

Comparative effects of seed priming approaches on germination, growth, and yield of mungbean

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Abstract

Mungbean production in Bangladesh is seriously constrained by poor germination, weak seedling establishment, delayed emergence, and a high susceptibility to early-stage stress, resulting in lower yield potential. To overcome these limitations, a study was conducted from February to June 2023 at the Department of Agronomy, Hajee Mohammad Danesh Science and Technology University, Bangladesh. This study aimed to evaluate the effects of various seed priming techniques on germination, growth and yield of mungbean. Three varieties BARI Mung-6, BARI Mung-7, and BARI Mung-8 were tested with five priming methods: control (without primed), hydropriming, halopriming (2% NaCl), and hormonal priming using gibberellic acid (GA₃) at 100 and 200 ppm. The germination test followed a completely randomized design using petri dish and plastic pots, while field trials used a randomized complete block design with three replications. GA₃ at 200 ppm significantly enhanced germination percentage, germination index, plant height, branch number, biomass, seedling vigor, and yield components such as pods plant⁻¹, pod length, seeds pod⁻¹, 1,000-seed weight, and overall yield. The highest yield (565.67 kg ha⁻¹) was observed in BARI Mung-7 primed with GA₃ at 200 ppm. In contrast, 2% NaCl priming produced the lowest performance, with BARI Mung-6 yielding only 33.33 kg ha⁻¹. The results suggest that BARI Mung-7, when primed with GA₃ at 200 ppm for 24 hours, is optimal for improving mungbean production under the studied conditions.

Keywords: Seed priming, Gibberellic acid, Seed germination, Mungbean, PCA

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Introduction

Seed priming, a pre-sowing intervention that comprises regulated hydration and dehydration without radicle protrusion, is now recognized as an efficient approach to improve seed germination, seedling vigor, plant establishment, crop yield, and abiotic stress tolerance by activating metabolic processes (Fregonezi et al., 2024).

Mungbean, *Vigna radiata* L., an important pulse crop, known as green gram, has been a food staple for almost 3,500 years, demonstrating its global significance (Uppalwar et al., 2021). It offers a high concentration of protein, dietary fiber, and bioactive phytochemicals especially polyphenols and oligosaccharides, which contribute to its antioxidant, antimicrobial, anti-inflammatory, and lipid-regulating properties (Sehrawat et al., 2020; Kishore and Sharma, 2023; Karami et al., 2025).

Despite its nutritional and economic importance, mungbean cultivation in Bangladesh meets challenges due to abiotic stress and inefficient techniques for farming. The country's pulse production is 0.65 million tons, much lower than the 2.7 million tons necessary, resulting in an 80% shortage (Rahman and Ali, 2007). Pulses are currently growing at 0.356 million hectares, with mungbean taking up 0.00453 million hectares and yielding only 0.046 million tons which is decreasing rapidly (BBS, 2023). The low yield is due to factors impacting seed germination, seedling establishment, optimum plant density, susceptibility to early-stage stress, growth, and total production (Douglas et al., 2020).

To overcome these limitations, a multitude of seed priming strategies have been applied in agriculture, including hydropriming, osmopriming with salts (e.g., KNO_3 , K_3PO_4 , NaCl), (Sher et al., 2019; Thapa et al., 2020) and the use of plant growth regulators such as gibberellic acid (GA_3) (Tombegavani et al., 2020; Mohammed and Baldwin, 2023). The application of GA_3 improves germination and growth by increasing enzyme activity, principally amylase, which mobilizes starch in cotyledons (Siega et al., 2025). GA_3 -primed seeds have improved root development, higher tolerance to abiotic stresses such as heavy metal toxicity (Bhat et al., 2023), low humidity and temperature (Xia et al., 2023), salinity (Tsegay and Andargie, 2018), and water deficit, as well as earlier flowering and improved yield (Du et al., 2022). Seed priming utilizing NaCl has been shown to increase crop growth and yield against abiotic and biotic stress

while treated during the time of seed sowing (Farooq et al., 2019), and equivalent results have been reported in different crops (Khan et al., 2022; Jatana et al., 2024).

In order to improve sustainable mungbean production, this study intends to evaluate the effects of various priming approaches on seed germination, seedling growth, field performance, and overall production.

Material and Methods

Experimental location

From February to June 2023, the study was laid out in the Agronomy Laboratory and Experimental Field at Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, Bangladesh. The experimental site (Agronomic Research Field, HSTU) is located at 25.56°N latitude, 88.41°E longitude, and 37.5 meters above mean sea level. The soil in the research region belongs to the Old Himalayan Piedmont Plain, classed under Agro-Ecological Zone 1 (AEZ-1).

Soil characteristics

The soil underlying this experiment was collected from the HSTU farm at depths ranging from 0 to 15 cm. The gathered soil samples were air-dried and sanitized. The soil's properties were studied at Dinajpur's Soil Resource Development Institute (SRDI). The soil type is a non-calcareous dark grey floodplain with a sandy loam texture, and the elevation is 37 meters above sea level. The physical investigation found 58% sand, 28% silt, and 14% clay. The chemical parameters included a pH of 5.41, organic matter content of 1.48%, organic carbon 0.72%, total nitrogen 0.08%, available phosphorus 11.20 ppm, and exchangeable calcium (2.48 meq) and magnesium (2.29 meq).

Climatic conditions

The experimental site has a subtropical environment with seasonal changes in rainfall. Heavy rainfall occurs throughout the Kharif season (March to mid-October), whereas the Rabi season (mid-October to February) receives comparatively little precipitation. Figure 1 shows major climatic parameters reported from January to July 2023, such as monthly mean maximum and minimum temperatures (°C), rainfall (mm), and relative humidity (%).

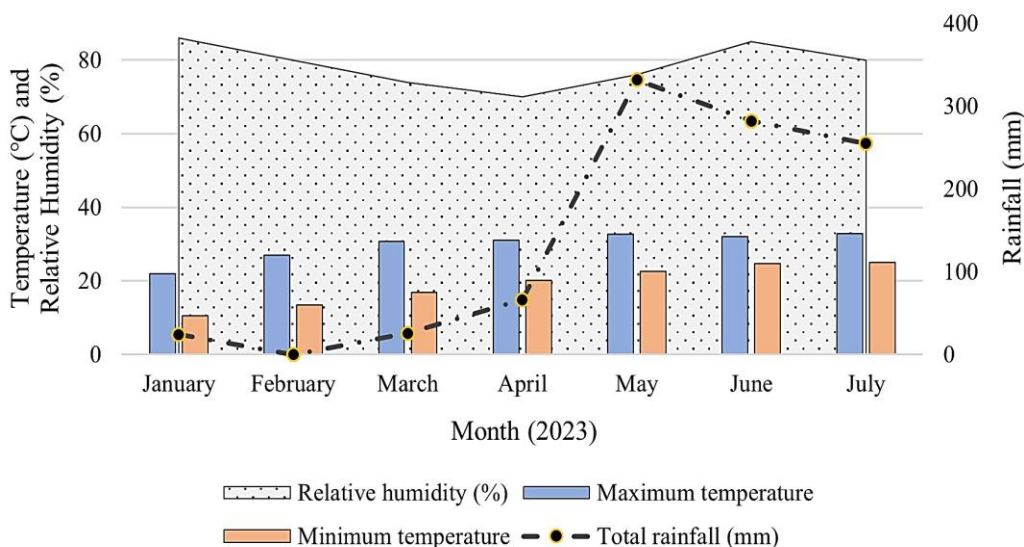


Figure-1. Maximum and minimum temperature, relative humidity and rainfall of the research site from January to July 2023.

Experimental design

The experimental treatments included two factors: Factor A (Priming approach) consisted of no priming (control) (T_1), hydro priming (T_2), halo priming with 2% NaCl (T_3), and hormonal priming with 100 ppm GA_3 (T_4) and 200 ppm GA_3 (T_5). Factor B (Variety) contained three mungbean varieties: BARI Mung-6 (V_1), BARI Mung-7 (V_2), and BARI Mung-8 (V_3). A laboratory experiment on seed germination was done employing a completely randomized design, and a field experiment was arranged in a randomized complete block design with 3 replications. Before priming, homogenous mungbean seeds were thoroughly rinsed with distilled water after being surface sterilized for two minutes in a 0.01M $HgCl_2$ solution. Each variety's seeds were allocated to the appropriate priming treatment: distilled water was used for hydro priming (T_2), a 2% NaCl solution was used for halo priming (T_3), 100 ppm and 200 ppm GA_3 solutions were used for hormonal priming (T_4 and T_5). After soaking for a full day at room temperature, the seeds were allowed to air dry. Plastic pots of 7.5 cm in diameter and 11.3 cm in height were utilized for germination, and they were filled with sandy soil. The seeds were kept at room temperature after being watered with a disinfectant chemical solution, and 10 seeds variety⁻¹ were put in each glass. The necessary amount of water was irrigated every day. The field experiment involved 45 plots measuring 10 m² each.

After prepping the field, the priming mungbean seeds were carefully sown in it.

Intercultural operations

Thinning was done to maintain an optimal plant population. Irrigation was administered as needed. Weed severity increased throughout the pre-flowering period, necessitating hand weeding. A pod borer infestation developed at maturity, damaging seeds by burrowing into pods; Karate was used for pest control, and a fungicide was used to avoid fungal diseases. Harvesting was done in three stages; at the time, 90% of the pods had gone from deep brown to black.

Data collection

The data collection technique included recording germination characteristics and field experiment conditions. Germination percentage (GP) is the ratio of germinated seeds to the total seeds set for germination and was measured by the following equation:

$$GP = \frac{\text{No. of germinated seeds}}{\text{Total seeds set for germination}} \times 100$$

The germination index (GI) was determined by employing the formula:

$$GI = \sum \frac{Gt}{Dt}$$

where Gt denotes germinated seeds on day t, and Dt indicates the corresponding time in days. The seedling vigor index (VI) was calculated as:

$$VI = GI \times S$$

where S represents plant dry weight. A meter scale was used to measure the height, shoot, and root length of the seedlings. The fresh weights of the shoots and roots were recorded using a digital scale, and their dry weights were determined after 72 hours of oven drying at 80°C. The field experiment measured plant height at the final harvest as well as 20, 40, and 60 days after sowing (DAS). The number of branches plant⁻¹, the fresh and dry weights of the shoots and roots, and yield-contributing variables such as the number of pods plant⁻¹, pod length, number of seeds pod⁻¹, and 1,000-seeds weight were all recorded. After drying the harvested seeds to 14% moisture content, the seed yield (kg ha⁻¹) was estimated.

Statistical analysis

The data documented from the investigations were analyzed using STATISTIX 10 Two-way ANOVA, with significant differences between means assessed by the LSD test at a 5% significance level for pairwise comparison. Graphs, PCA biplots, and dendrogram

cluster analyses were generated with MS Excel and Origin Pro.

Results

Effect on seed germination of mungbean

Germination percentage and germination Index

The germination percentage of mungbean seeds differed greatly depending on variety and seed priming combinations. V₁T₅ had the most prominent germination percentage (96.66%), surpassing the majority of treatments. This was followed by V₁T₂, V₁T₄, and V₃T₅, all with statistically comparable values of 93.33%. V₃T₃ showed the lowest germination percentage (63.33%), which was significantly lower (Figure 2).

Figure 2 illustrates that significant differences were seen in the germination index between the various treatments. Priming treatments increased the germination index in V₁, as evidenced by the maximum germination index (22.16) in V₁T₅, which was closely followed by V₁T₂ (20.58) and V₁T₄ (20.36). On the other side, V₃T₃ exhibited the minimum germination index (9.82), which was considerably lower than that of any other treatment (Figure 3).

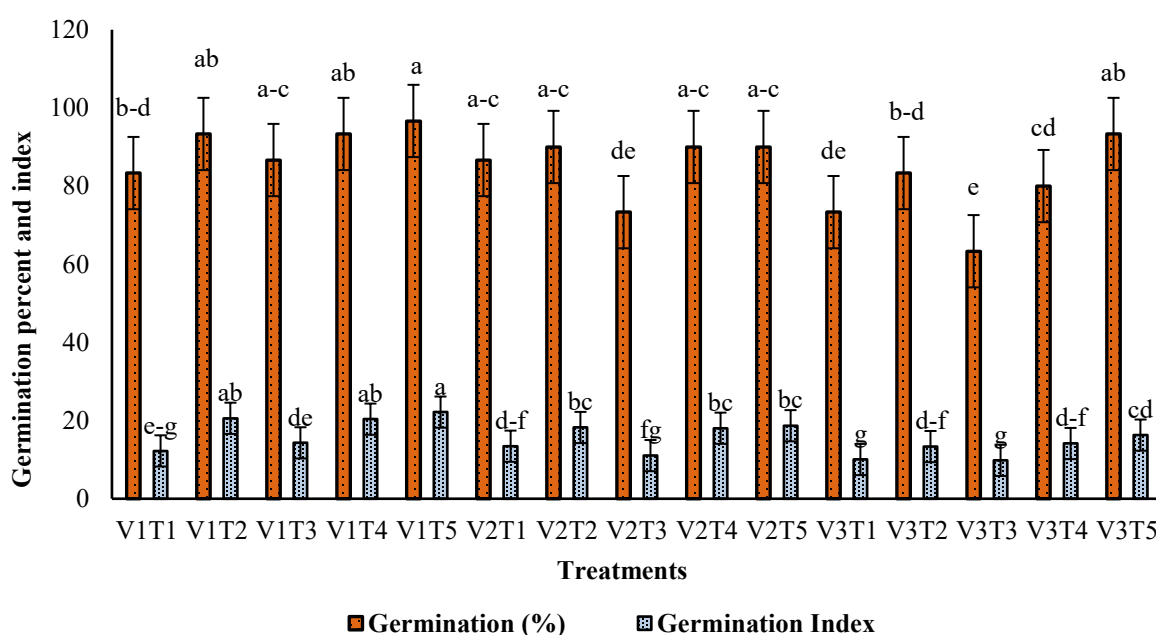
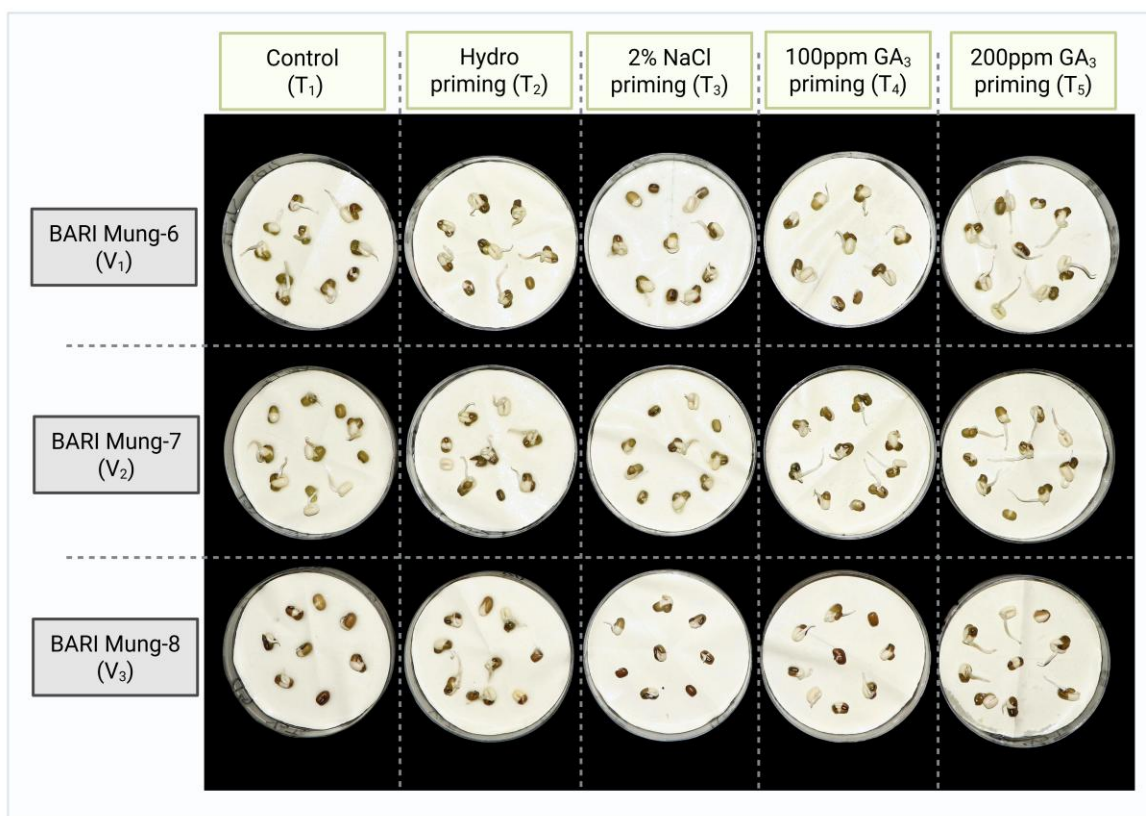


Figure-2. Expression of germination percentage and germination Index across the treatment combinations.**Figure-3.** Visible responses of seed germination according to specific priming were observed among multiple mungbeans. Seeds were grown on moistened filter paper in petri dishes under regulated laboratory conditions. Visual differences in germination appear, demonstrating the impact of priming tactics on seed vigor and emergence.

Seedling height, shoot and root length

The combined effects of mungbean variety and seed priming approaches on seedling height, including shoot and root length, are depicted in Figure 4. Significant variation was observed among treatments. The tallest seedlings (22.26 cm) were recorded in V₂T₅, followed by V₂T₄ (20.56 cm) and V₁T₂ (18.88 cm), whereas V₃T₃ produced the shortest seedlings (8.83 cm). Shoot length varied greatly, with V₃T₃ demonstrating the lowest length (5.21 cm) and the longest (12.70 cm). The length of the roots also differed substantially; V₂T₅ had the longest roots (9.56 cm), with V₂T₄ ranking in close (9.30 cm), and V₃T₃ had the shortest (3.61 cm). Overall, V₂T₅

consistently demonstrated superior seedling growth, while V₃T₃ was the least effective (Figure 5).

Seedling vigor

Seed vigor is a significant indicator in determining seed priming efficacy since it directly affects germination rate, uniformity, and seedling development. High-vigor seeds respond more effectively to priming treatments, resulting in better seedling establishment and field performance. The present study demonstrated significant variation in seedling vigor within treatments (Figure 6). V₂T₅ provided the maximum vigor index (15.57), followed by V₃T₅ (10.24) and V₂T₂ (10.09). The lowest vigor index was found in V₃T₃ (2.86).

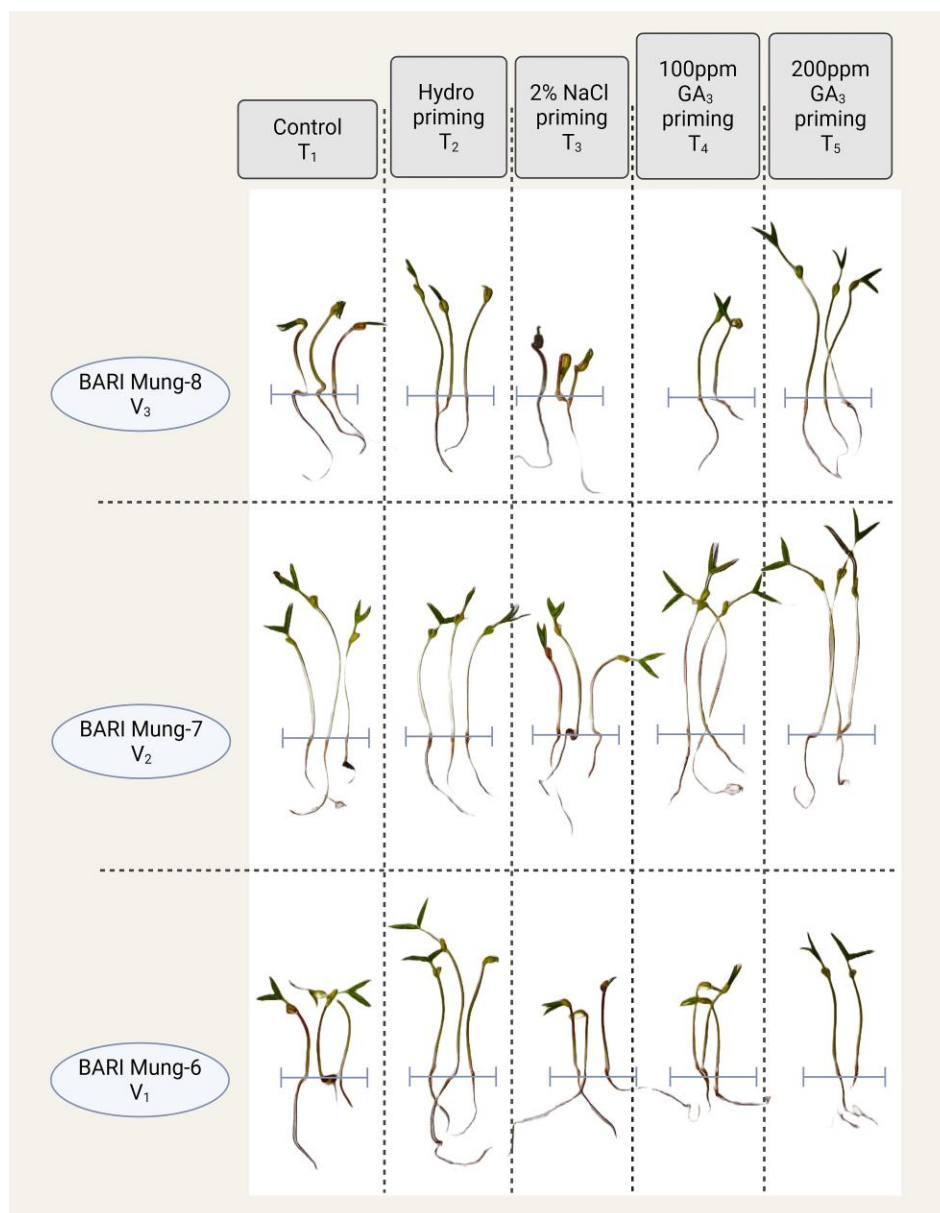


Figure-4. Visual comparison of mungbean seedling growth under different priming treatments. Representing seedlings from various varieties and priming combinations, showing clear differences in shoot vigor and root development.

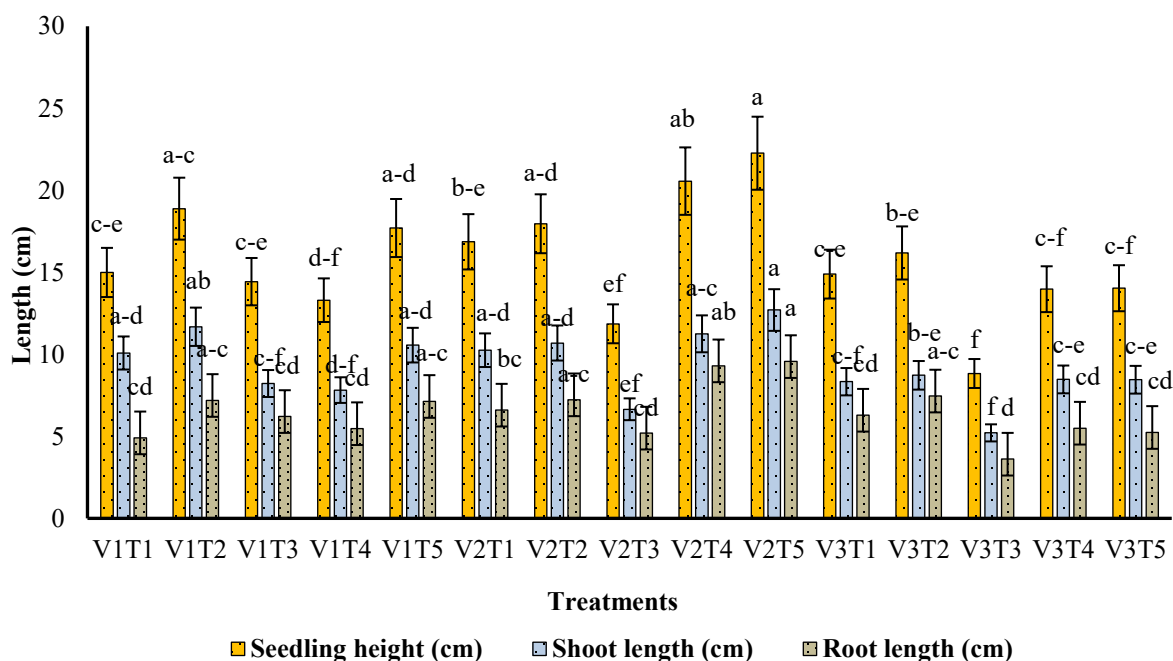


Figure-5. Expression of seedling height, shoot length, and root length among the treatment combinations.

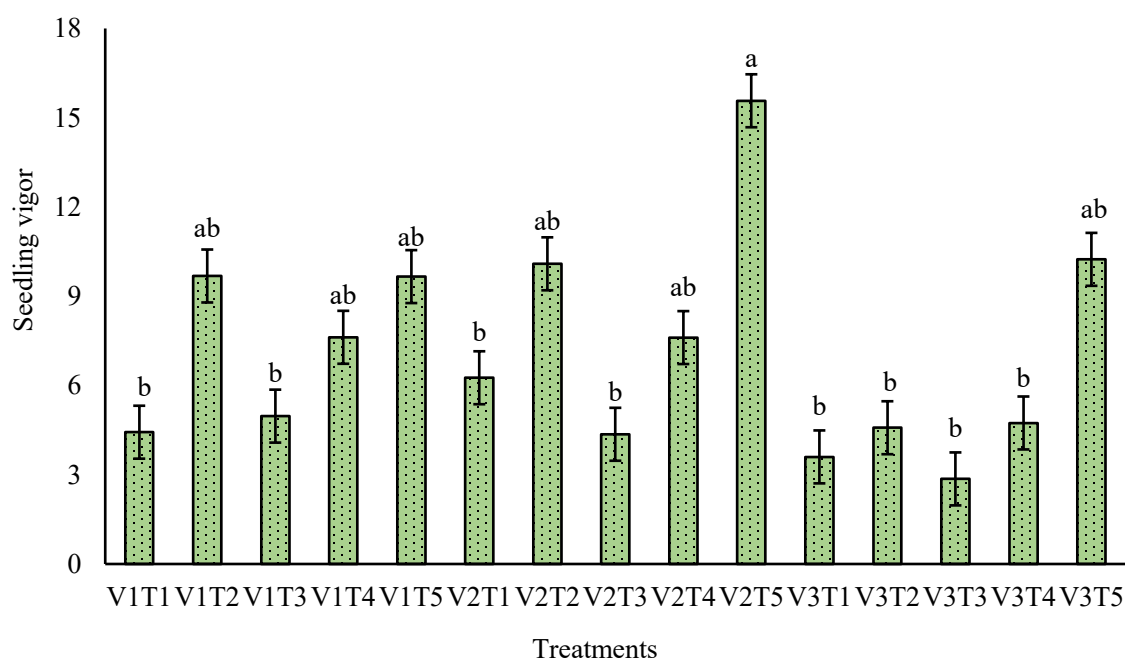


Figure-6. Expression of seedling vigor among the treatment combinations.

Shoot fresh and dry weight

Mungbean seedlings' shoot fresh weight varied greatly depending on the type and seed priming combination. V₂T₅ demonstrated the most shoot fresh weight (1.81 g), followed by V₂T₂ (1.79 g) and V₂T₄ (1.70 g), although there was no discernible difference

between them. V₃T₃ had the lowest shoot fresh weight (0.95 g), significantly lower than any other. There were notable variations in shoot dry weight among the various treatments. V₃T₃ possessed the lowest value (0.17 g), while V₂T₅ had the highest (0.37 g), followed by V₂T₂ (0.31 g) (Table 1).

Root fresh and dry weight

Table 1 also reveals that the root fresh weight of mungbean seedlings further varied significantly among treatment combinations. V₂T₅ recorded the greatest root fresh weight (1.64 g), followed by V₂T₂ (1.56 g). V₃T₃ showed the minimum root fresh weight

(0.64 g), compared to other treatments. V₂T₅ possessed the maximum root dry weight at 0.25 g, followed by V₂T₂ (0.24 g). The lowest root dry weight (0.12 g) was found in V₃T₃, followed by (0.13 g) V₃T₅ and V₁T₃.

Table-1. Root fresh and dry weight, shoot fresh and dry weight across the treatment combinations.

Treatment combinations	Root fresh weight (g)	Shoot fresh weight (g)	Root dry weight (g)	Shoot dry weight (g)
V ₁ T ₁	0.96 ^{b-d}	1.44 ^{ab}	0.15 ^{cd}	0.20 ^b
V ₁ T ₂	1.22 ^{a-d}	1.69 ^a	0.18 ^{a-d}	0.28 ^b
V ₁ T ₃	0.86 ^{cd}	1.45 ^{ab}	0.13 ^{cd}	0.21 ^b
V ₁ T ₄	0.92 ^{b-d}	1.25 ^{ab}	0.16 ^{cd}	0.21 ^b
V ₁ T ₅	1.11 ^{a-d}	1.58 ^a	0.18 ^{a-d}	0.25 ^b
V ₂ T ₁	1.46 ^{a-c}	1.67 ^a	0.20 ^{a-c}	0.25 ^b
V ₂ T ₂	1.56 ^b	1.79 ^a	0.24 ^{ab}	0.31 ^b
V ₂ T ₃	1.06 ^{a-d}	1.53 ^{ab}	0.16 ^{b-d}	0.23 ^b
V ₂ T ₄	1.19 ^{a-d}	1.70 ^a	0.17 ^{a-d}	0.25 ^b
V ₂ T ₅	1.64 ^a	1.81 ^a	0.25 ^a	0.37 ^a
V ₃ T ₁	0.86 ^{cd}	1.40 ^{ab}	0.15 ^{cd}	0.21 ^b
V ₃ T ₂	0.88 ^{cd}	1.22 ^{ab}	0.14 ^{cd}	0.19 ^b
V ₃ T ₃	0.64 ^d	0.95 ^b	0.12 ^d	0.17 ^b
V ₃ T ₄	0.85 ^{cd}	1.21 ^{ab}	0.14 ^{cd}	0.19 ^b
V ₃ T ₅	0.76 ^d	1.57 ^a	0.13 ^{cd}	0.27 ^a
Level of significance	*	*	*	*
LSD _{5%}	0.57	1.90	0.09	0.06
CV (%)	8.41	7.55	3.60	1.40

Legends: * = significant at the 5% level. Where, V₁ = BARI Mung-6, V₂ = BARI Mung-7, V₃ = BARI Mung-8, T₁ = No Priming, T₂ = Hydro priming, T₃ = 2% NaCl, T₄ = 100 ppm GA₃, T₅ = 200 ppm GA₃.

Effect on yield and yield contributing characters**Plant height**

Plant height assessments at several growth periods (20, 40, 60 DAS, and final harvest) varied considerably within the treatments. At 20 DAS, the

largest plant height (6.57 cm) was found in V₂T₅, whereas the lowest (3.40 cm) was in V₂T₃ and V₃T₃. At 40 DAS, V₂T₅ had the highest height (11.50 cm), whereas V₂T₃ showed the lowest (6.23 cm). By 60 DAS, V₂T₅ continued to show the maximum growth (32.00 cm), followed by V₂T₄ (29.87 cm), while V₃T₃ reported the least height (20.00 cm). The tallest plants

at the last harvest stage were found in V₂T₅ (47.67 cm), followed by V₂T₄ (44.60 cm). On the other hand, V₁T₃ had the shortest plants (28.41 cm), which were followed by V₃T₃ (29.13 cm). These findings imply

that V₂T₅ offered the potential for improved growth performance because it continuously demonstrated greater plant height across all growth phases (Table 2).

Table-2. Effects of variety and treatments on plant height of mungbean at 20, 40, 60 days after sowing and final harvest.

Treatment combinations	Plant height (cm)			
	20 DAS	40 DAS	60 DAS	Final harvest
V ₁ T ₁	4.83 ^{de}	7.60 ^{fg}	23.60 ^h	29.89 ^{c-g}
V ₁ T ₂	5.60 ^c	8.20 ^c	25.10 ^{fg}	32.16 ^{c-g}
V ₁ T ₃	4.23 ^f	6.63 ^h	21.60 ⁱ	28.41 ^g
V ₁ T ₄	5.53 ^c	8.83 ^d	26.10 ^{d-f}	35.67 ^{c-e}
V ₁ T ₅	6.23 ^b	9.33 ^c	27.20 ^{cd}	37.87 ^{bc}
V ₂ T ₁	4.57 ^e	7.83 ^f	23.73 ^{gh}	36.16 ^{cd}
V ₂ T ₂	5.33 ^c	8.23 ^e	28.20 ^c	42.41 ^{ab}
V ₂ T ₃	3.40 ^h	6.23 ⁱ	26.60 ^{de}	34.06 ^{c-g}
V ₂ T ₄	5.60 ^c	10.67 ^b	29.87 ^b	44.60 ^a
V ₂ T ₅	6.57 ^a	11.50 ^a	32.00 ^a	47.67 ^a
V ₃ T ₁	3.87 ^g	6.30 ^{hi}	23.60 ^h	31.83 ^{d-g}
V ₃ T ₂	4.67 ^{de}	7.27 ^g	24.07 ^{gh}	33.13 ^{c-g}
V ₃ T ₃	3.40 ^h	6.30 ^{hi}	20.00 ^j	29.13 ^{fg}
V ₃ T ₄	4.97 ^d	7.37 ^g	25.13 ^{fg}	34.70 ^{c-f}
V ₃ T ₅	5.30 ^c	7.57 ^{fg}	25.70 ^{ef}	35.67 ^{c-e}
Level of significance	*	*	*	*
LSD _{5%}	0.43	1.21	1.35	1.63
CV (%)	2.17	1.51	1.89	5.44

Legends: * = significant at the 5% level. Where, V₁ = BARI Mung-6, V₂ = BARI Mung-7, V₃ = BARI Mung-8, T₁ = No Priming, T₂ = Hydro priming, T₃ = 2% NaCl, T₄ = 100 ppm GA₃, T₅ = 200 ppm GA₃.

Number of branches

The number of branches plant⁻¹ fluctuated greatly between treatment combinations, suggesting that variety and priming had an impact. The maximum branch number (9.67) was observed in V₃T₅, indicating that diversity and priming approach in concert. Additionally, V₁T₅ and V₂T₅ displayed quite high branch numbers (8.33), supporting the role of seed priming in enhancing vegetative growth. Conversely, V₃T₃ produced the fewest branches

(5.67), reflecting a less effective combination (Table 3).

Fresh weight

The fresh weight of plants also differed significantly among treatment combinations, demonstrating the effect of seed priming and varietal response on vegetative biomass. V₁T₅ had the highest fresh weight (4,790.00 g), followed by V₁T₄ (4,676.00 g), demonstrating higher vegetative development in the

V₁ variety after priming treatments. V₃T₃ had the lowest fresh weight (2,722.30 g), indicating a less desirable effect. Higher fresh weight indicates more physiological activity, water intake, and nutrient assimilation. These findings (Table 3) demonstrate the possibility of tailored priming to boost early plant vigor and biomass accumulation.

Dry weight

As shown in Table 3, dry weight followed a trend similar to fresh weight, with the highest value recorded in V₁T₅ (2254.30 g) and the lowest in V₃T₃ (998.70 g). This substantial variation reflects differences in biomass accumulation efficiency among treatments. The superior dry weight in V₁T₅ suggests enhanced photosynthetic activity and assimilate partitioning. Conversely, the reduced biomass in V₃T₃ indicates suboptimal growth conditions or treatment response.

Number of pods plant⁻¹

Table 3 further demonstrates a significant difference in pod formation among treatments, with V₃T₅ producing the maximum number of pods plant⁻¹ (27.67), followed by V₃T₄ (22.33), indicating their higher efficacy in increasing reproductive development. In contrast, V₂T₃ having the lowest pod number (7.67), indicating a poor response to treatment. The observed rise in pod production in V₃T₅ and V₃T₄ may be assigned to improved physiological and morphological features under these treatment combinations.

Pod length

Pod length differed significantly between treatments, supporting the role of seed priming in reproductive development. The longest pods (8.10 cm) were found in V₂T₅, and the shortest (6.13 cm) in V₃T₃. These results highlight the role of priming in nutrient mobilization and hormonal regulation during pod elongation, indicating that genotype–treatment interactions substantially affect pod morphology and yield attributes (Table 3).

Number of seeds pod⁻¹

The number of seeds pod⁻¹ is a substantial yield-contributing feature driven by variety and treatment interactions. In the present study, V₂T₅ reported the maximum seeds pod⁻¹ (9.00), indicating more significant production efficiency under the conditions studied. Numerous treatment combinations, including V₁T₄, V₁T₅, V₂T₄, and V₂T₂, produced 8.00 seeds pod⁻¹, suggesting instead satisfactory results. In comparison, the lowest value (6.00 seeds pod⁻¹) was found in V₃T₃, indicating its poor effectiveness (Table 4).

1,000-seed weight

Significant differences in terms of 1,000-seed weight were observed across the various treatment combinations, as shown in Table 4. The highest weight was noted in V₂T₅ (56.30 g), followed by V₁T₅ (55.10 g), demonstrating that 200 ppm GA₃ seed priming combined with BARI Mung-7 (V₂) provided favorable conditions for improved seed formation. In contrast, the lowest weight was reported in V₃T₃ (28.93 g).

Table-3. Number of branches, plant fresh weight, plant dry weight, pods plant⁻¹, pod length, across the treatment combinations.

Treatment combinations	Number of branches	Fresh weight (g 10m ⁻²)	Dry weight (g 10m ⁻²)	Pods plant ⁻¹	Pod length (cm)
V ₁ T ₁	6.00 ^{ef}	4,086.00 ^{cd}	1,132.70 ^f	12.00 ^{fg}	7.23 ^{ef}
V ₁ T ₂	7.00 ^{c-e}	4,148.70 ^{b-d}	1,236.00 ^e	14.00 ^{ef}	7.43 ^{de}
V ₁ T ₃	6.67 ^{d-f}	3,996.70 ^{c-e}	1,025.00 ^h	9.00 ^{hi}	7.07 ^{fg}
V ₁ T ₄	8.00 ^{bc}	4,676.00 ^a	2,086.00 ^b	16.00 ^{de}	7.63 ^{b-d}
V ₁ T ₅	8.33 ^b	4,790.00 ^a	2,254.30 ^a	18.33 ^c	7.77 ^{a-d}
V ₂ T ₁	7.00 ^{c-e}	3,792.70 ^e	1,135.30 ^f	11.00 ^{gh}	7.67 ^{b-d}
V ₂ T ₂	7.67 ^{b-d}	4,044.00 ^{c-e}	1,244.70 ^e	12.67 ^{fg}	7.80 ^{a-c}
V ₂ T ₃	7.33 ^{b-d}	3,392.30 ^f	1,042.70 ^{gh}	7.67 ⁱ	7.47 ^{c-e}
V ₂ T ₄	8.00 ^{bc}	4,279.30 ^{bc}	1,839.00 ^c	15.00 ^{de}	7.93 ^{ab}
V ₂ T ₅	8.33 ^b	4,388.30 ^b	2,083.30 ^b	17.00 ^{cd}	8.10 ^a
V ₃ T ₁	6.00 ^{ef}	3,010.00 ^g	1,100.70 ^{fg}	16.00 ^{de}	6.33 ^{ij}
V ₃ T ₂	7.00 ^{c-e}	3,266.30 ^{fg}	1,140.00 ^f	18.67 ^c	6.50 ^{hi}
V ₃ T ₃	5.67 ^f	2,722.30 ^h	998.70 ^h	12.67 ^{fg}	6.13 ^j
V ₃ T ₄	8.00 ^{bc}	3,890.00 ^{de}	1,762.70 ^d	22.33 ^b	6.60 ^{hi}
V ₃ T ₅	9.67 ^a	4,008.30 ^{c-e}	1,886.00 ^c	27.67 ^a	6.83 ^{gh}
Level of significance	*	*	*	*	*
LSD _{5%}	0.78	5.21	3.83	1.26	0.65
CV (%)	5.43	2.41	1.51	4.36	1.63

Legends: * = significant at the 5% level. Where, V₁ = BARI Mung-6, V₂ = BARI Mung-7, V₃ = BARI Mung-8, T₁ = No Priming, T₂ = Hydro priming, T₃ = 2% NaCl, T₄ = 100 ppm GA₃, T₅ = 200 ppm GA₃.

Seed yield

Seed yield exhibited significant variation towards the treatment combinations, exhibiting a strong effect of seed priming and varietal combination on productivity. V₁T₃ yielded the lowest (33.33 kg ha⁻¹), explaining its weak responsiveness to that treatment. Surprisingly, the maximum yield was obtained in V₂T₅ (565.67 kg ha⁻¹), where variety V₂ (BARI Mung-7) was primed with GA₃ at 200 ppm (T₅), followed by V₂T₄ (497.33kg ha⁻¹). The findings emphasize the enhanced effectiveness of variety under the priming approach (Table 4).

Harvest index

The harvest index (HI) was considerably affected by the combination of variety and treatment (Table 4). The highest HI (43.63) was obtained in treatment V₂T₂, which was very near to V₂T₅ (43.40), showing that these treatments have higher assimilate partitioning efficiency for the economy. In contrast, V₃T₃ reported the lowest HI (28.07), followed by V₂T₃ (31.78), indicating inefficient conversion of total biomass.

Correlation analysis

The correlation analysis indicated significant positive relationships among several agronomic traits, with stronger associations indicated by larger and more intensely colored red circles ($p \leq 0.05$, $p \leq 0.001$). Plant height (PH) showed significant positive correlations with number of branches (NB), number of seeds pod⁻¹ (NSP), 1,000-seed weight (1,000-SW), and seed yield (SY), especially with SY ($p \leq 0.001$). NB was positively associated with fresh weight (FW), dry weight (DW), pod length (PL), NSP, 1,000 SW, and SY. FW and DW displayed strong positive

correlations with most traits, notably SY. While number of pods branch⁻¹ (NPB) had weaker and mostly non-significant associations, PL showed positive correlations with NSP, 1,000-SW, and SY, but a weak negative one with NPB. NSP was significantly correlated with FW, DW, 1,000-SW, and SY, while 1,000-SW had strong positive correlations with all traits except NPB. SY, the key trait, showed significant positive correlations with nearly all others, especially FW, DW, NSP, and 1,000-SW, suggesting these traits play a critical role in enhancing yield performance (Figure 7).

Table-4. Number of seeds pod⁻¹, 1,000-seeds weight, seed yield and harvest index across the treatment combinations.

Treatment combinations	Seeds pod ⁻¹	1,000-seed weight (g)	Seed yield (kg ha ⁻¹)	Harvest index
V ₁ T ₁	7.00 ^{cd}	49.07 ^{b-d}	172.33 ^c	35.59 ^{e-h}
V ₁ T ₂	7.00 ^{cd}	51.00 ^{a-d}	265.33 ^d	41.69 ^{a-c}
V ₁ T ₃	6.67 ^{c-e}	45.97 ^d	33.33 ^f	33.21 ^{g-h}
V ₁ T ₄	8.00 ^b	53.83 ^{ab}	342.00 ^c	37.41 ^{c-g}
V ₁ T ₅	8.00 ^b	55.10 ^{ab}	479.00 ^b	39.55 ^{a-e}
V ₂ T ₁	7.33 ^{bc}	51.50 ^{a-d}	219.00 ^{de}	38.93 ^{b-e}
V ₂ T ₂	8.00 ^b	52.77 ^{a-c}	456.00 ^b	43.63 ^a
V ₂ T ₃	7.00 ^{cd}	47.97 ^{cd}	64.33 ^f	31.78 ^{h-i}
V ₂ T ₄	8.00 ^b	54.57 ^{ab}	497.33 ^b	38.73 ^{c-f}
V ₂ T ₅	9.00 ^a	56.30 ^a	565.67 ^a	43.40 ^{ab}
V ₃ T ₁	6.33 ^{de}	31.33 ^{fg}	87.67 ^f	34.16 ^{f-g}
V ₃ T ₂	7.00 ^{cd}	33.03 ^{e-g}	169.33 ^e	40.53 ^{a-d}
V ₃ T ₃	6.00 ^e	28.93 ^g	72.33 ^f	28.07 ⁱ
V ₃ T ₄	7.00 ^{cd}	35.20 ^{ef}	217.00 ^{de}	35.98 ^{d-h}
V ₃ T ₅	7.00 ^{cd}	37.23 ^c	353.33 ^c	40.76 ^{a-c}
Level of significance	*	*	*	*
LSD _{5%}	0.79	1.17	5.63	4.67
CV (%)	3.63	4.21	7.59	4.14

Legends: * = significant at the 5% level. Where, V₁ = BARI Mung-6, V₂ = BARI Mung-7, V₃ = BARI Mung-8, T₁ = No Priming, T₂ = Hydro priming, T₃ = 2% NaCl, T₄ = 100 ppm GA₃, T₅ = 200 ppm GA₃.

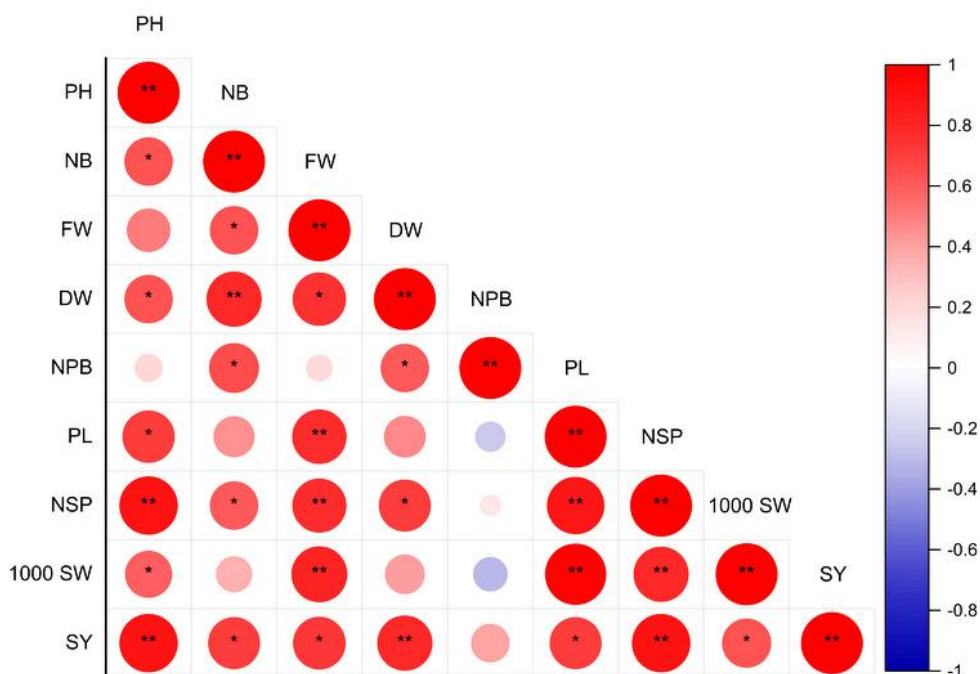


Figure-7. Correlation matrix illustrates the relationships among key agronomic traits in the study. Circle size and color represent the strength and direction of Pearson's correlation coefficients, with red indicating positive and blue indicating negative correlations. Stronger correlations are represented by larger and more intensely colored circles. Asterisks denote significance levels (* $p \leq 0.05$, ** $p \leq 0.001$).

Principal component analysis

Principal component analysis (PCA) was utilized to determine the correlations between multiple agronomic characteristics across treatment combinations (Figure 8). The first two principal components (PCs) described a total variance of 88.04%, with PC1 accounting for 66.22% and PC2 providing 21.82%. The biplot showed a distinct clustering of genotypes based on trait features. The plot indicated that PC1 had a significant association with plant height (PH), fresh weight (FW), dry weight (DW), number of pods plant⁻¹ (NPB), and seed yield (SY). Similarly, pod length (PL), number of seeds pod⁻¹ (NSP), and 1,000-seed weight (1,000-SW) all closely

aligned with PC1, demonstrating that this component is mostly concerned with yield attributes. In contrast, variation in individual features altered treatment distribution along PC2, including some treatment combinations, particularly V₃T₅ and V₃T₄, exhibiting more dispersion, indicating greater variability in their performance. Overall, treatments placed on the right side of the biplot, such as V₂T₅ and V₁T₅, showed better relationships with important agronomic features, indicating potential options for the investigation. In contrast, genotypes in the left quadrants, particularly V₃T₃, V₃T₁, and V₃T₂, were separated from main yield-contributing characteristics, indicating poorer productivity-related features.

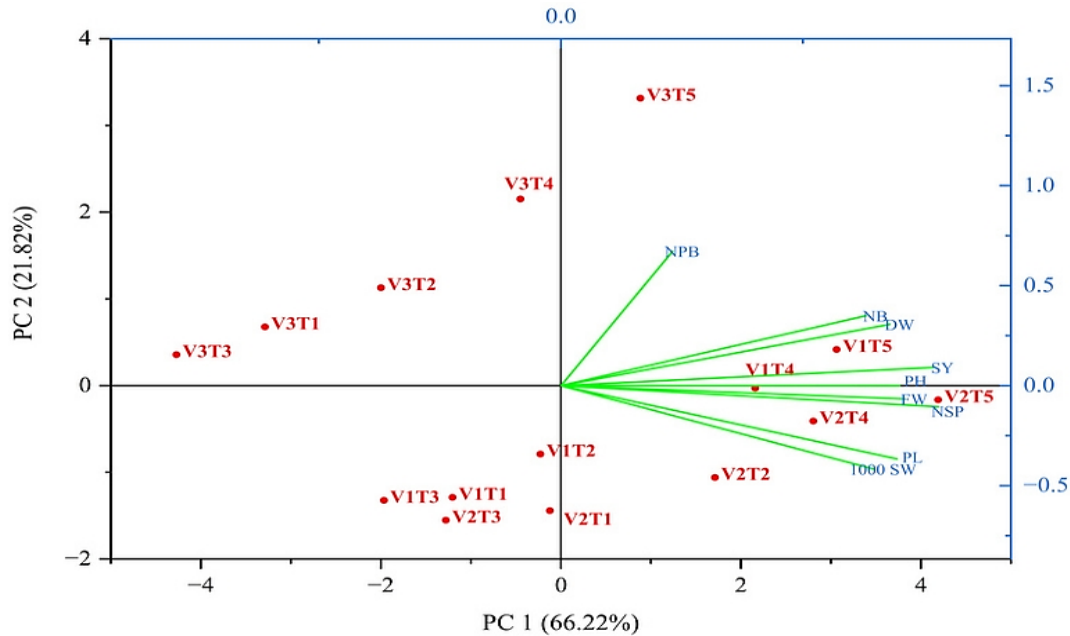


Figure-8. Principal component analysis biplot depicting the distribution of treatments and their association with major morphological, yield, and yield-related traits. Red vectors represent treatment combinations, while blue vectors indicate key contributing traits.

Cluster analysis

The combined treatments were grouped using hierarchical cluster analysis (Figure 9) based on their similarity in morphological and yield related attributes. The dendrogram depicted different clusters showing varying degrees of similarity between treatments. The similarity index performed from 0 to 100, with higher similarity levels indicating that treatment combinations share more common traits. The clustering pattern identified three significant

groups. The first group included V_1T_1 , V_1T_2 , V_2T_1 , and V_2T_3 , which have the most similarities. The second group consists of V_3T_1 , V_3T_3 , V_3T_2 , and V_2T_2 , which constitute a unique cluster, implying that these treatments have similar growth or yield characteristics. The third group includes V_1T_4 , V_3T_4 , V_1T_5 , V_3T_5 , V_2T_5 , and V_2T_4 , which appear to be less connected to the previous groups, with V_2T_5 slightly distanced from V_3T_5 and V_1T_5 , demonstrating distinct performance traits.

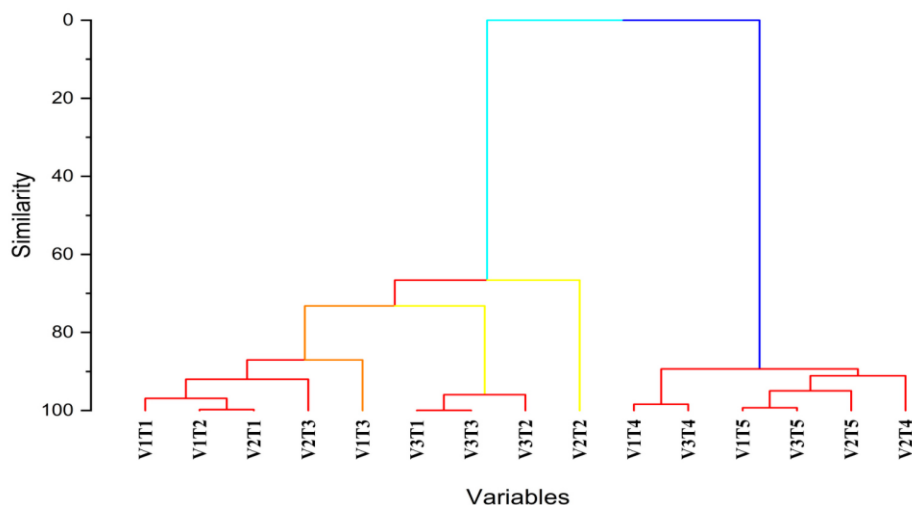


Figure-9. Dendrogram from cluster analysis illustrating the grouping of treatments based on major morphological, yield, and yield-related traits.

Discussion

Gibberellic acid is a vital plant hormone involved in the processes of development, notably seed germination (Shah et al., 2023). This study revealed that BARI Mung-6 seeds primed with 200 ppm GA₃ showed the highest germination rate, indicating its significance for facilitating germination. GA₃ improved seed germination by promoting cell elongation and division in the embryo, thereby allowing radicle emergence (Lando et al., 2020; Şahin and Okumuş, 2025).

Similar findings have been reported by Kumar et al. (2018). In addition, seed priming greatly increased the germination index when compared to unprimed seeds, as demonstrated by Adhikari and Subedi (2022). The germination index was impacted by seed priming and mungbean variety. BARI Mung-6 treated with 200 ppm GA₃ had the highest. GA₃ priming could strengthen mungbean seed germination and early seedling growth.

The evaluation of primed seedling achenes for seedling production demonstrated significant improvements in seedling elongation and dry mass, as well as enhanced shoot length, and root length (Pangtu et al., 2024). Similar findings have been reported in other studies (Waqas et al., 2019; Al-Taweel et al., 2021; Zhu et al., 2021), indicating the efficiency of seed priming in promoting seedling growth. This study found that GA₃ was essential for internode elongation, cell division, and growth. GA₃ boosts cell elongation via releasing DELLA-mediated regulation of the BZR1 transcription factor, resulting in increased growth responses (He and Li, 2013). BARI Mung-7 had the maximum seedling height and considerable increases in shoot and root weight when primed with 200 ppm GA₃. These findings are consistent with those of Thapa et al. (2022), who demonstrated that different priming methods alter seedling traits. In addition to its activity in cell division, multiplication, and expansion, GA₃ enhanced the number of plant⁻¹ branches. Reddy and Luikham (2021) also found that applying gibberellic acid increased the number of branches.

The fresh and dried weights of shoots and roots are important indications of mungbean growth and production. Higher fresh weight indicates better water and nutrient uptake, whereas dry weight signifies biomass accumulation and overall plant vigor. BARI Mung-7 treated with 200 ppm GA₃ delivered the highest fresh and dry shoot weights. BARI Mung-7 with 200 ppm GA₃ provided the maximum fresh and

dry root weights and retained maximum seed vigor. These findings align with previous investigations by Reddy and Luikham (2021) and Khan et al. (2019). Additionally, GA₃ used to treat mungbean seeds promoted seed vigor by improving metabolic activity, seedling development, and germination (Wang et al., 2020; Navya et al., 2021).

In the production of mungbeans, plant height is crucial simply because it influences light interception, photosynthesis, and the entire yield. Treatment with GA₃ greatly increases stem elongation, which enhances pod formation and nutrient intake (Ravat and Makani, 2015). In this investigation, the utilization of GA₃ led to a considerable increase in plant height at final harvest and at 20, 40, and 60 days after sowing (DAS). Plants treated with 200 ppm of GA₃ grew the tallest (6.57 cm, 11.50 cm, 32 cm, and 47.67 cm, respectively) in BARI Mung-7. Conversely, the mungbean plants that were exposed to 2% NaCl had the shortest plant heights. According to Nandan et al. (2021) and Kumar et al. (2018) the application of GA₃ resulted in the maximum plant height among the treatments; these results are consistent with their findings. Ahmad et al. (2020) also showed that GA₃ plays a function in controlling plant development by strengthening the enzymatic antioxidant defense system in *Pisum sativum* L. under NaCl stress.

The number of pods plant⁻¹ is an important aspect of mungbean production, as it directly impacts yield. GA₃ (gibberellic acid) seed treatment stimulates growth, pod formation, and overall productivity. The data indicate that GA₃ at 200 ppm with BARI Mung-8 was the most effective treatment, exceeding the majority of other incidents. This is consistent with the findings of Nandan et al. (2021), who established that GA₃ has a positive impact on pod formation. Furthermore, BARI Mung-7 treated with GA₃ at 200 ppm developed the longest pod length and the maximum seed number pod⁻¹, which confirmed the findings of Nandan et al. (2021); Kalubarme and Madakemohekar (2019). GA₃ also promotes cell elongation and enhances overall plant development, resulting in increased germination, growth, and seed output. Table 3 shows that BARI Mung-7, primed with GA₃ at 200 ppm, produced the highest seed yield. GA₃, when given by foliar or soil methods, stimulates metabolic processes and increases photosynthate production through photosynthesis. These photosynthates are most likely transferred to pod development, enhancing length, seed number and test

weight. These findings are consistent with the results reported by Nawaz et al. (2021).

The results of PCA and hierarchical cluster analysis provide illumination for the correlations between agronomic characteristics across different treatment combinations. The first two principal components comprised 88.04% of the entire variance, indicating significant relationships with yield-related parameters such as plant height, seed yield, and pod length. The grouping of treatment combinations in the biplot revealed treatments with improved performance, particularly V_2T_5 , which had greater associations with that's crucial agronomic parameters. Conversely, treatment combinations in the biplot's left quadrant, including V_3T_3 and V_3T_1 , indicated poor alignment with yield-contributing characteristics, reflecting less productive traits. The hierarchical clustering highlighted the treatment groups' similarities and differences even more. Similar morphological and yield features were suggested by the close clustering of treatments such as V_1T_1 , V_1T_2 , and V_2T_1 . The third group, which included V_1T_4 and V_3T_5 , on the other hand, showed different features, suggesting more pronounced performance patterns. This clearly shows that the most efficient overall production is achieved by utilizing (V_2T_5) mungbeans with GA_3 at 200 ppm. These results provide a more focused method for choosing promising treatments in this study and highlight the value of PCA and HCA in identifying high-performing treatments for additional agronomic research and enhancement.

Conclusion

This study found that seed priming had a considerable impact on mungbean development and yield attributes involving germination, seedling vigor, and crop performance. The combination of 200 ppm GA_3 with BARI Mung-7 demonstrated to be the most effective in improving seed germination, seedling vigor, and yield-related characteristics. BARI Mung-7 demonstrated the most vegetative development, and seed vigor after being treated with GA_3 at 200 ppm. This combination also yielded the highest values for pod length, number of pods plant⁻¹, seeds pod⁻¹, 1000-seed weight, and overall seed output hectare⁻¹, demonstrating its potential to increase mungbean production. These data imply that treating BARI Mung-7 seeds with 200 ppm GA_3 prior to sowing can improve germination, reduce establishment risks, and increase overall yield.

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Contribution of Authors

Rashid MM: Data curation, investigation, formal analysis, visualization, validation, software and writing-original draft.

Mim AH: Data curation, investigation, formal analysis, visualization and writing-original draft.

Turjo AA: Data curation, investigation, validation and formal analysis.

Sikdar MSI: Supervision, methodology, writing-review and editing.

Rahman MM: Supervision, resources, funding acquisition, methodology, conceptualization and writing-review and editing.

Islam SS: Conceptualization, investigation, writing-review and editing.

Khomphet T: Validation, writing-original draft, writing-review and editing.

All authors read and approved final draft of the manuscript.

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