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Germination and early physiological responses of Mung Bean (*Vigna radiata* L.) to gibberellic acid seed priming under PEG-induced osmotic stress

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Abstract

Drought is a major abiotic stress factor that affects germination, seedling establishment, and early growth in legume crops such as mung bean (*Vigna radiata* L.). This study evaluated the effects of seed priming with gibberellic acid (GA_3) at 200 ppm for 24 h on germination and early physiological traits of five mung bean cultivars (MB1–MB5) subjected to polyethylene glycol (PEG 6000)-induced osmotic stress at 0, 5, 10, and 20%. Seed surface sterilization and priming with either H_2O (control) or GA_3 were performed before the experiment. On the seventh day, the germination percentage (GP), tissue water content (TWC), seedling vigor indices (SVI-I and SVI-II), and early growth parameters such as root length (RL), shoot length (SL), root fresh weight (RFW), shoot fresh weight (SFW), root dry weight (RDW), and shoot dry weight (SDW) were evaluated. Increasing PEG concentration adversely affected germination and seedling growth across all cultivars. GA_3 priming was associated with partial improvement in overcoming the detrimental effects of stress, as indicated by increased germination stability percentage, tissue water content, vigor indices, and growth parameters, particularly at 5–10% PEG concentration; however, these responses varied among cultivars. MB4 and MB5 generally maintained higher GP, TWC, and vigor indices, whereas MB3 exhibited greater sensitivity to osmotic stress. Overall, the findings indicate that the response to GA_3 priming is strongly genotype-dependent and suggest that GA_3 seed priming may represent a practical, low-cost approach to support early seedling performance under moderate osmotic stress conditions in mung bean.

Keywords: Germination, Tissue water content, Seedling vigor, Mung bean (*Vigna radiata* L.), Gibberellic acid (GA_3), Osmotic stress

INTRODUCTION

Drought is one of the most important abiotic stressors limiting plant growth, productivity, and global food security. Its severity is expected to increase under current climate change scenarios. Seed germination, a critical and vulnerable phase of plant development, is very sensitive to water deficit, and its inhibition often results in poor seedling establishment and reduced yields (Almansouri et al., 2001; Farooq et al., 2009). Seed tolerance to water stress varies among species and genotypes, affecting both germination percentage and early seedling performance (Arjenaki et al., 2011; Zare et al., 2013). Previous studies have demonstrated that exogenous treatments applied before radicle emergence can partially alleviate the adverse effects of drought stress by activating metabolic and physiological processes during early growth stages (Brown et al., 1989; Khajeh-Hosseini et al., 2003). Among various strategies adopted to improve plant drought tolerance, seed priming is considered an easily applied, low-cost, and effective approach (Ashraf and Foolad, 2005). Nevertheless, drought continues to affect plants across morphological, physiological, and molecular levels, particularly in short-duration crops such as mung bean (*Vigna radiata* L.) (Zare et al., 2013). Mung bean (*Vigna radiata* L. Wilczek) is an important warm-season grain legume because of its high nutritional content, short life cycle, and high adaptability as a crop (Allahmoradi et al., 2011). Although *Vigna radiata* is generally regarded as relatively drought-tolerant, its productivity can decline dramatically under severe water-deficit conditions (Khatun et al., 2021; Islam et al., 2022). Seed priming is a technique that partially hydrates seeds, thereby activating metabolic processes that support rapid and uniform germination under drought-stress conditions (Ali et al., 2020; Farooq et al., 2017). Plant growth regulators (PGRs) are commonly used for their roles in stress-responsive pathways. As a PGR, Gibberellic acid (GA_3) is a class of phytohormones that regulates different aspects of plant growth and development, and is also known to promote seed germination by stimulating hydrolytic enzyme activity, cell

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elongation, and reserve mobilization (Tuna et al., 2007; Iqbal et al., 2023). Although many studies have reported beneficial effects of GA_3 pretreatment on seed germination under non-stress conditions, few have examined specific GA_3 effects under PEG-induced osmotic stress, particularly in legumes. Previous studies have suggested that exogenous GA_3 application may partially alleviate drought-induced constraints by influencing osmotic adjustment, antioxidant activity, and root growth; however, these responses are often cultivar- and stress-dependent.

Therefore, improving drought tolerance during the early growth phase remains a critical challenge for *V. radiata.* This study aimed to evaluate the effects of GA_3 seed priming on germination and early physiological responses of five mung bean (*Vigna radiata* L.) varieties exposed to PEG 6000-induced osmotic stress, with particular emphasis on a genotype-dependent manner.

MATERIALS AND METHODS

Plant Material, Treatments, and Growth Conditions

Five mung bean (*Vigna radiata* L. Wilczek) varieties were used: MB1 (Argentina), MB2 (Uzbekistan), MB3 (India), MB4 (local variety), and MB5 (Southeast Asia). Seeds were obtained from commercial sources. Seeds were separated by flotation and surface-sterilized by immersion in 70% ethanol for 30s, then rinsed with distilled water. 5% sodium hypochlorite solution was applied to the seeds for 10 minutes. At the end of the 10-minute period, the seeds were rinsed 4 times in sterile distilled water. There were two priming treatments: GA_3 priming, in which seeds were submerged in a 200 mg L^{-1} GA_3 solution for 24 hours at 25+1 °C; and H_2O (control), in which seeds were immersed in distilled water (0 mg L^{-1} GA_3) solution. Following priming, the seeds were rinsed in distilled water to remove the solution and allowed to dry. The experiment was conducted in a controlled growth chamber. Drought stress was simulated using polyethylene glycol (PEG 6000) at 0% (control), 5%, 10%, and 20% (w/v), as described by Kaya et al. (2005). Ten seeds were placed in each sterilized Petri dish (90 mm diameter) lined with two layers of Whatman No. 1 filter paper moistened with 10 mL of the respective PEG solution. Petri dishes were incubated in a dark chamber at 26 ± 2°C. In the experiment, a Factorial Completely Randomized Design (FCRD) was used, with five genotypes, two pre-treatments, and four PEG doses (Table 1). The experiment was repeated three times.

Table 1. Priming treatments and PEG levels applied to mung bean (*Vigna radiata* L.) genotypes.

Priming Treatment	Priming Duration (h)	PEG Concentration (% w/v)	Application Volume (mL)
H_2O (Control)	24	0, 5, 10, 20	10
GA_3 (200 mg L^{-1})	24	0, 5, 10, 20	10

Physiological Measurements

On day seven, randomly selected seedlings for each repetition were used to measure physiological characteristics. Root length (RL) and shoot length (SL) have been measured in millimeters. Root fresh weight (RFW), shoot fresh weight (SFW), root dry weight (RDW), and shoot dry weight (SDW) have been measured using a precise scale. Dry weights were determined after the samples were dried at 70 °C until a constant weight was reached.

Germination Percentage, Water Status, and Vigor Indices

The International Seed Testing Association (ISTA, 2010) protocol was used to determine the Germination Percentage (GP).

GP (%) *= Number of germinated seeds / Total number of seeds x 100*

The equation from Black and Pritchard (2002) was used to determine the Tissue Water Content (TWC).

TWC (%) *= Fresh weight - Dry weight / Fresh weight x 100*

The seedling vigor indices were evaluated following the protocols established by Abdul-Baki and Anderson (1970).

Seedling Vigor Index I (SVI I):

SVI (I) = Germination percentage x Root length (cm) + Shoot length (cm)

Seedling Vigor Index II (SVI II):

SVI (II) = Dry weight of seedling (mg) x Germination percentage

Statistical Analysis

Data were analyzed using a three-factor factorial completely randomized design (CRD), with genotype, priming treatment, and PEG level as fixed factors. Analysis of variance (ANOVA) was performed to evaluate the main effects and their interactions. When significant differences were detected ($p \leq 0.05$), mean comparisons were conducted using Tukey's honestly significant difference (HSD) test. All statistical analyses were performed using SPSS Statistics 25.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Root Length (RL) and Shoot Length (SL)

Exposure to increasing PEG concentrations caused a decline in root length across all genotypes. This decline was more pronounced under higher PEG levels. GA_3 priming was associated with numerical increases in root length, resulting in longer roots than the control in several genotypes, particularly under 5–10% PEG-induced osmotic stress; however, these responses varied by genotype, and stress intensity At 10% PEG, MB2 and MB5 maintained relatively greater root elongation compared with other genotypes, whereas MB3 exhibited a more pronounced reduction in root length under increasing PEG levels (Table 2a, 2b; Figure 1a).

Shoot length was significantly influenced by PEG concentration and genotype. The highest shoot elongation was observed under non-stress conditions, while severe osmotic stress (20% PEG) markedly reduced shoot length in all genotypes. At PEG levels of 5–10%. GA_3-primed seedlings showed numerical increases in shoot length in some genotypes, with more pronounced responses observed in MB2 and MB3; however, these effects were not consistent across all treatments (Table 2a, 2b; Figure 1b).

Root Fresh Weight (RFW) and Shoot Fresh Weight (SFW)

A decrease in RFW was observed in all genotypes as PEG concentration increased, with more pronounced reductions at higher PEG levels. Although the overall effect of GA_3 priming was inconsistent across treatments, higher root fresh weights were observed in some GA_3-pre-treated genotypes, notably MB1 and MB5, particularly under 5–10% PEG-induced osmotic stress (Table 2a, 2b; Figure 1c).

Shoot fresh weight (SFW) declined progressively with increasing PEG concentration, following a trend similar to that of root fresh weight, and the lowest SFW values were observed at 20% PEG across all genotypes. However, under stress levels of 5-10% PEG, GA_3-treated seedlings of specific genotypes, particularly MB3 and MB5, exhibited numerical increases in shoot fresh weight compared with control plants; however, these responses were not uniform across all genotypes (Table 2a, 2b; Figure 1d).

Root Dry Weight (RDW) and Shoot Dry Weight (SDW)

Root dry weight varied primarily by genotype and PEG level. In contrast to fresh weight parameters, reductions in RDW under PEG-induced osmotic stress were generally less pronounced. In some genotypes, including MB2, GA_3 priming was associated with numerical increases in RDW values at 10–20% PEG, although these responses were genotype-dependent (Table 2a, 2b; Figure 1e).

Data analysis showed that SDW was significantly influenced by genotypes, PEG concentration, and their interaction with pre-treatment. However, across all genotypes, the highest SDW was observed under non-stressed conditions. Increasing PEG concentration resulted in progressive reductions in SDW, and in most genotypes, GA_3 pre-treatment at 5-10% PEG was associated with numerical increases in SDW rather than a consistent statistically significant enhancement (Table 2a, 2b; Figure 1f).

Seedling Vigor

Increasing PEG concentrations resulted in progressive reductions in GP, TWC, and seedling vigor indices (SVI-I and SVI-II) across all genotypes. These reductions were less pronounced in GA_3-primed seedlings at 5-10% PEG, although the magnitude of the response varied among genotypes. Clear genotypic variation in vigor responses to osmotic stress was observed. MB3 showed greater numerical declines in GP and vigor indices as PEG concentration increased, whereas MB4 and MB5 tended to maintain comparatively higher TWC and vigor values, especially following GA_3 priming (Table 3).

Table 2a. Effects of PEG-induced osmotic stress on root and shoot growth traits of mung bean (*Vigna radiata* L.) genotypes under H_2O priming. Values are presented as mean ± SD (n = 7). Different letters within the same genotype across PEG concentrations indicate significant differences ($p < 0.05$) according to Tukey's HSD test.

H_2O							
Variety	**PEG (%)**	**RL (cm)**	**SL (cm)**	**RFW (g)**	**SFW (g)**	**RDW (g)**	**SDW (g)**
MB1	0	5.14 ± *1.52 a*	5.64 ± *0.70 b*	0.04 ± *0.004 a*	0.19 ± *0.023 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB1	5	3.51 ± *0.44 a*	3.11 ± *0.35 a*	0.06 ± *0.008 a*	0.18 ± *0.015 a*	0.01 ± *0.000 a*	0.03 ± *0.004 a*
MB1	10	4.93 ± *0.67 a*	5.64 ± *0.82 b*	0.07 ± *0.004 a*	0.20 ± *0.019 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB1	20	3.29 ± *0.36 a*	1.00 ± *0.00 a*	0.04 ± *0.004 a*	0.13 ± *0.008 a*	0.01 ± *0.000 a*	0.06 ± *0.004 a*
MB2	0	4.29 ± *0.88 a*	5.43 ± *0.48 b*	0.11 ± *0.011 b*	0.27 ± *0.026 a*	0.01 ± *0.000 a*	0.04 ± *0.008 a*
MB2	5	6.07 ± *0.98 b*	4.07 ± *0.56 b*	0.07 ± *0.008 a*	0.19 ± *0.015 a*	0.02 ± *0.015 a*	0.04 ± *0.004 a*
MB2	10	5.07 ± *0.65 a*	2.71 ± *0.43 a*	0.08 ± *0.004 a*	0.17 ± *0.015 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB2	20	3.21 ± *0.69 a*	1.00 ± *0.02 a*	0.04 ± *0.004 a*	0.15 ± *0.011 a*	0.01 ± *0.000 a*	0.04 ± *0.000 a*
MB3	0	3.74 ± *0.91 a*	4.00 ± *0.58 b*	0.14 ± *0.019 d*	0.31 ± *0.023 c*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB3	5	1.57 ± *0.20 a*	2.14 ± *0.26 a*	0.07 ± *0.008 a*	0.29 ± *0.038 c*	0.01 ± *0.000 a*	0.11 ± *0.042 a*
MB3	10	1.57 ± *0.20 a*	1.43 ± *0.20 a*	0.07 ± *0.000 a*	0.27 ± *0.004 a*	0.01 ± *0.000 a*	0.14 ± *0.087 b*
MB3	20	1.71 ± *0.19 a*	1.00 ± *0.00 a*	0.02 ± *0.004 a*	0.17 ± *0.026 a*	0.00 ± *0.000 a*	0.07 ± *0.004 a*
MB4	0	5.07 ± *0.97 a*	4.71 ± *0.42 b*	0.07 ± *0.011 a*	0.19 ± *0.030 a*	0.01 ± *0.000 a*	0.03 ± *0.004 a*
MB4	5	4.43 ± *0.92 a*	4.29 ± *0.64 b*	0.07 ± *0.008 a*	0.16 ± *0.008 a*	0.01 ± *0.000 a*	0.03 ± *0.004 a*
MB4	10	4.29 ± *0.68 a*	2.71 ± *0.47 a*	0.06 ± *0.011 a*	0.12 ± *0.008 a*	0.01 ± *0.000 a*	0.03 ± *0.004 a*
MB4	20	1.29 ± *0.19 c*	1.00 ± *0.00 a*	0.01 ± *0.004 c*	0.09 ± *0.008 b*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB5	0	6.86 ± *1.03 b*	5.57 ± *0.37 b*	0.09 ± *0.015 b*	0.25 ± *0.019 a*	0.01 ± *0.000 a*	0.03 ± *0.004 a*
MB5	5	4.00 ± *0.76 a*	3.86 ± *0.40 b*	0.10 ± *0.015 b*	0.25 ± *0.015 a*	0.02 ± *0.011 a*	0.07 ± *0.008 a*
MB5	10	4.29 ± *0.60 a*	2.57 ± *0.20 a*	0.09 ± *0.008 b*	0.19 ± *0.011 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB5	20	2.29 ± *0.52 a*	1.00 ± *0.00 a*	0.03 ± *0.004 a*	0.08 ± *0.015 b*	0.01 ± *0.000 a*	0.08 ± *0.008 a*

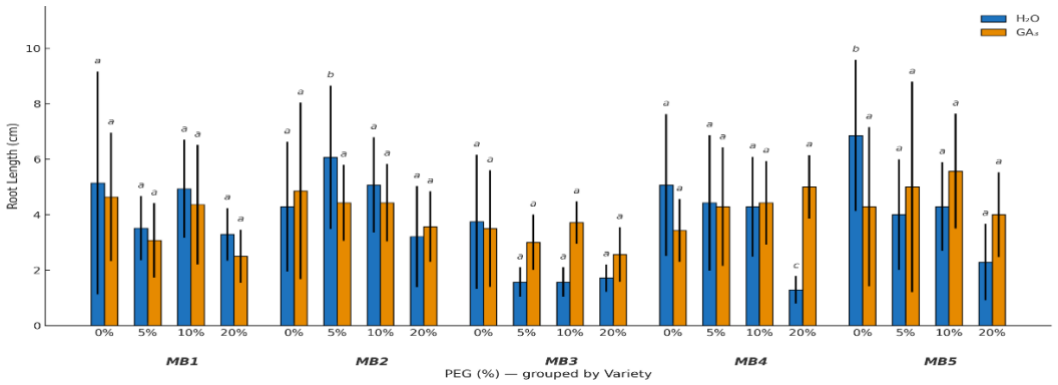
Table 2b. Effects of PEG-induced osmotic stress on root and shoot growth traits of mung bean (*Vigna radiata* L.) genotypes under GA_3 seed priming. Values are presented as mean ± SD (n = 7). Different letters within the same genotype across PEG concentrations indicate significant differences ($p < 0.05$) according to Tukey's HSD test.

GA_3							
Variety	**PEG (%)**	**RL (cm)**	**SL (cm)**	**RFW (g)**	**SFW (g)**	**RDW (g)**	**SDW (g)**
MB1	0	4.64 ± *0.88 a*	5.14 ± *0.80 b*	0.09 ± *0.015 b*	0.25 ± *0.026 a*	0.01 ± *0.000 a*	0.03 ± *0.004 a*
MB1	5	3.07 ± *0.51 a*	3.50 ± *0.36 b*	0.06 ± *0.008 a*	0.14 ± *0.015 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB1	10	4.36 ± *0.81 a*	4.21 ± *0.37 b*	0.10 ± *0.011 b*	0.21 ± *0.015 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB1	20	2.50 ± *0.36 a*	1.43 ± *0.20 a*	0.04 ± *0.008 a*	0.15 ± *0.015 a*	0.01 ± *0.000 a*	0.04 ± *0.000 a*
MB2	0	4.86 ± *1.20 a*	5.57 ± *0.87 b*	0.07 ± *0.011 a*	0.26 ± *0.030 a*	0.01 ± *0.000 a*	0.03 ± *0.004 a*
MB2	5	4.43 ± *0.52 a*	4.43 ± *0.54 b*	0.06 ± *0.008 a*	0.16 ± *0.015 a*	0.03 ± *0.015 a*	0.03 ± *0.004 a*
MB2	10	4.43 ± *0.53 a*	3.50 ± *0.25 b*	0.05 ± *0.004 a*	0.12 ± *0.008 a*	0.02 ± *0.011 a*	0.04 ± *0.004 a*
MB2	20	3.57 ± *0.48 a*	1.71 ± *0.19 a*	0.05 ± *0.026 a*	0.23 ± *0.113 a*	0.03 ± *0.015 b*	0.05 ± *0.004 a*
MB3	0	3.50 ± *0.79 a*	3.14 ± *0.34 a*	0.08 ± *0.008 a*	0.26 ± *0.045 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB3	5	3.00 ± *0.38 a*	3.43 ± *0.53 a*	0.09 ± *0.008 b*	0.35 ± *0.038 c*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB3	10	3.71 ± *0.29 a*	3.21 ± *0.31 a*	0.05 ± *0.008 a*	0.20 ± *0.030 a*	0.01 ± *0.000 a*	0.06 ± *0.000 a*
MB3	20	2.57 ± *0.37 a*	1.00 ± *0.00 a*	0.03 ± *0.004 a*	0.18 ± *0.015 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB4	0	3.43 ± *0.43 a*	5.00 ± *0.62 b*	0.06 ± *0.008 a*	0.22 ± *0.019 a*	0.01 ± *0.004 a*	0.03 ± *0.004 a*
MB4	5	4.29 ± *0.81a*	4.14 ± *0.63 b*	0.05 ± *0.008 a*	0.16 ± *0.011 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB4	10	4.43 ± *0.57 a*	3.57 ± *0.20 b*	0.05 ± *0.004 a*	0.17 ± *0.015 a*	0.01 ± *0.000 a*	0.05 ± *0.004 a*
MB4	20	5.00 ± *0.43 a*	2.43 ± *0.37 a*	0.04 ± *0.004 a*	0.14 ± *0.015 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB5	0	4.29 ± *1.08 a*	5.00 ± *0.31 b*	0.07 ± *0.011 a*	0.23 ± *0.026 a*	0.01 ± *0.000 a*	0.04 ± *0.004 a*
MB5	5	5.00 ± *1.43 a*	3.71 ± *0.64 b*	0.07 ± *0.008 a*	0.23 ± *0.015 a*	0.02 ± *0.000 a*	0.05 ± *0.008 a*
MB5	10	5.57 ± *0.78 a*	3.00 ± *0.38 a*	0.08 ± *0.015 b*	0.20 ± *0.023 a*	0.01 ± *0.000 a*	0.05 ± *0.004 a*
MB5	20	4.00 ± *0.58 a*	1.57 ± *0.20 a*	0.04 ± *0.004 a*	0.15 ± *0.011 a*	0.01 ± *0.000 a*	0.05 ± *0.004 a*

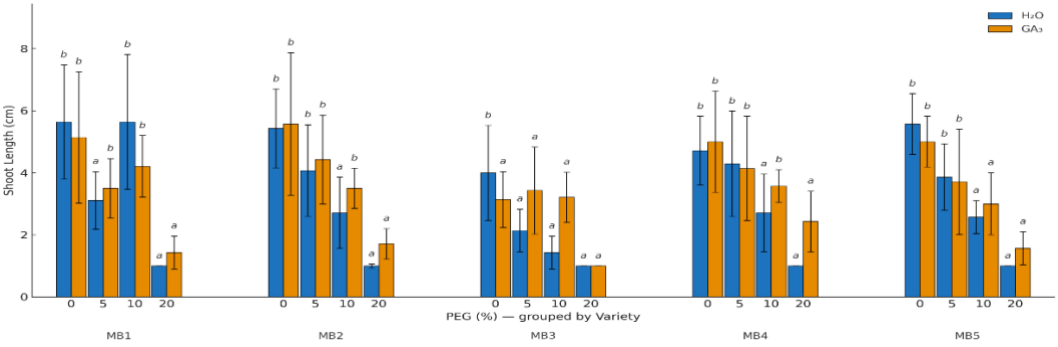
Table 3. Effects of gibberellic acid (GA_3) seed priming on germination percentage (GP), tissue water content (TWC), seedling vigor index I (SVI-I), and seedling vigor index II (SVI-II) of five mung bean (*Vigna radiata* L.) genotypes under PEG-induced osmotic stress. Values are presented as mean ± SD. Different letters indicate significant differences among treatments at $p < 0.05$, as determined by Tukey's HSD test.

Variety	Priming	PEG (%)	GP (%)	TWC (%)	SVI-I	SVI-II (g)
MB1	GA_3	0	100.00 ± *0.00 a*	88.10 ± 2.03 a	978.57 ± *131.77 a*	3.711 ± *0.310 b*
MB1	GA_3	5	100.00 ± *0.00 a*	75.15 ± 2.04 b	657.14 ± *77.48 a*	4.774 ± *0.203 a*
MB1	GA_3	10	100.00 ± *0.00 a*	82.35 ± 1.72 a	857.14 ± *100.25 a*	5.366 ± *0.208 a*
MB1	GA_3	20	100.00 ± *0.00 a*	71.75 ± 2.29 b	392.86 ± *44.22 b*	4.993 ± *0.085 a*
MB1	H_2O	0	100.00 ± *0.00 a*	80.50 ± 2.46 a	1078.57 ± *175.21 a*	4.150 ± *0.478 a*
MB1	H_2O	5	71.43 ± *0.00 d*	81.93 ± *2.11 a*	473.48 ± *55.26 b*	3.081 ± *0.291 b*
MB1	H_2O	10	85.71 ± *0.00 b*	82.20 ± *1.76 a*	842.81 ± *85.47 a*	3.768 ± *0.229 b*
MB1	H_2O	20	85.71 ± *0.00 b*	63.00 ± *3.01 c*	367.33 ± *30.81 b*	5.476 ± *0.399 a*
MB2	GA_3	0	100.00 ± *0.00 a*	84.19 ± *2.50 a*	1133.33 ± *180.12 a*	4.487 ± *0.093 a*
MB2	GA_3	5	100.00 ± *0.00 a*	80.46 ± *2.66 a*	970.00 ± *84.56 a*	4.388 ± *0.340 b*
MB2	GA_3	10	100.00 ± *0.00 a*	68.69 ± *1.57 b*	808.33 ± *80.02 a*	5.073 ± *0.246 a*
MB2	GA_3	20	85.71 ± *0.00 b*	57.91 ± *3.21 c*	497.12 ± *32.07 b*	4.992 ± *0.320 a*
MB2	H_2O	0	100.00 ± *0.00 a*	89.45 ± *1.25 a*	991.67 ± *120.01 a*	3.655 ± *0.210 b*
MB2	H_2O	5	100.00 ± *0.00 a*	82.17 ± *2.39 a*	1083.33 ± *148.70 a*	4.798 ± *0.400 a*
MB2	H_2O	10	100.00 ± *0.00a*	74.97 ± *3.89 b*	778.57 ± *85.12 a*	5.696 ± *0.360 a*
MB2	H_2O	20	71.43 ± *0.00 d*	71.96 ± *1.89 b*	301.03 ± *49.47 b*	3.626 ± *0.110 b*
MB3	GA_3	0	85.71 ± *0.00 b*	84.32 ± *3.30 a*	569.36 ± *79.74 a*	3.908 ± *0.447 b*
MB3	GA_3	5	85.71 ± *0.00 b*	86.47 ± *1.80 a*	550.99 ± *72.09 a*	4.612 ± *0.234 a*
MB3	GA_3	10	85.71 ± *0.00 b*	75.21 ± *1.44 b*	607.11 ± *54.68 a*	5.944 ± *0.164 a*
MB3	GA_3	20	85.71 ± *0.00 b*	73.77 ± *3.16 b*	306.11 ± *31.61 b*	4.551 ± *0.237 a*
MB3	H_2O	0	71.43 ± *0.00 d*	88.77 ± *0.99 a*	553.07 ± *102.67 a*	3.487 ± *0.172 b*
MB3	H_2O	5	57.14 ± *0.00 e*	80.43 ± *1.73 a*	209.51 ± *24.09 b*	4.472 ± *0.927 a*
MB3	H_2O	10	42.86 ± *0.00 f*	83.01 ± *0.93 a*	135.72 ± *13.17 b*	2.484 ± *0.138 b*
MB3	H_2O	20	42.86 ± *0.00 f*	63.56 ± *3.37 c*	114.29 ± *9.04 b*	3.303 ± *0.202 b*
MB4	GA_3	0	100.00 ± *0.00 a*	86.40 ± *1.96 a*	842.86 ± *92.21 a*	3.654 ± *0.337 b*
MB4	GA_3	5	100.00 ± *0.00 a*	77.84 ± *1.22 a*	842.86 ± *132.48 a*	4.719 ± *0.193 a*
MB4	GA_3	10	85.71 ± *0.00 b*	73.72 ± *1.87 b*	685.68 ± *59.15 a*	4.894 ± *0.200 a*
MB4	GA_3	20	85.71 ± *0.00 b*	72.44 ± *1.96 b*	636.70 ± *61.63 a*	4.158 ± *0.333 a*
MB4	H_2O	0	100.00 ± *0.00 a*	84.43 ± *1.95 a*	983.33 ± *135.20 a*	3.223 ± *0.123 b*
MB4	H_2O	5	100.00 ± *0.00 a*	78.32 ± *2.26 a*	871.43 ± *149.15 a*	4.814 ± *0.291 a*
MB4	H_2O	10	100.00 ± *0.00 a*	77.18 ± *2.59 a*	700.00 ± *113.39 a*	3.853 ± *0.256 a*
MB4	H_2O	20	71.43 ± *0.00 d*	56.30 ± *5.21 c*	163.27 ± *13.17 b*	3.026 ± *0.262 b*
MB5	GA_3	0	100.00 ± *0.00 a*	81.28 ± *4.32 a*	928.57 ± *134.01 a*	4.683 ± *0.397 b*
MB5	GA_3	5	85.71 ± *0.00 b*	80.12 ± *0.43 a*	514.26 ± *34.99 b*	4.791 ± *0.054 b*
MB5	GA_3	10	85.71 ± *0.00 b*	75.44 ± *4.20 a*	734.66 ± *76.79 b*	5.286 ± *0.328 b*
MB5	GA_3	20	85.71 ± *0.00 b*	70.65 ± *1.18 a*	445.69 ± *68.57 b*	4.543 ± *0.137 b*
MB5	H_2O	0	100.00 ± *0.00 a*	87.80 ± *0.67 a*	1242.86 ± *130.67 a*	4.047 ± *0.304 b*
MB5	H_2O	5	85.71 ± *0.00 b*	68.89 ± *5.90 b*	642.82 ± *90.57 b*	8.150 ± *1.355 a*
MB5	H_2O	10	85.71 ± *0.00 b*	81.26 ± *1.27 a*	587.73 ± *65.94 b*	4.456 ± *0.253 b*
MB5	H_2O	20	42.86 ± *0.00 f*	23.84 ± *7.40 c*	142.87 ± *26.34 c*	3.557 ± *0.220 b*

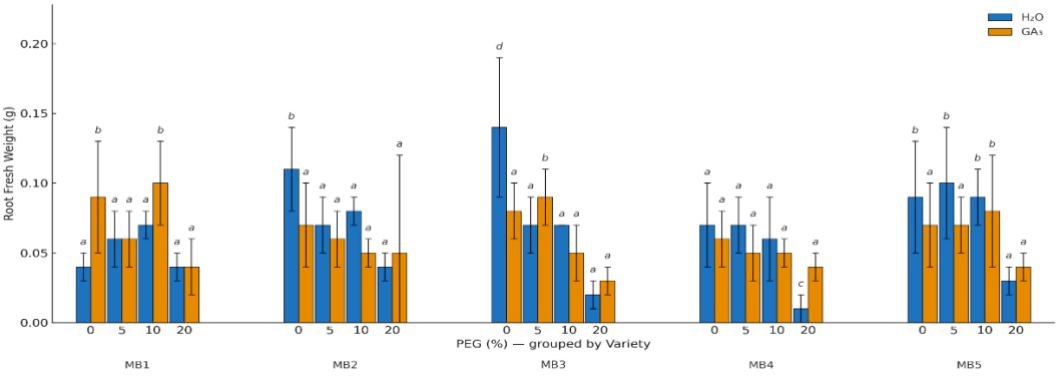
(a)


H₂O
GA₃
Root Length (cm)
0%
5%
10%
20%
MB1
MB2
MB3
MB4
MB5
PEG (%) — grouped by Variety

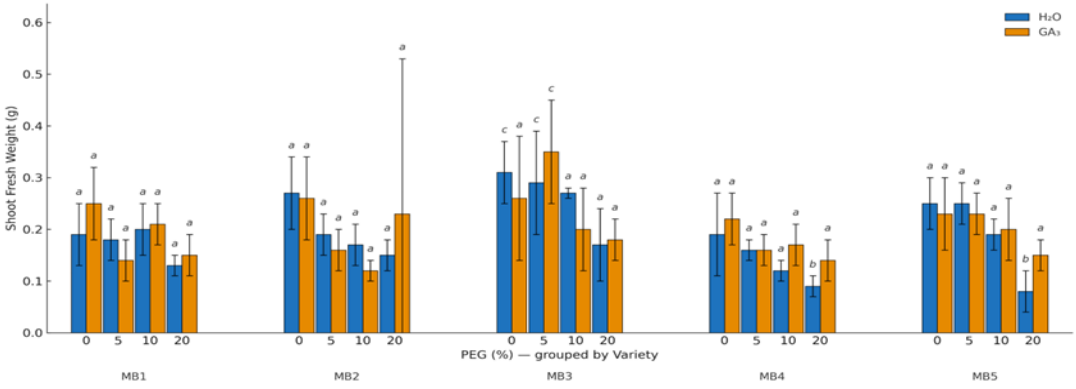
(b)


H₂O
GA₃
Shoot Length (cm)
MB1
MB2
MB3
MB4
MB5
PEG (%) — grouped by Variety

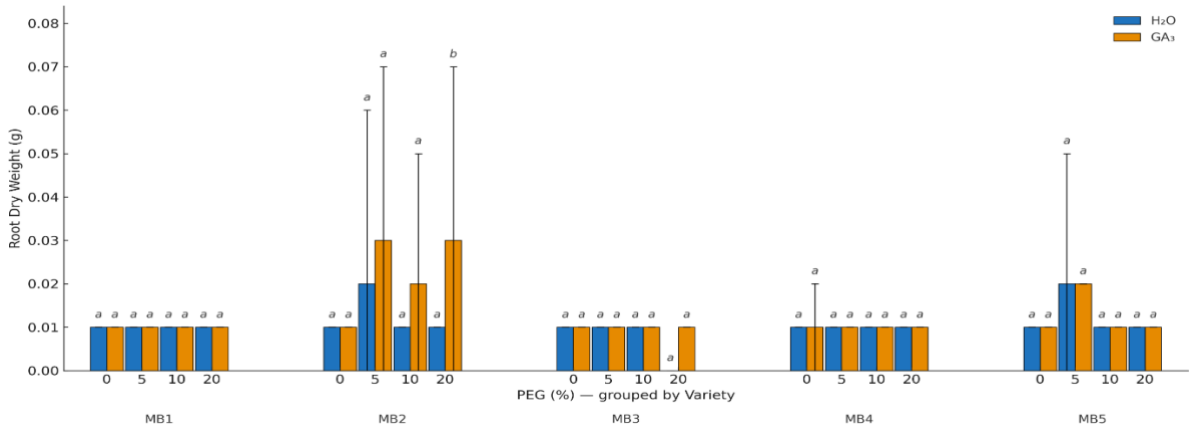
(c)


H₂O
GA₃
Root Fresh Weight (g)
MB1
MB2
MB3
MB4
MB5
PEG (%) — grouped by Variety

(d)


H₂O
GA₃
Shoot Fresh Weight (g)
MB1
MB2
MB3
MB4
MB5
PEG (%) — grouped by Variety

(e)



(f)

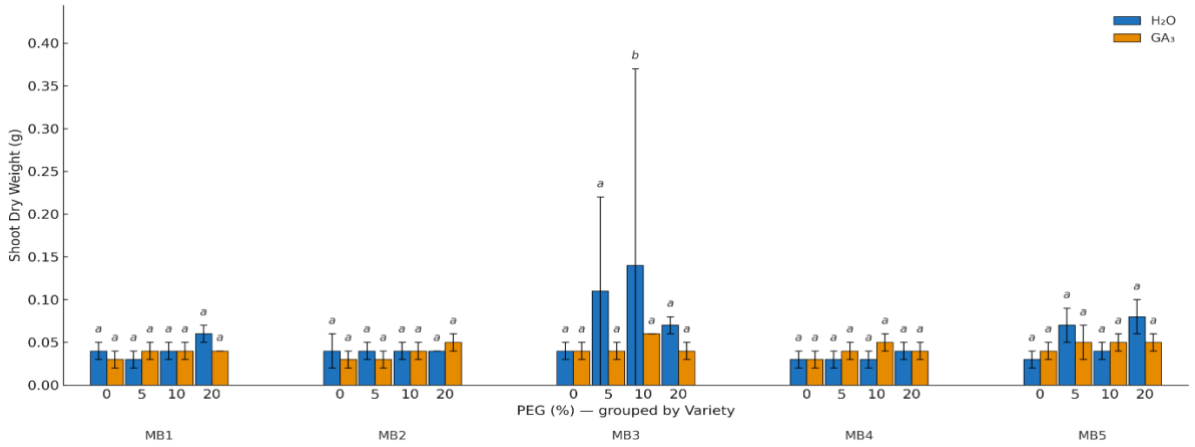


Figure 1. Effects of GA_3 seed priming and PEG-induced osmotic stress on early growth and biomass accumulation in five mung bean (*Vigna radiata* L.) genotypes. (a) Root length (RL), (b) Shoot length (SL), (c) Root fresh weight (RFW), (d) Shoot fresh weight (SFW), (e) Root dry weight (RDW), and (f) Shoot dry weight (SDW). Bars represent mean ± SD (n = 7). Different lowercase letters above bars indicate significant differences among treatments according to Tukey's HSD test at $p < 0.05$.

DISCUSSION

Osmotic stress induced by polyethylene glycol (PEG 6000) is known to constrain seed germination and early seedling development in mung beans. In the present study, the progressive reduction in root and shoot length, together with decreased biomass accumulation at increasing PEG concentrations, reflects an inhibitory effect of osmotic stress during early developmental stages. The differences among genotypes exposed to the same PEG concentrations, previously reported for legumes and other crops (Munns and Gilliham, 2015), also highlight the importance of genetic background in determining tolerance to osmotic stress. Seed priming with gibberellic acid (GA_3) has been reported to influence early seedling growth under water-limited conditions by stimulating α-amylase activity, enhancing reserve mobilization, and promoting cell elongation (Iqbal and Ashraf, 2013). In the present study, GA_3 priming was associated with improved root and shoot growth in certain genotypes under PEG-induced osmotic stress, particularly at 5–10% PEG; however, these responses were not consistent across all genotypes or stress levels. Similar genotype-dependent responses to GA_3 priming under drought stress have been reported previously in mung bean and other crops (Abdel et al., 2011), suggesting that the effectiveness of GA_3 application depends strongly on both genetic background and stress intensity. GA_3-induced changes in root growth may reflect enhanced water-uptake capacity under osmotic stress. This response has been associated with improved osmotic adjustment and osmolyte accumulation, which contribute to cell hydration (Afzal et al., 2006; Meramanbhai et al., 2019). Although biomass generally declined with increasing PEG concentration, GA_3 priming was associated with slight numerical increases in root dry biomass in some genotypes. However, this response was diminished at the highest PEG level, suggesting that severe osmotic stress may exceed the capacity of hormonal regulation to sustain growth. Dry weight parameters were less sensitive to PEG-induced stress than fresh weight traits, reflecting the greater susceptibility of water-related traits to osmotic restriction. The relative stability of dry matter accumulation under stress conditions may indicate adaptive responses, such as osmotic adjustment and accumulation of solutes, including proline and soluble sugars, which help preserve cell

integrity and turgor (Hasanuzzaman et al., 2017; Jisha and Puthur, 2016). At 5-10% PEG, GA_3 priming was associated with numerical increases in root and shoot dry weight in certain genotypes, suggesting improved metabolic efficiency and reserve mobilization. Similar genotype- and stress-dependent responses to GA_3 priming have been reported in soybean and chickpea (Salehi-Lisar and Bakhshayeshan-Agdam, 2016; Meramanbhai et al., 2019). Higher PEG-6000 concentrations resulted in marked reductions in germination percentage, tissue water content, and seed emergence index, indicating that osmotic stress is detrimental to germination. PEG 6000 is known to restrict water uptake, thereby limiting root hair emergence and early seedling development (Islam et al., 2024). Among the analyzed genotypes, MB3 showed greater sensitivity to osmotic stress, with pronounced numerical declines in the parameters described above. In contrast, MB4 and MB5 tended to maintain relatively higher water content and vigor indices, particularly following GA_3 application. These responses may be related to earlier metabolic activation during germination and more effective mobilization of reserve materials. The role of GA_3 in stimulating α-amylase activity has been suggested to contribute to improved energy availability, cell elongation, and water relations under stress conditions.

Overall, the response to GA_3 priming was strongly genotype dependent. MB4 and MB5 exhibited greater responsiveness to GA_3 treatment than the other genotypes, showing relatively improved performance under 5–10% PEG-induced osmotic stress. These findings indicate that the effectiveness of GA_3 priming cannot be generalized across genotypes and is closely linked to each genotype's inherent adaptive capacity, highlighting the importance of genotype-specific priming strategies to improve early seedling performance under water-limited conditions.

CONCLUSION

The effect of PEG-induced osmotic stress on the early growth of mung bean seedlings was evident, as reflected by progressive reductions in germination percentage, water content, and vigor with increasing PEG concentration. Decreases in root and shoot length, as well as in fresh and dry weight, indicate that water uptake and metabolic activity were reduced under osmotic stress. However, the degree of these responses differed among genotypes, indicating variation in stress sensitivity. GA_3 priming partially mitigated these inhibitory effects, especially at PEG concentrations of 5-10%. Numerical improvements in germination and water status, root elongation, and dry biomass were observed in GA_3-primed seedlings, although these responses were genotype dependent and not consistent across all stress levels. Clear genotypic differences were observed, indicating that genetic background strongly influences both osmotic stress tolerance and responsiveness to GA_3 priming. In conclusion, GA_3 seed priming may be a practical, low-cost approach to enhance early seedling performance under osmotic stress, particularly in genotypes with inherent adaptive capacity. Further studies integrating biochemical and molecular markers are required to better elucidate the mechanisms underlying genotype-specific responses and to optimize priming strategies for water-limited environments.

Conflict of Interest

The author declares that there is no conflict of interest.

Author Contribution

The author solely conceived, designed, and conducted the study, analyzed the data, and wrote the manuscript.

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