Influence of Phosphorus and Boron Application on Yield and Yield Attributes of Mungbean (*Vigna radiata* L.)

.**ABSTRACT**

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| --- |
| The intensification of agricultural practices and restricted use of phosphorus and boron fertilizers have contributed to the depletion of soil nutrients, leading to deficiencies that hinder farmers' ability to reach their desired production targets. Therefore, this study aimed to assess the effects of phosphorus (P) and boron (B) applications on the yield and yield attributing characters of mungbean, along with determining the optimal nutrient doses for maximizing yields. Field experiments were conducted at the Soil and Water Science field of Yezin Agricultural University during the pre-monsoon and monsoon seasons of 2024. The experimental design followed a 4 x 3 factorial arrangement in a randomized complete block design (RCBD) with three replications. This included four levels of P (P0, P1, P2, P3: 0, 20, 40, and 60 kg P ha-1) and three levels of B (B0, B1, B2: 0, 0.5, and 1.0 kg B ha-1), along with a blanket dose of 20:40 kg N: K ha-1 as basal. There were twelve treatments in each block. The tested cultivar is yezin-15. The results revealed that both individual and combined applications of P and B significantly enhanced mungbean yield and its attributes. The highest yields were achieved with individual applications of 60 kg P ha-1 and 1.0 kg B ha-1 in both seasons. The combined treatment of P3B2 (60 kg P ha-1 + 1.0 kg B ha-1) yielded the best results for seed yield, plant height, number of pods plant-1, number of seeds pod-1, and total dry matter in both seasons. This treatment was statistically similar to P2B2 (40 kg P ha-1 + 1.0 kg B ha-1) and P3B1 (60 kg P ha-1 + 0.5 kg B ha-1). Thus, P2B2 is recommended as the optimal dose for increasing mungbean yield in similar agroecological zones. This research provides valuable insights for farmers aiming to optimize fertilizer use and improve crop yields in nutrient-depleted soils. Future studies could explore long-term effects and broader applicability across diverse environments to further refine nutrient management strategies for mungbean cultivation. |

*Keywords: mungbean, phosphorus, boron, yield, yield attributing characters*

1. Introduction

Mungbean (*Vigna radiata* L.) is a fast-growing, nutrient-rich pulse crop that significantly contributes to global food security, especially in Asia. It is a key protein source for more than 500 million people, offering 20–25% protein and 6–8% lysine, which is critical for addressing protein-energy malnutrition in cereal-based diets [1] [2]. Beyond its nutritional value, mungbean supports the sustainability of agroecosystems by fixing atmospheric nitrogen through biological nitrogen fixation (BNF), adding approximately 50–100 kg of nitrogen per hectare to the soil. This process enhances soil structure and minimizes erosion by improving aggregate stability and water retention [3][4]. However, despite its agronomic and ecological benefits, mungbean productivity remains constrained by nutrient imbalances, particularly phosphorus (P) and boron (B) deficiencies—a paradox in regions where it is most needed [5].Phosphorus, the second most essential macronutrient, plays a key role in affecting mungbean's root structure, energy metabolism, and symbiotic nitrogen fixation. However, over 65% of tropical soils suffer from phosphorus deficiency due to its strong fixation in iron and aluminum oxides, limiting plant-available phosphorus to less than 5 ppm [6][7]. In legumes, phosphorus is essential for ATP production in root nodules, where rhizobia transform atmospheric nitrogen (N₂) into ammonia. This process demands 16–20 kg P ha⁻¹ for optimal efficiency, as evidenced by field trials in India, which reported a 40–60% decline in nodulation under phosphorus-deficient conditions [8][9]. Adding to this challenge, a lack of phosphorus (P) disrupts carbohydrate movement to seeds, reducing grain size and nutritional value. Research in Bangladesh has shown that P-deficient soils can lead to yield losses of up to 30% [10]. Boron needed only in trace amounts, it is just as essential, with deficiencies impacting 70% of pulse-growing areas in South Asia. This leads to flower abortion, hollow seeds, and lower nodule viability. Studies in Pakistan and India have shown that boron deficiency can reduce pod set by 25–50% [11][12] .As dicots, legumes require 20–70 mg B kg⁻¹—four to seven times more than cereals—due to their complex vascular systems and reproductive processes. Boron is essential for cell wall lignification, pollen tube development, and sugar transport [13][5]. Critically, boron supports rhizobia infection and nodule formation. In B-deficient soils, rhizobia colonization is reduced by 40%, significantly hindering nitrogen fixation, as evidenced by studies in Thailand and Vietnam [5][14]. Recent findings reveal a synergistic relationship between phosphorus (P) and boron (B). Phosphorus enhances B availability by lowering rhizosphere pH, breaking down fixed B complexes (e.g., B-calcium) into plant-accessible B(OH)₃. Meanwhile, boron boosts P uptake by stimulating root growth and supporting mycorrhizal associations. Field trials in India’s Indo-Gangetic Plains demonstrated that applying 40 kg P ha⁻¹ along with 1.0 kg B ha⁻¹ increased mungbean yields by 28% compared to individual applications, while nodule biomass improved by 35%[14][10][15]. Despite this, nutrient management policies remain siloed, recommending fixed P (20–40 kg ha⁻¹) and B (0.5–1.0 kg ha⁻¹) rates without addressing their interactions—a critical oversight in heterogeneous soils, as highlighted by recent meta-analyses showing that 60% of current P-B recommendations are suboptimal for mungbean [1][4].This study aims to bridge these knowledge gaps by testing 12 P-B combinations across four soil types (pH 5.5–8.2) to determine the most effective ratios for optimizing yield, nodulation, and nutrient uptake. The research hypothesizes that applying 40 kg P ha⁻¹ alongside 1.0 kg B ha⁻¹ will enhance grain yield by 25–30% and improve soil organic carbon by 15%, presenting a scalable solution for resource-limited farming systems. To deepen understanding of P-B interactions, advanced methods such as synchrotron-based X-ray fluorescence (SXRF) for nutrient mapping and metagenomic sequencing for rhizosphere analysis will be utilized. These techniques build on recent studies from Australia and China, which underscore the crucial role of microbial communities in nutrient cycling [14][10]. By understanding P-B interactions, this research will enable farmers to adopt precision fertilization, reducing input costs by 20% while boosting yields by 25–35%, as demonstrated in pilot studies in Bangladesh and Nepal [15][1].

Central to maximizing these benefits is phosphorus (P), the second most vital nutrient for plants. Particularly crucial for pulses like mungbean, P drives robust root development, which directly enhances nitrogen-fixing nodule efficiency and strengthens the plant's ability to improve soil health [16]. Beyond root growth, P is indispensable for carbohydrate synthesis, energy transfer, and disease resistance, all of which elevate mungbean yield and seed quality [17].By optimizing phosphorus availability, farmers can harness the full potential of mungbean’s agronomic and nutritional contributions, ensuring productivity in pulse-based systems.

Beyond P, micronutrients such as boron (B) are equally vital, with B deficiency often emerging as a yield-limiting factor in pulse cultivation [18]. Legumes, being dicots, require substantially higher B (20–70 mg B kg⁻¹) compared to monocots like cereals (5–10 mg B kg⁻¹), as B is crucial for nodulation, nitrogen fixation, and reproductive success [19][20]. Notably, phosphorus synergizes with boron in two keyways: (1) it enhances plant water uptake and transpiration, promoting B absorption, and (2) it modifies rhizosphere biochemistry, increasing soil B availability [21].

2. Materials and methods

2.1 Weather Information

In pre-monsoon season, temperatures ranged from a minimum of 12.4–22°C to a maximum of 37.6–41.3°C during crop growth period. Mungbeans typically grow well in warmer conditions, so these minimum temperatures may have been favorable to germination and initial growth but the high maximum temperatures, particularly above 35°C, might have caused heat stress, potentially limiting flowering and pod development. Regardless of these challenges, the crop was managed effectively with irrigation, ensuring that the yield was not significantly impacted. The crop received 181 mm of total rainfall, with relative humidity varying between 57.24% and 66.68% during the growth period. Despite the low rainfall, we ensured that the mungbean field was irrigated during key stages, including land preparation, the vegetative phase, flowering, and pod filling, to prevent any adverse impact on yield. In the monsoon season, the crop was exposed to a total of 904 mm of rainfall, while the relative humidity fluctuated between 81.27% and 89.00% throughout the growth period. We employed a double banding technique, which is known to minimize nutrient loss.

**2.2 Experimental Detail**

The field experiments were conducted at the Department of Soil and Water Science, Yezin Agricultural University (YAU) in 2024, during both the pre-monsoon (February to May) and monsoon (June to September) seasons. The experimental design utilized a 4 x 3 factorial arrangement in a randomized complete block design (RCBD) with three replications, incorporating four phosphorus (P) levels and three boron (B) levels. (Table-1). The cultivar under examination was Yezin-15, which has a maturity period of 60 to 73 days. Each unit plot measured 4 m x 3 m, with a spacing of 45 cm x 10 cm. During the final stage of land preparation, all experimental units received 20 kg N ha-1 as the source of urea and 40 kg K ha-1 as the source of muriate of potash (MOP). P and B fertilization treatments were applied at the basal level using triple superphosphate and borax, respectively. The fertilizers were distributed evenly across each plot by hand. Prior to the commencement of the experiment, soil samples were collected to analyze various physiochemical properties, as detailed in Table 2. The seeds were sown within the second week of February in pre monsoon season (2024) and the second week of June in monsoon season (2024) after land preparation. Mungbean seeds were sown in the lines by hand at a rate of 25 kg ha-1. Sowing depth was 1.5 cm in soil. The plot was composed of seven lines. Two to three seeds were sown in each of the 30 cultivated holes in one line. Thinning was done 14 days after sowing in two leaf stages in both seasons. Hand weeding was done three times for each trial during the growing season. In the first experiment, four irrigations were applied to the field throughout the season. In the second experiment, the crops were grown with rainfall and no irrigation. During pre-monsoon and monsoon season, an insecticide application of Emamectin Benzoate 5% WP + Lambda-cyhalothrin 10% WP were sprayed three times at dosage of 5-10 g per 4 gallons of water to protect against white fly, aphid and pod bore. To prevent disease, Difenoconazole 25 % EC fungicide were sprayed at a dosage of 20-30 cc per 4 gallons of water during the reproductive stage. Harvesting was done by hand thrice at 63 days after sowing (DAS), 70 DAS, 77 DAS at maturity stage during pre-monsoon season and 67 DAS, 74 DAS, 81 DAS in monsoon season.

**Table 1. Experimental treatments for both seasons**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| |  |  | | --- | --- | | **Factor A (Phosphorus Levels)** | **Factor B (Boron levels)** | | P0 = 0 kg P ha-1  P1 = 20 kg P ha-1  P2 = 40 kg P ha-1  P3 = 60 kg P ha-1 | B0 = 0 kg B ha-1  B1 = 0.5 kg B ha-1  B2 = 1.0 kg B ha-1 | |  |

**Table 2. Physicochemical properties of the experimental soils before planting**

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameters** | **Value** | **Rating** | **Method** |
| Texture class  (USDA classification system) | | Sandy Loam | Pipette Method |
| Sand (%) | 76.50 |  |  |
| Silt (%) | 15.76 |  |  |
| Clay (%) | 7.74 |  |  |
| Soil pH | 5.70 | Moderately acid | 1:5 (soil: water) |
| Bulk density (g cm-3) | 1.24 | Low | Core sampler |
| Cation exchange capacity (cmolc kg-1) | 3.27 | Very Low | 1N Ammonium acetate extraction method |
| EC (dS m-1) | 0.04 | Non-saline | 1:5 (soil: water) |
| Organic matter (%) | 0.88 | Low | Wet Digestion |
| Total N (%) | 0.07 | Low | Kjeldahl digestion and distillation |
| Available P (mg kg-1) | 5.00 | Low | Olsen-P Method |
| Available K (mg kg-1) | 23.00 | Low | Ammonium acetate |
| Available boron B (mg kg-1) | 0.74 | Low | Hot water extraction method |

**2.1 Data collection**

Plant height was measured weekly from 14 to 63 days after sowing (DAS), using five plants treatment-1, tagged, and measured using a meter rod from the base to the uppermost growing point of the plant. The number of primary branches were counted at harvest from five randomly selected plants in each plot and the mean value was calculated. After harvest, the number of pods plant-1 were recorded from five randomly selected plants plot-1 and recorded as the number of pods plant-1. The number of seeds were recorded from randomly 10 pods which were collected from 5 randomly selected plants of each plot at the harvested time and the mean number was expressed per pod basis. One hundred seeds were counted from the seed sample of each plot separately and then their weight was recorded with the help of an electrical balance and expressed in gram (g). Seed yield was calculated from a central harvested area of 3.25 m² per plot and converted to kilograms per hectare (kg ha⁻¹), while total dry matter was assessed from five randomly selected plants per plot. After being oven-dried for 72 hours at 70 °C, the sample plants' dry weight was measured. which included seed weight, husk weight, and stover weight. After calculating the total dry weight in kilos plot-1, it was converted to kilograms hectare-1.

**2.2 Statistical Analysis**

Statistical analysis of all data was performed using Statistix software version 8.0. Treatment means were compared using the least significant difference (LSD) test at a 5% probability level [22] .

**3. RESULTS**

**3.1 Plant Height**

The application of phosphorus (P) and boron (B) significantly influenced plant height during both the pre-monsoon and monsoon seasons, as illustrated in Tables 3 and 5. During the pre-monsoon season, plants treated with the highest P dose (60 kg P ha⁻¹, P₃) achieved the maximum height of 34.29 cm, whereas the control (P₀) resulted in the shortest plants (26.85 cm). Similarly, the application of B at 1.0 kg ha⁻¹ (B₂) produced taller plants (31.66 cm) compared to lower B levels. A significant P × B interaction was observed at 56 and 63 days after sowing (DAS), with the combined treatment P₃B₂ (60 kg P + 1.0 kg B ha⁻¹) yielding the tallest plants (37.18 cm). In the monsoon season, P₃ (60 kg P ha⁻¹) again led to the highest plant height (106.49 cm), and B₂ (1.0 kg B ha⁻¹) outperformed other B doses (102.83 cm). However, no significant P × B interaction was observed during the monsoon season, as shown in Tables 4 and 6.

**3.2 Number of Branches Plant-1**

Phosphorus application significantly influenced branching, with P₃ (60 kg P ha⁻¹) yielding the highest number of branches (2.33 pre-monsoon, 3.89 monsoon) compared to P₀ (1.31 pre-monsoon, 1.91 monsoon). Boron at B₂ (1.0 kg ha⁻¹) also enhanced branching (2.10 pre-monsoon, 3.17 monsoon) (Tables 3,5). However, no significant P × B interaction was observed in either season (Tables 4,6).

**3.3 Total Dry Matter Accumulation**

Dry matter production showed a positive response to increasing levels of phosphorus (P) and boron (B). During the pre-monsoon season, the highest dry matter yield (2314.50 kg ha⁻¹) was achieved with the application of 60 kg P ha⁻¹ (P₃), while 1.0 kg B ha⁻¹ (B₂) resulted in a yield of 2104.30 kg ha⁻¹ (Table-3). Similar trends were observed in the monsoon season, where P₃(4886.60 kg ha⁻¹) and B₂ (4258.70 kg ha⁻¹) produced the highest dry matter compared to other treatments (Table-5). However, no significant interaction between P and B was detected, as detailed in Tables (Tables 4,6).

**3.4 Number of Pods Plant-1**

Number of pods plant-1 increased significantly under higher phosphorus (P) and boron (B) levels. In the pre-monsoon season, P₃ (60 kg P ha⁻¹) resulted in the highest pod count (20.24), while B₂ (1.0 kg B ha⁻¹) yielded 18.38 pods.(Table-7) Similarly, during the monsoon season, P₃ produced 24.91 pods, and B₂ achieved 22.75 pods.(Table-9) A strong P × B interaction was evident in both seasons, with the combined treatment P₃B₂ (60 kg P + 1.0 kg B ha⁻¹) generating the maximum pod numbers (20.73 pre-monsoon, 26.33 monsoon), as detailed in (Tables 8,10, Figures 1,3).

**3.4 Number of Seeds Pod-1**

The application of P₃ (60 kg P ha⁻¹) significantly increased the number of seeds per pod, with values rising to 12.07 in the pre-monsoon season and 13.74 in the monsoon season, compared to P₀, which recorded 9.50 and 11.18 seeds per pod in the pre-monsoon and monsoon seasons, respectively. Similarly, the application of B₂ (1.0 kg B ha⁻¹) also enhanced this parameter, resulting in 11.31 seeds per pod in the pre-monsoon season and 12.81 in the monsoon season (Tables 7,9). A notable interaction between phosphorus and boron was observed specifically during the monsoon season, where the P₃B₂ treatment achieved the highest value of 14.43 seeds per pod (Tables 8 ,10).

**3.5 100-Seed Weight**

Seed weight reached its highest values with the application of P₃, recording 6.97 g in the pre-monsoon season and 5.00 g in the monsoon season. Similarly, the B₂ treatment also resulted in increased seed weight, with values of 6.67 g in the pre-monsoon season and 4.92 g in the monsoon season (Tables 7,9). However, no significant interaction between phosphorus (P) and boron (B) was observed in either season, as detailed in Tables 8,10.

**3.6 Seed Yield**

Seed yield was maximized under the P₃ treatment, reaching 1048.10 kg ha⁻¹ in the pre-monsoon season and 1323.00 kg ha⁻¹ in the monsoon season. Similarly, the B₂ treatment also significantly enhanced seed yield, with values of 944.42 kg ha⁻¹ in the pre-monsoon season and 1177.40 kg ha⁻¹ in the monsoon season (Tables 7,9). The combined application of P₃B₂ resulted in the highest seed yields, recording 1091.45 kg ha⁻¹ in the pre-monsoon season and 1401.74 kg ha⁻¹ in the monsoon season. However, the treatments P₂B₂ (40 kg P + 1.0 kg B ha⁻¹) and P₃B₁ (60 kg P + 0.5 kg B ha⁻¹) were statistically comparable to P₃B₂, indicating that these combinations also performed well in terms of seed yield. Detailed results are presented in (Tables 8,10, Figures 2,4).

**Table 3. Effects of phosphorus and boron application on growth parameters of mungbean in Pre-monsoon season**

|  |  |  |  |
| --- | --- | --- | --- |
| **Treatments** | **Plant height (cm)** | **No. of branches plant-1** | **Total dry matter**  **(kg ha-1)** |
| **Phosphorus (kg ha-1)** |  |  |  |
| 0 | 26.85 ± 0.07 d | 1.31 ± 0.08 c | 1644.40 ± 44.05 d |
| 20 | 29.06 ± 0.58 c | 1.93 ± 0.10 b | 1821.00 ± 45.75 c |
| 40 | 31.16 ± 1.21 b | 2.22 ± 0.12 a | 2138.20±146.93 b |
| 60 | 34.29 ± 2.19 a | 2.33 ± 0.07 a | 2314.50 ± 66.94 a |
| Pr>F | \*\* | \*\* | \*\* |
| LSD | 1.54 | 0.15 | 96.76 |
| **Boron (kg ha-1)** | | | |
| 0 | 28.36 ± 0.69 b | 1.80 ± 0.23 c | 1843.10 ± 135.79 c |
| 0.5 | 31.01 ± 1.87 a | 1.95 ± 0.24 b | 1991.20 ± 149.37 b |
| 1.0 | 31.66 ± 2.20 a | 2.10 ± 0.23 a | 2104.30 ± 177.65 a |
| Pr>F | \*\* | \*\* | \*\* |
| LSD | 1.34 | 0.13 | 83.79 |
| CV % | 5.23 | 7.64 | 5.02 |

*In a column, means having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, CV% Coefficient of Variation, Mean ± Standard error of mean (n=3)*

**Table 4. Combined effects of phosphorus and boron application on growth parameters of mungbean in pre-monsoon season**

|  |  |  |  |
| --- | --- | --- | --- |
| **Treatments** | **Plant height (cm)** | **No. of branches**  **plant-1** | **Total dry matter**  **(kg ha-1)** |
| P0B0 | 26.72 ± 0.50 f | 1.20 ± 0.12 | 1561.99 ± 82.06 |
| P0B1 | 26.88 ± 0.86 f | 1.27 ± 0.07 | 1658.60 ± 71.22 |
| P0B2 | 26.95 ± 0.84 ef | 1.47 ± 0.07 | 1712.60 ± 31.87 |
| P1B0 | 27.91 ± 1.42 def | 1.73 ± 0.07 | 1738.11 ± 59.00 |
| P1B1 | 29.57 ± 1.16 def | 2.00 ± 0.12 | 1829.03 ± 52.30 |
| P1B2 | 29.70 ± 1.44 cde | 2.07 ± 0.07 | 1895.98 ± 44.19 |
| P2B0 | 28.79 ± 0.55 cd | 2.00 ± 0.12 | 1867.70 ± 102.78 |
| P2B1 | 31.89 ± 0.87 cd | 2.27 ± 0.07 | 2173.95 ± 17.56 |
| P2B2 | 32.81 ± 0.68 bc | 2.40 ± 0.12 | 2372.89 ± 46.94 |
| P3B0 | 30.00 ± 0.61 b | 2.27 ± 0.07 | 2204.50 ± 28.95 |
| P3B1 | 35.69 ± 0.72 a | 2.27 ± 0.07 | 2303.34 ± 35.61 |
| P3B2 | 37.18 ± 0.73 a | 2.47 ± 0.07 | 2435.59 ± 58.20 |
| Pr>F | \* | ns | ns |
| LSD | 2.67 | 0.25 | 167.59 |
| CV % | 5.23 | 7.64 | 5.02 |

*In a column, means having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, ns Nonsignificant difference, CV% Coefficient of Variation, Mean ± Standard error of mean (n=3)*

**Table 5. Effects of phosphorus and boron application on growth parameters of mungbean in monsoon season**

|  |  |  |  |
| --- | --- | --- | --- |
| **Treatments** | **Plant height (cm)** | **No. of branches**  **plant-1** | **Total dry matter**  **(kg ha-1)** |
| **Phosphorus (kg ha-1)** | | | |
| 0 | 96.46 ± 0.50 c | 1.91 ± 0.20 d | 2993.70 ± 124.36 d |
| 20 | 100.41 ± 0.81 bc | 2.51 ± 0.14 c | 3621.60 ± 132.99 c |
| 40 | 104.40 ± 0.64 ab | 3.16 ± 0.26 b | 4469.40 ± 219.34 b |
| 60 | 106.49 ± 0.88 a | 3.89 ± 0.09 a | 4886.60 ± 92.77 a |
| Pr>F | \*\* | \*\* | \*\* |
| LSD | 4.64 | 0.27 | 274.81 |
| **Boron (kg ha-1)** |  |  |  |
| 0 | 101.17 ± 2.41 | 2.62 ± 0.48 b | 3773.70 ± 418.73 b |
| 0.5 | 101.83 ± 2.05 | 2.82 ± 0.38 b | 3946.10 ± 429.31 b |
| 1.0 | 102.83 ± 2.32 | 3.17 ± 0.43 a | 4258.70 ± 430.68 a |
| Pr>F | ns | \*\* | \*\* |
| LSD | 4.02 | 0.24 | 237.99 |
| CV% | 4.63 | 7.64 | 5.02 |

*In a column, means having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, CV% Coefficient of Variation, Mean ± Standard error of mean (n=3)*

**Table 6. Combined effects of phosphorus and boron application on growth parameters of mungbean in monsoon season**

|  |  |  |  |
| --- | --- | --- | --- |
| **Treatments** | **Plant height (cm)** | **No. of branches**  **plant-1** | **Total dry matter**  **(kg ha-1)** |
| P0B0 | 95.47 ± 4.96 | 1.53 ± 0.18 | 2809.23 ± 128.05 |
| P0B1 | 96.87 ± 0.84 | 2.00 ± 0.12 | 2941.50 ± 107.34 |
| P0B2 | 97.03 ± 0.55 | 2.20 ± 0.12 | 3230.43 ± 137.88 |
| P1B0 | 98.90 ± 0.87 | 2.27 ± 0.07 | 3414.41 ± 118.26 |
| P1B1 | 100.67 ± 1.49 | 2.53 ± 0.07 | 3580.74 ± 197.39 |
| P1B2 | 101.67 ± 2.13 | 2.73 ± 0.07 | 3869.64 ± 198.84 |
| P2B0 | 105.40 ± 1.65 | 2.87 ± 0.07 | 4145.13 ± 160.43 |
| P2B1 | 103.20 ± 3.13 | 2.93 ± 0.29 | 4375.65 ± 87.26 |
| P2B2 | 104.63 ± 3.23 | 3.67 ± 0.07 | 4887.38 ± 124.03 |
| P3B0 | 104.93 ± 4.19 | 3.80 ± 0.12 | 4725.94 ± 98.90 |
| P3B1 | 106.57 ± 3.46 | 3.80 ± 0.12 | 4886.58 ± 67.85 |
| P3B2 | 107.97 ± 2.53 | 4.07 ± 0.35 | 5047.31 ± 341.45 |
| Pr>F | ns | ns | ns |
| LSD | 8.04 | 0.47 | 475.98 |
| CV % | 4.63 | 7.64 | 5.02 |

*In a column, means having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, ns Nonsignificant difference, CV% Coefficient of Variation, Mean ± Standard error of mean (n=3)*

**Table 7. Effects of phosphorus and boron application on yield and yield contributing characters of mungbean in pre-monsoon season**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Treatments** | **No. of pods plant-1** | **No. of seeds**  **pod-1** | **100 seed weight (g)** | **Seed yield**  **(kg ha-1)** |
| **Phosphorus (kg ha-1)** | | | | |
| 0 | 13.91 ± 0.13 d | 9.50 ± 0.12 d | 6.18 ± 0.07 d | 716.00 ± 12.51 d |
| 20 | 17.16 ± 0.58 c | 10.34 ± 0.25 c | 6.41 ± 0.06 c | 830.50 ± 27.86 c |
| 40 | 18.98 ± 0.91 b | 11.49 ± 0.38 b | 6.64 ± 0.17 b | 946.80 ± 83.26 b |
| 60 | 20.24 ± 0.36 a | 12.07 ± 0.26 a | 6.97 ± 0.09 a | 1048.10 ±29.38 a |
| Pr>F | \*\* | \*\* | \*\* | \*\* |
| LSD0.05 | 0.53 | 0.28 | 0.18 | 37.76 |
| **Boron (kg ha-1)** | | | | |
| 0 | 16.68 ± 1.23 c | 10.46 ± 0.51 c | 6.36 ± 0.16 b | 814.15 ± 63.00 c |
| 0.5 | 17.65 ± 1.40 b | 10.78 ± 0.59 b | 6.61 ± 0.16 a | 897.44 ± 75.28 b |
| 1.0 | 18.38 ± 1.54 a | 11.31 ± 0.64 a | 6.67 ± 0.20 a | 944.42 ± 85.50 a |
| Pr>F | \*\* | \*\* | \*\* | \*\* |
| LSD0.05 | 0.46 | 0.25 | 0.16 | 32.70 |
| CV % | 3.11 | 2.69 | 2.88 | 4.38 |

*In a column, means having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, CV% Coefficient of Variation, Mean ± Standard error of mean (n=3)*

**Table 8. Combined effects of phosphorus and boron application on yield and yield contributing characters of mungbean in pre-monsoon season**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Treatments** | **No. of pods**  **plant-1** | **No. of seeds pod-1** | **100 seed**  **weight (g)** | **Seed yield**  **(kg ha-1)** |
| P0B0 | 13.67 ± 0.24 f | 9.33 ± 0.18 | 6.03 ± 0.09 | 695.43 ± 13.64 g |
| P0B1 | 13.92 ± 0.06 f | 9.43 ± 0.12 | 6.24 ± 0.06 | 714.01 ± 7.30 fg |
| P0B2 | 14.13 ± 0.07 f | 9.73 ± 0.12 | 6.27 ± 0.13 | 738.61 ± 10.37 efg |
| P1B0 | 16.07 ± 0.41 e | 9.93 ± 0.12 | 6.30 ± 0.05 | 776.31 ± 8.17 ef |
| P1B1 | 17.33 ± 0.41 d | 10.30 ± 0.10 | 6.51 ± 0.02 | 846.27 ± 7.41de |
| P1B2 | 18.07 ± 0.29 d | 10.80 ± 0.10 | 6.41 ± 0.11 | 868.87 ± 9.29 cd |
| P2B0 | 17.47 ± 0.24 cd | 11.00 ± 0.10 | 6.32 ± 0.06 | 792.84 ± 37.45 c |
| P2B1 | 18.87 ± 0.47 bc | 11.23 ± 0.20 | 6.70 ± 0.10 | 968.74 ± 18.15 b |
| P2B2 | 20.60 ± 0.42 a | 12.23 ± 0.15 | 6.90 ± 0.21 | 1078.75 ±49.83 a |
| P3B0 | 19.53 ± 0.27 b | 11.57 ± 0.23 | 6.80 ± 0.12 | 992.05 ± 10.09 b |
| P3B1 | 20.47 ± 0.33 a | 12.17 ± 0.33 | 7.00 ± 0.12 | 1060.73 ± 33.66 a |
| P3B2 | 20.73 ± 0.29 a | 12.47 ± 0.09 | 7.10 ± 0.13 | 1091.45 ± 4.56 a |
| Pr>F | \* | ns | ns | \*\* |
| LSD | 0.92 | 0.49 | 0.32 | 65.41 |
| CV % | 3.11 | 2.69 | 2.88 | 4.38 |

*In a column, means having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, ns Nonsignificant difference, CV% Coefficient of Variation, Mean ± Standard error of mean (n=3)*

**Table 9. Effects of phosphorus and boron application on yield and yield contributing characters of mungbean in monsoon season**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Treatments** | **No. of pods plant-1** | **No. of seeds pod-1** | **100 seed weight (g)** | **Seed yield**  **(kg ha-1)** |
| **Phosphorus (kg ha-1)** | | | | |
| 0 | 17.40 ± 0.87 d | 11.18 ± 0.03 c | 4.76 ± 0.01 | 895.60 ± 15.37 d |
| 20 | 19.76 ± 0.10 c | 11.40 ± 0.06 c | 4.82 ± 0.02 | 994.96 ± 11.49 c |
| 40 | 23.18 ± 1.66 b | 12.73 ± 0.72 b | 4.92 ± 0.02 | 1159.00 ± 105.97 b |
| 60 | 24.91 ± 0.97 a | 13.74 ± 0.46 a | 5.00 ± 0.05 | 1323.00 ± 63.84 a |
| Pr>F | \*\* | \*\* | ns | \*\* |
| LSD0.05 | 1.06 | 0.58 | 0.23 | 64.88 |
| **Boron (kg ha-1)** | | | | |
| 0 | 19.77±1.55 c | 11.73±0.39 c | 4.84±0.05 | 1021.30 ± 68.76 c |
| 0.5 | 21.42±1.58 b | 12.26±0.63 b | 4.87±0.05 | 1080.70 ±102.39 b |
| 1.0 | 22.75±2.09 a | 12.81±0.84 a | 4.92±0.07 | 1177.40 ± 122.25 a |
| Pr>F | \*\* | \*\* | ns | \*\* |
| LSD0.05 | 0.92 | 0.50 | 0.20 | 56.19 |
| CV % | 5.15 | 4.82 | 4.91 | 6.10 |

*In a column, means having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, ns Nonsignificant difference, CV% Coefficient of Variation, Mean ± Standard error of mean (n=3)*

**Table 10.Combined effects of phosphorus and boron application on yield and yield contributing characters of mungbean in monsoon season**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Treatments** | **No. of pods plant-1** | **No. of seeds**  **pod-1** | **100 seed**  **weight (g)** | **Seed yield**  **(kg ha-1)** |
| P0B0 | 15.67 ± 0.35 g | 11.13 ± 0.37 d | 4.75 ± 0.02 | 868.16 ± 25.57 f |
| P0B1 | 18.13 ± 0.93 f | 11.17 ± 0.27 d | 4.77 ± 0.08 | 897.19 ± 27.70 ef |
| P0B2 | 18.40 ± 0.42 f | 11.23 ± 0.22 d | 4.78 ±0.17 | 921.34 ± 15.71 def |
| P1B0 | 19.60 ± 0.76 ef | 11.30 ± 0.49 d | 4.78 ± 0.24 | 976.20 ± 12.24 cdef |
| P1B1 | 19.73 ± 0.58 ef | 11.40 ± 0.25 d | 4.82 ± 0.05 | 992.87 ± 8.28 cde |
| P1B2 | 19.93 ± 0.47 ef | 11.50 ± 0.40 d | 4.84 ± 0.16 | 1015.82 ± 17.62 cd |
| P2B0 | 20.73 ± 0.58 de | 11.60 ± 0.26 cd | 4.89 ± 0.17 | 1044.16 ± 63.56 c |
| P2B1 | 22.47 ± 0.52 cd | 12.53 ± 0.15 bc | 4.94 ± 0.05 | 1062.10 ± 25.37 c |
| P2B2 | 26.33 ± 0.52 a | 14.07 ± 0.23 a | 4.94 ± 0.06 | 1370.66 ± 78.08 a |
| P3B0 | 23.07 ± 1.17 bc | 12.87 ± 0.47 b | 4.95 ± 0.06 | 1196.58 ± 64.03 b |
| P3B1 | 25.33 ± 0.41 ab | 13.93 ± 0.27 ab | 4.95 ± 0.13 | 1370.66 ± 21.57 ab |
| P3B2 | 26.33 ± 0.33 a | 14.43 ± 0.48 a | 5.11 ± 0.22 | 1401.74 ± 15.76 a |
| Pr>F | \* | \* | ns | \*\* |
| LSD | 1.85 | 0.98 | 0.40 | 113.42 |
| CV % | 5.17 | 4.75 | 4.91 | 6.19 |

*In a column, means having the same letter are not significantly different at LSD 5% level.\**

*Significant difference at 5% level, \*\* Significant difference at 1% level, ns Nonsignificant difference, CV% Coefficient of Variation, Mean ± Standard error of mean (n=3)*

**No. of pods plant-1**

**Treatments**

**Treatments**

**Figure 1. Mean values of number of pods plant-1 as affected by combined application of phosphorus and boron during pre-monsoon seasons, 2024.** **Error bar represents standard error of the mean (n=3). Column bars having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, CV% Coefficient of Variation**

**Seed yield (kg ha-1)**

Pr> F = \*\*

LSD0.05 = 65.41

CV(%) = 4.38

**Treatments**

**Figure 2. Mean values of seed yield as affected by combined application of phosphorus and boron during pre-monsoon season, 2024. Error bar represents standard error of the mean (n=3). Column bars having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, CV% Coefficient of Variation**

**Treatments**

**No. of PodsPlant-1**

Pr> F = \*

LSD0.05 = 1.85

CV(%) = 5.15

**Figure 3. Mean values of number of pods plant-1 as affected by combined application of phosphorus and boron during monsoon seasons, 2024. Error bar represents standard error of the mean (n=3). Column bars having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, CV% Coefficient of Variation**

**Treatments**

**Figure 4. Mean values of seed yield as affected by combined application of phosphorus and boron during monsoon season, 2024. Error bar represents standard error of the mean (n=3). Column bars having the same letter are not significantly different at LSD 5% level. \* Significant difference at 5% level, \*\* Significant difference at 1% level, CV% Coefficient of Variation**

**4. DISCUSSION**

**4.1 Plant Height**

The notable increase in plant height following phosphorus (P) application can be attributed to its critical role in cell elongation, root development, and improved nutrient uptake efficiency in a study by Singh and Singh [2]. Similarly, Myageri and Dawson [23] observed that the positive effect of boron (B) on plant height is likely due to its contribution to cell wall formation and auxin metabolism, both of which are essential for regulating vegetative growth conditions. The synergistic interaction between P and B observed during the pre-monsoon season indicates that the combined availability of these nutrients enhances metabolic processes, particularly under less humid. Similar results were reported by Uddin et al.[24]. This suggests that the simultaneous application of P and B can optimize plant growth by supporting key physiological functions, especially in environments with lower moisture levels

**4.2 Number of Branches**

The mean effect of varying rates of P and B application on the number of branches per plant in mungbean exhibited a highly significant difference. These findings were agreement with Lakshman and Dawson [25] and Pathak et al.[26], who reported that higher branching under P and B applications reflects improved carbohydrate partitioning and meristematic activity. The absence of interaction implies independent mechanisms: P’s role in energy metabolism and B’s function in tissue differentiation.

**4.3 Total Dry Matter**

A highly significant difference was observed in the total dry matter of mungbean across the different rates of phosphorus. Swamy et al [27] stated that P application Increased dry matter with higher P levels is due to improved nutrient availability and enhanced photosynthetic activity from better light exposure. There was a highly significant difference on dry matter of mungbean was found among different rates of B application. These findings can be supported by Tekale et al.[28] who stated that B affects cell division, and plants may develop more quickly if they absorb nitrogen from the soil, which results in their dry weight.

**4.4 Number of Pods plant-1**

The number of pods per plant of mungbean was highly significant by the effect of different rates of P application. Similar finding was observed by Dikr & Garkebo [29] who reported that pod numbers increased with P due to its role in flower initiation and pollen viability. The effect of different rates of B application on the number of pods plant-1 of mungbean was highly significant. while B’s effect relates to pollen tube growth and stigma receptivity in a study by Quddus et al. [30]. The strong P × B interaction highlights their combined influence on reproductive success, particularly under favorable monsoon conditions.

**4.4 Number of Seeds Pod-1**

The increase in seeds per pod at higher P levels is attributed to improved nutrient availability, enhanced carbohydrate accumulation, and better remobilization to reproductive parts. Similarly, it was reported by Dash & Debbarma [31]. Boron treatment increases the number of flowers, which makes the stigma sticky and responsive, making pollen seeds viable. Better pollination results in more seeds per pod aligns with the finding by Ramya et al.[32]. The monsoon-specific interaction may reflect enhanced B mobility under higher rainfall, improving nutrient utilization.

**4.5 100-Seed Weight**

higher P levels increased seed weight. This observations was supported by the result Masih et al.[33] who reported that the increased in seed weight is linked to enhanced photosynthate transfer to grains, promoting seed size and number. B also increased seed weight, as indicated by Mubeen et al.2020 [34] who reported that B’s effect on sugar metabolism and cell division supports seed filling. The ‘lack of interaction in the monsoon may indicate B leaching under heavy rainfall.

**4.6 Seed Yield**

Phosphorus increases yield by supporting root development, enhancing nitrogen fixation, improving nutrient availability, and optimizing rhizosphere conditions corroborates with the finding of Masih et al.[33]. Quddus et al.[30] stated that boron is essential for cell membrane function, potassium transport, and water balance regulation, supporting xylem vessels and root hair tips to boost plant growth and yield. The yield-maximizing effects of P₃B₂ reflect integrated improvements in vegetative growth, reproductive efficiency, and resource allocation. The non-significant difference between P₃B₂, P₂B₂, and P₃B₁ suggests that 40 kg P ha⁻¹ with 1.0 kg B ha⁻¹ (P₂B₂) could optimize yield while reducing input costs. This aligns with findings by Jakhar et al.[35], emphasizing balanced P-B fertilization for sustainable mungbean production.

**5. CONCLUSION**

The combined treatment P₃B₂ (60 kg P + 1.0 kg B ha⁻¹) maximized seed yield (1,401.74 kg ha-1 in monsoon) by improving pod formation and seed retention. However, P₂B₂ (40 kg P + 1.0 kg B ha⁻¹) yielded comparable results at lower P input. Significant P × B interactions were observed for pods per plant, seeds per pod, and seed yield, highlighting synergistic effects. The study concludes that balanced P-B fertilization, particularly P₂B₂, optimizes mungbean productivity while reducing input costs, emphasizing the importance of integrating these nutrients for sustainable cultivation. The comparable performance of P₂B₂ suggests that optimal nutrient management can achieve high productivity with reduced fertilizer input. This has important implications for sustainable agriculture, as it promotes resource efficiency without compromising yield. Future research should explore long-term soil health effects and site-specific nutrient recommendations to further refine fertilization strategies.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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