27 g) at par and superior to the rest. The lowest dry weight was found in T₀ (0.23 g). This enhancement in biomass illustrates efficient mobilization of storage reserves boosted by zinc's metabolic regulatory functions (Imran *et al.*, 2015; Cakmak, 2008) [15]. While T₄ (0.26 g) and T₅ (0.25 g) showed some reduction, suggesting the narrow optimum window of zinc concentrations, excessive zinc leads to phytotoxicity with impaired metabolism and oxidative stress (Broadley *et al.*, 2007; Fageria *et al.*, 2002) [4, 9].

Field Conditions

The results of different seed priming treatments on Mungbean under field conditions are presented in Table 2 and depicted in Figure 3. Significant differences were observed among the treatments for all growth and yield parameters studied.

Field emergence (%)

Field emergence was significantly highest in treatment T₃ (90.78%) and was markedly superior to all other treatments. Treatments T₆ (85.45%) and T₂ (82.55%) were statistically at par and followed next in effectiveness, while T₀ (78.22%) and T₁ (79.43%) were significantly inferior. The enhanced emergence in T₃ suggests that zinc priming not only improves seed metabolic activity leading to more uniform and rapid emergence but may also enhance seed vigor and soil-root interaction, thus promoting better seedling establishment under field conditions (Cakmak, 2008; Farooq *et al.*, 2012) [7, 12]. These results coincide with findings from earlier studies where micronutrient priming facilitated improved emergence performance compared to hydropriming or untreated seeds (Waqas *et al.*, 2019; Hafeez *et al.*, 2013) [24, 14].

Days to 50% flowering: Treatment T₃ (32.67 days) flowered significantly earlier than all other treatments, demonstrating an accelerated phenological development. Treatments T₂ (35.33 days) and T₆ (35.00 days) were at par and next in order of earliness, while the control treatment T₀ flowered significantly later at 39.67 day.

Table 2: Effect of different seed priming treatments on Mungbean under field conditions

Treatment No.	Field Emergence (%) [#]	Days to 50% flowering [*]	Plant height (cm)	No of branches per plant [*]	No of pods per plant [*]	No of seeds per pod [*]	Days to maturity [*]	Yield per plant (g)	Yield per plot (kg)	Yield per hectare (q)	100 seed weight (g)
T ₀	78.22 (62.24) ^c	39.67 (6.34) ^a	48.66 ^c	3.00 (1.87) ^e	20.80 (4.61) ^c	9.37 (3.13) ^c	73.22 (8.59) ^a	11.04 ^d	0.72 ^c	10.58 ^c	3.43 ^c
T ₁	79.43 (63.11) ^{bc}	37.00 (6.12) ^{ab}	52.70 ^b	3.73 (2.06) ^d	22.33 (4.78) ^{bc}	10.87 (3.37) ^{bc}	72.89 (8.57) ^a	11.75 ^{cd}	0.82 ^{bc}	12.04 ^{bc}	3.47 ^c
T ₂	82.55 (65.35) ^{bc}	35.33 (5.98) ^{bc}	55.60 ^b	5.17 (2.38) ^b	24.93 (5.04) ^b	11.80 (3.51) ^{ab}	69.40 (8.36) ^{ab}	12.85 ^{bc}	0.86 ^b	12.64 ^b	3.90 ^{bc}
T ₃	90.78 (72.40) ^a	32.67 (5.76) ^c	62.20 ^a	6.43 (2.63) ^a	28.83 (5.42) ^a	13.68 (3.76) ^a	65.00 (8.09) ^c	14.80 ^a	0.98 ^a	14.38 ^a	4.73 ^a
T ₄	81.33 (64.51) ^{bc}	36.33 (6.07) ^b	54.64 ^b	4.43 (2.22) ^c	24.00 (4.94) ^{bc}	11.43 (3.45) ^b	70.33 (8.42) ^{ab}	12.33 ^{bc}	0.85 ^b	12.49 ^b	3.50 ^c
T ₅	80.78 (64.00) ^{bc}	36.67 (6.10) ^{ab}	53.95 ^b	4.03 (2.13) ^{cd}	23.40 (4.89) ^{bc}	11.02 (3.39) ^{bc}	71.78 (8.50) ^{ab}	11.91 ^{cd}	0.84 ^b	12.29 ^b	3.67 ^{bc}
T ₆	85.45 (67.63) ^b	35.00 (5.96) ^{bc}	57.00 ^b	5.60 (2.47) ^b	25.41 (5.09) ^b	12.37 (3.59) ^{ab}	67.67 (8.26) ^{bc}	13.22 ^b	0.87 ^b	12.77 ^b	4.13 ^b
S.E.(m) ±	1.50	0.08	1.30	0.05	0.12	0.09	0.08	0.38	0.03	0.49	0.19
CD at 5%	4.62	0.24	4.02	0.15	0.37	0.27	0.25	1.15	0.10	1.49	0.57

= Values in parenthesis are arcsine transformed.

* = Values in parenthesis are square root transformed ($\sqrt{x + 0.5}$)

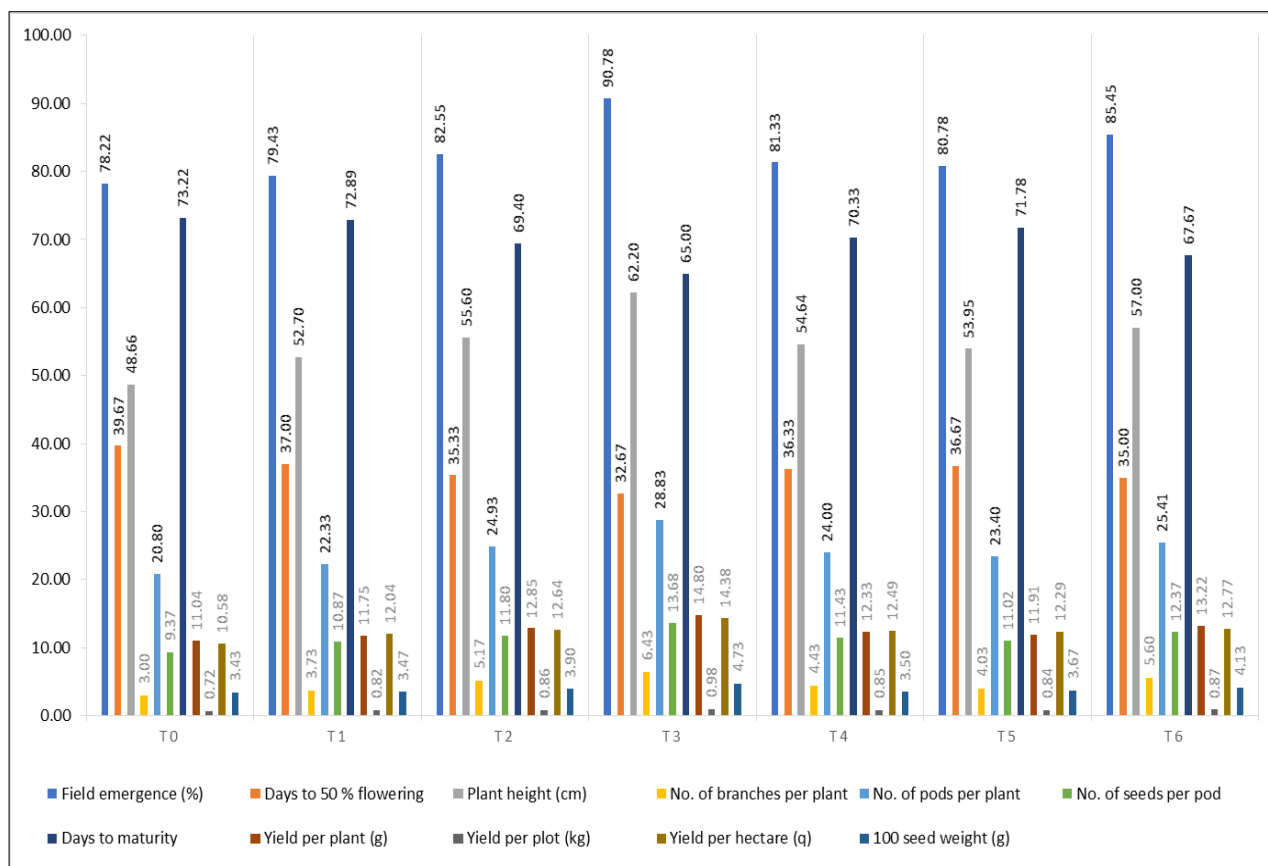


Fig 3: Effect of different seed priming treatments on various growth parameters of Mungbean under field conditions

The reduction in flowering time under zinc priming can be attributed to improved nutrient availability and hormonal regulation accelerating vegetative to reproductive transition (Marschner, 2012) [17].

This is in agreement with reports indicating that zinc facilitates enzyme functions involved in flowering regulation and can thereby enhance crop cycle efficiency (Shivay *et al.*, 2007) [21].

Plant height (cm)

Treatment T₃ produced the tallest plants (62.20 cm), significantly exceeding all other treatments. Treatments T₆ (57.00 cm), T₂ (55.60 cm), T₄ (54.64 cm), and T₅ (53.95 cm) were statistically comparable and ranked next. The control (48.66 cm) was significantly shorter. Increased plant height in zinc-primed seeds indicates improved cell elongation and division supported by zinc's crucial role in nucleic acid metabolism and auxin biosynthesis (Brown *et al.*, 1993; Cakmak, 2000) [5, 6]. These physiological enhancements contribute to stronger vegetative growth and align with previous observations where zinc treatments positively influenced height in legumes (Imran *et al.*, 2015) [15].

Number of branches per plant

The highest number of branches per plant was noted in T₃ (6.43), which was significantly superior to all others. Treatment T₂ (5.17) and T₆ (5.60) were statistically at par and followed next. Control plants produced significantly fewer branches (3.00). Enhanced branching under zinc priming can be linked to better nutrient assimilation and hormonal balance that promotes axillary bud growth (Marschner, 2012) [17]. Increased branching is critical for pod development potential and yield improvement, as

supported by findings in Mungbean and related legumes (Hafeez *et al.*, 2013) [14].

Number of pods per plant

Treatment T₃ had significantly the highest number of pods per plant (28.83), followed by T₆ (25.41) and T₂ (24.93), which were at par. The lowest was observed in the control (20.80). This increase likely results from improved flowering and branch development and is consistent with zinc's role in facilitating reproductive processes and sink strength allocation (Shivay *et al.*, 2007) [21]. Enhanced pod set positively influences yield components, a pattern commonly reported in field experiments with zinc treatments (Rehman *et al.*, 2015) [18].

Number of seeds per pod

Treatment T₃ produced the greatest number of seeds per pod (13.68), which was significantly superior to the rest. Treatments T₂ (11.80), T₆ (12.37), and T₄ (11.43) were statistically comparable and ranked next, while the control (9.37) had the lowest seed count. Zinc enhances seed development by optimizing pollen viability and fertilization, as well as early embryonic growth, which promote higher seed numbers per pod (Marschner, 2012; Broadley *et al.*, 2007) [17, 4]. Similar improvements have been reported in zinc-primed legume studies.

Days to maturity

Treatment T₃ reached maturity earliest at 65.00 days, which was significantly faster than all other treatments. Treatments T₆ (67.67), T₂ (69.40), and T₄ (70.33) were at par and followed next, while T₀ (73.22) matured last. Accelerated maturity with zinc priming can be explained by improved nutrient uptake and metabolic rates leading to a shortened

crop cycle (Shivay *et al.*, 2007) ^[17]. Early maturity is advantageous for fitting cropping sequences and reducing exposure to stresses during late growth stages (Farooq *et al.*, 2012) ^[12].

Yield per plant (g)

Yield per plant showed the highest value in T₃ (14.80 g), which was significantly superior to all other treatments. Treatments T₆ (13.22 g), T₂ (12.85 g), and T₄ (12.33 g) were at par as subsequent high performers. Control plants produced the lowest yield per plant (11.04 g). Yield improvements can be directly linked to enhancements in plant height, branch number, pod set, and seed number per pod due to zinc priming, supporting better photosynthetic capacity and assimilate partitioning (Cakmak, 2008; Imran *et al.*, 2015) ^[7, 15].

Yield per plot (kg)

Treatment T₄ again yielded the highest weight per plot (0.98 kg), significantly exceeding all other treatments. Treatments T₆ (0.87 kg), T₂ (0.86 kg), and T₄ (0.85 kg) were statistically similar and next best, whereas the control recorded the lowest plot yield (0.72 kg). This increase reflects the cumulative effect of improved emergence, growth, and reproductive traits in zinc-primed plants (Farooq *et al.*, 2005) ^[2].

Yield per hectare (q)

Yield per hectare followed the pattern of treatment superiority with T₃ (14.38 q) significantly outperforming others. Treatments T₆ (12.77 q) and T₂ (12.64 q) were statistically comparable and ranked next, while T₀ (10.58 q) produced the lowest yield. The enhanced yield is indicative of direct agronomic benefits of zinc priming on crop productivity and is consistent with prior reports in Mungbean and other grain legumes (Alloway, 2009; Shivay *et al.*, 2007) ^[1, 21].

100 seed weight (g)

The maximum 100-seed weight was recorded in T₃ (4.73 g), which was significantly higher than all other treatments. Treatments T₆ (4.13 g) and T₂ (3.90 g) were statistically comparable and next in rank, while T₀ (3.43 g) produced significantly lighter seeds. Seed weight improvements under zinc priming highlight enhanced seed filling and nutrient remobilization during reproductive development (Marschner, 2012) ^[17]. This contributes to both yield quality and seedling vigor in subsequent planting cycles.

Conclusion

The results of this study demonstrate that seed priming with zinc, particularly using ZnSO₄ at 450 ppm, significantly enhances Mungbean seed germination, seedling vigour, and overall plant growth both under controlled laboratory conditions and field environments. This treatment consistently outperformed other zinc concentrations, seed coating, hydropriming, and the untreated control by improving early metabolic activity, reducing seed dormancy, accelerating phenological development, and increasing yield attributes such as plant height, branch and pod number, and seed weight. Treatments with excessively high zinc concentrations showed comparatively diminished benefits, highlighting the importance of optimizing zinc levels for priming. These findings underscore the critical role of zinc seed priming as a practical and effective

approach to improve Mungbean crop establishment, growth, and productivity, offering a valuable tool for enhancing legume cultivation in zinc-deficient soils and variable agro-climatic conditions.

Acknowledgement

The authors acknowledge the Department of Botany (Seed Science and Technology), PGI, MPKV, Rahuri, for providing facilities and institutional support. We thank co-workers, field staff, and colleagues for their assistance. All authors contributed to this work, and no conflict of interest is declared.

References

1. Alloway BJ. *Zinc in soils and crop nutrition*. 2nd Ed. Brussels: International Zinc Association; 2009.
2. Basra SMA, Farooq M, Tabassum R, Ahmad N. Physiological and biochemical aspects of seed vigor enhancement treatments in fine rice (*Oryza sativa* L.). *Seed Sci Technol*. 2005;33(3):623-628.
3. Basra SMA, Farooq M, Tabassum R, Ahmad N, Khan MB. Physiological and biochemical aspects of seed vigor enhancement treatments in indica rice (*Oryza sativa* L.). *Seed Sci Technol*. 2003;31:381-93.
4. Broadley MR, White PJ, Hammond JP, Zelko I, Lux A. Zinc in plants. *New Phytol*. 2007;173(4):677-702.
5. Brown PH, Cakmak I, Zhang Q. Form and function of zinc in plants. In: Robson AD, editor. *Zinc in soils and plants*. Dordrecht: Springer; 1993, p. 93-106.
6. Cakmak I. Possible roles of zinc in protecting plant cells from damage by reactive oxygen species. *New Phytol*. 2000;146(2):185-205.
7. Cakmak I. Enrichment of cereal grains with zinc: agronomic or genetic biofortification? *Plant Soil*. 2008;302(1-2):1-17.
8. Duncan DB. Multiple range and multiple F tests. *Biometrics*. 1955;11(1):1-42.
9. Fageria NK, Baligar VC, Clark RB. Micronutrients in crop production. *Adv Agron*. 2002;77:185-268.
10. Farooq M, Basra SMA, Wahid A, Ahmad N, Saleem BA. Improving the drought tolerance in rice (*Oryza sativa* L.) by exogenous application of glycinebetaine and salicylic acid. *J Agron Crop Sci*. 2005;191(6):386-393.
11. Farooq M, Basra SMA, Ahmad N. Improving the performance of transplanted rice by seed priming. *Plant Growth Regul*. 2007;51(2):129-137.
12. Farooq M, Basra SMA, Wahid A. Priming of field-sown rice seed enhances germination, seedling establishment, allometry and yield. *Plant Growth Regul*. 2012;37:129-33.
13. Gomez KA, Gomez AA. *Statistical procedures for agricultural research*. 2nd Ed. New York: John Wiley & Sons; 1984.
14. Hafeez B, Khanif YM, Saleem M. Role of zinc in plant nutrition: a review. *Am J Exp Agric*. 2013;3(2):374-391.
15. Imran M, Mahmood A, Parveen A, Hussain S, Majeed A, Imtiaz M, *et al.* Role of zinc in plant nutrition: implications in crop production and human health. *Pak J Bot*. 2015;47(3):1-16.
16. International Seed Testing Association (ISTA). *International rules for seed testing*. Bassersdorf: ISTA; 2019.

17. Marschner P. *Marschner's mineral nutrition of higher plants*. 3rd Ed. London: Academic Press; 2012.
18. Rehman HU, Aziz T, Farooq M, Wakeel A, Rengel Z. Zinc nutrition in rice production systems: A review. *Plant Soil*. 2015;361:203-26.
19. Rengel Z. Availability of Mn, Zn and Fe in the rhizosphere. *J Soil Sci Plant Nutr*. 2015;15(2):397-409.
20. Shahzad B, Cheema SA, Farooq M, Ahmad R, Masood S. Seed priming with silicon modulates growth, water relations, antioxidant capacity, and ionic balance in maize plants under salinity stress. *Plant Growth Regul*. 2013;70(2):157-170.
21. Shivay YS, Kumar D, Prasad R, Ahlawat IPS. Relative performance of zinc sources and methods of application in rice-wheat cropping system. *Nutr Food Sci*. 2007;37(3):160-172.
22. Steel RGD, Torrie JH, Dickey DA. *Principles and procedures of statistics: a biometrical approach*. 3rd Ed. New York: McGraw Hill; 1997.
23. Umar AS, Moniruzzaman M, Rafii MY, Ismail MR, Islam MR. Seed priming for abiotic stress tolerance: A review. *Int J Agron Plant Prod*. 2018;9:119-128.
24. Waqas M, Manaf A, Azeem M, Hussain MA, Wang X. Mechanistic perspectives of seed priming in improving plant performance under environmental stresses. *Plant Physiol Biochem*. 2019;145:234-249.