

Research article

Impact of Phosphorus and *Rhizobium* on Mungbean Seed Yield and Nodulation

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Abstract

Mungbean plays a crucial role as a rotational crop, enhancing soil fertility and contributing to sustainable nutrient management. The integration of biofertilizers further supports environmentally friendly and sustainable farming practices. To investigate the combined influence of *Rhizobium* inoculation and phosphorus fertilization on the yield of mungbean (cv. Binamoog-8), an experiment was conducted at the Agronomy Field Laboratory, Bangladesh Agricultural University, Mymensingh, from October 2023 to February 2024. The study was designed as a split-plot with three replications. *Rhizobium* inoculation (two levels: without inoculation and with inoculation) was assigned to the main plots, while phosphorus levels (five levels: 0, 10, 15, 20, and 25 kg P ha⁻¹) were allocated to the subplots. Seeds were pre-treated with molasses and subsequently coated with microbial (*Rhizobium*) fertilizer before sowing. The findings showed that the application of *Rhizobium* inoculation and 20 kg of phosphorus ha⁻¹ enhanced the growth parameters (plant height, number of branches plant⁻¹ at 60 DAS and number of nodules plant⁻¹ at 45 DAS) and the yield parameters of mungbean (number of seeds pod⁻¹, pod length, 1000 seeds weight, seed yield, stover yield, biological yield, and harvest index). The results of interaction effect revealed that the combined application of *Rhizobium* inoculation and 20 kg of phosphorus ha⁻¹ improved the growth parameters (plant height, number of branches plant⁻¹ at 60 DAS and number of nodules plant⁻¹ at 45 DAS) and the yield parameters of the crop (pod length, 1000 seeds weight, seed yield). The soil quality was also improved by the combined application of *Rhizobium* and phosphorus. The result showed an effective improvement of soil pH, organic matter, soil nitrogen, sulfur, potassium, and phosphorus from the combination of *Rhizobium* inoculation and 20 kg of phosphorus ha⁻¹.

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application. Thus, the use of *Rhizobium* inoculation and 20 kg of phosphorus ha⁻¹ in mungbean cultivation is recommended in order to obtain the maximum seed output.

Keywords: *Rhizobium* inoculation; phosphorus; biological yield; mungbean; Bangladesh

1. Introduction

Mungbean (*Vigna radiata*) is a prominent pulse crop which is also known as green gram. It encompasses around 7.3 million hectares of cultivable areas worldwide, mostly in South Asia (Nair et al., 2020). The demand for this crop is increasing globally, driven by its nutritional benefits and versatility in various culinary applications. This pulse crop is particularly favored in developing countries, where it serves as a significant protein source and fits well into diverse cropping systems (Kumar et al., 2022). Due to its short duration crop cycle, mungbean has been easily adopted into the agro-ecosystem of Bangladesh during Kharif and Rabi seasons. It can be planted as an intercrop or used as a rotational crop and cash crop due to its quick growth and early maturity. However, because of biotic and abiotic restrictions, the yields of mungbean in Bangladesh are significantly lower than those in other nations (Nair et al., 2020).

In Bangladesh, mungbean output has changed significantly in recent years. The area and production in 2017-18 were 93 thousand acres and 34 thousand metric tons respectively, whereas it increased in 2022-23 to 113 thousand acres and 46 thousand metric tons respectively (BBS, 2023). Therefore, about 11.35% of yield rate increases in recent times of mungbean production in Bangladesh. There is a huge possibility of extension of this pulse crop and to ensure food security for poor people by utilizing the protein requirement at lower budget. However, due to inadequate agricultural methods and nutritional imbalance, Bangladesh only produces 0.65 million tons of pulses compared to a requirement of 2.7 million tons, indicating a greater potential for mungbean growth (Hasan et al., 2023). Consequently, in order to increase mungbean production, farmers must concentrate on nodulation and seed yield. The nodulation rate is very low in most of the mungbean growing areas of Bangladesh due to several interrelated factors, including soil nutrient levels, environmental conditions, and the effectiveness of rhizobial inoculation (Hussain et al., 2014). Understanding these factors is crucial to study their effect for improving the yield and environment.

Mungbean is a leguminous crop; it forms a symbiotic relationship with *Rhizobium* bacteria in its root nodules, allowing it to fix atmospheric nitrogen. This significantly reduces its reliance on external nitrogen fertilization. Therefore, *Rhizobium* culture inoculation is an extremely economical and cost-effective way of nitrogen fertilization for legumes. Because of atmospheric nitrogen fixation, the demand for nitrogen in legume crops is lower than that for phosphorus (40-60 kg P₂O₅) (Rani et al., 2016). In addition to improving grain quality, phosphorus increases the productivity of both the primary crops and following crops. It is recommended to apply 20-40 kg K₂O ha⁻¹ of potassium from the muriate of potash source (Islam et al., 2024), which can enhance grain filling and seed quality (Kundu et al., 2025). However, recent research highlighted that the combined effects of phosphorus and *Rhizobium* inoculation had a synergistic effect on legume output and soil fertility (beneficial for subsequent crops), lowered greenhouse gas emissions, and was environmentally beneficial (Hannan et al., 2022; Ghafoor et al., 2023; Islam et al., 2024). The recent scientific community has acknowledged the importance of the interaction of phosphorus and *Rhizobium* for mungbean seed yield and nodulation (Ma & Chen, 2021; Hannan et al., 2022; Ghafoor et al., 2023).

The use of biofertilizer is necessary for the conversion of atmospheric nitrogen into a form that is readily absorbed by plants. It can improve nitrogen fixation and nodulation, solubilize insoluble phosphorus sources, promote plant growth, and speed up the breakdown of plant waste (Bam et al., 2022). It is eco-friendly, cost-effective, and environmentally sustainable contributing to the cause of sustainable agriculture. It also lessens reliance on chemical fertilizers (Sood et al., 2023). Chemical fertilizers enhance environment pollution and decrease the yield performance (Seleiman et al., 2020). Recently, several organisms including *Rhizobium* and *Bradyrhizobium* are being used in legume crops for producing atmospheric nitrogen fixation through symbiosis. Rhizobia are essential for crop yield because biological nitrogen fixation is the process that converts elemental N₂ into ammonia (Htwe et al., 2018). *Bradyrhizobium* is a typical agronomic inoculant used to enhance plant nodulation and nitrogen fixation (Gough et al., 2021). The Bangladesh Institute of Nuclear Agriculture (BINA) identified many *Rhizobium/Bradyrhizobium* strains for pulse crops (particularly mungbean) as a substitute for nitrogenous fertilizers to meet the demand and save cost. *Rhizobium* inoculation of mungbean was able to fix 20-40 kg nitrogen ha⁻¹ (Tena et al., 2016).

In contrast, phosphorus is a component of deoxyribonucleic acid (DNA), which is the genetic material found in all living things, and plants use adenosine triphosphate (ATP) as their energy currency (Dissanayaka et al., 2021). Mungbean, as a legume crop, needs more balanced forms of mineral nutrients, particularly phosphorus, when compared to other nutrients like potassium and nitrogen (Dubey et al., 2018). Without the right phosphorus delivery, rhizobial activity and nitrogen fixation are reduced. In order to increase phosphorus's efficiency, biofertilizer converts insoluble phosphorus into forms that are readily available. Phosphorus forms that are unavailable to plants can be dissolved by microorganisms such as plant growth promoting rhizobacteria (PGPR) (Alori et al., 2017). This microbial activity enhances nitrogen intake by encouraging nodulation and root growth. *Rhizobium* inoculant and phosphorus fertilizer usage affected legume crop nodulation and nitrogen fixation (Alene et al., 2021). Phosphorus frequently forms compounds that plants cannot use as it binds firmly to elements like Ca, Fe, and Al, among others. The administration of phosphorus and *Rhizobium* inoculant together were shown to enhance plant height, total number of pods, number of grains pod⁻¹, and number of nodules plant⁻¹ (Arif et al., 2014). Mungbean is a very important pulse crop, but its productivity is low in the tropical and subtropical regions. The main objective of this research is to increase productivity and decrease reliance on synthetic chemicals by the use of *Rhizobium*. Although several studies have been conducted in recent years, soil nutrient levels continue to decline and vary greatly across agro-ecological zones. Through this research, soil conditions and appropriate nutrient dosages were assessed. The available *Rhizobium* strains are often scarce and difficult to preserve, which makes it difficult for farmers to successfully use this biofertilizer due to a lack of understanding. Subsequently, the use of this biofertilizer in crops can lower fertilizer costs and lessen reliance on chemical fertilizers. Although controlled pot experiments using *Rhizobium* have often shown better results than field-level experiments, farmers are unable to achieve the same yield in the field. Even though several studies have examined changes in soil characteristics before and after fertilizer application, limited research has been focused on the combined effects of phosphorus and *Rhizobium* inoculation on soil properties under mungbean cultivation in this region. This experiment was also aimed at improving the soil nutrient level, with analysis of the soil parameters following the combination application. Thus, the current study was conducted to determine the effects of the optimal phosphorus and *Rhizobium* inoculant combination on nodulation, yield, and yield-contributing characteristics of Bangladeshi mungbean production.

2. Materials and Methods

2.1 Explanation of the experiment site and agro-climatic condition

The field experiment was carried out throughout the Rabi season, from October 2023 to February 2024, at the Agronomy Field Laboratory, Bangladesh Agricultural University, Mymensingh. The experimental field, located at 24.75° N latitude and 90.5° E longitude, is 18 meters above sea level and forms part of the Old Brahmaputra Sedimentary Floodplain (AEZ-9). The land is of medium height, and the soil was a silty loam, well-drained, and had a low fertility level. The soil at this location is classified as non-calcareous dark-grey floodplain soil. The experimental site experiences a subtropical climate during the Kharif season (April to September), characterized by high temperatures, high humidity, and substantial rainfall. Conversely, from October to March, the study area experiences little rainfall and relatively low temperatures.

2.2 Experimental design and treatments

Three replications and a split plot design were used for the experiment, with phosphorus being spread in subplots and *Rhizobium* in main plots. Every replication served as an experimental block. The experiment was laid out in thirty plots. The experimental design combined Factor A: Biofertilizer (two levels) with Factor B: Phosphorus (five levels), three replications, resulting in a $2 \times 5 \times 3$ factorial arrangement. Each unit plot had a net size of 10 m² (4 m $\times$ 2.5 m). Mungbean seeds were sown at a recommended rate of 25 kg ha⁻¹. Prior to sowing, the seeds underwent a two-step coating process. First, seeds were placed in a polythene bag and mixed with 25 grams of molasses per kilogram of seed to achieve a reddish-brown coating. Subsequently, 50 g of microbial (*Rhizobium*) fertilizer were mixed with one kilogram of these molasses-coated seeds, which resulted in a distinct black coating. Sowing was conducted in the early morning (before 9:00 AM).

Two factors were included in the study (A) biofertilizer and (B) phosphorus level.

Factor A: Biofertilizer (*Rhizobium* inoculation): without *Rhizobium* inoculation (R₀) and with *Rhizobium* inoculation (R₁).

Factor B: Fertilizer with phosphorus: five different phosphorus levels were used from DAP fertilizer: No phosphorus (P₀); 10 kg P ha⁻¹ (P₁); 15 kg P ha⁻¹ (P₂); 20 kg P ha⁻¹ (P₃); and 25 kg P ha⁻¹ (P₄).

2.3 Collection of *Rhizobium* and planting materials

The experimental crop used in this study was a high-yielding mungbean cultivar: Bina moog-8, which was developed by the Bangladesh Institute of Nuclear Agriculture (BINA). This mungbean cultivar can be grown in Bangladeshi pulse-growing regions and it is resistant to *Cercospora* leaf spot and yellow mosaic virus. *Bradyrhizobium* (a subgroup of *Rhizobium*) strain BAUR-604 obtained from BINA's Soil Microbiology Laboratory in Mymensingh was used for the mungbean production.

2.4 Experimental land and layout preparation

In order to attain the medium tilth needed for the crop, the experimental plot was first opened on October 16, 2023, using a power tiller. It was then ploughed twice using a country plough and laddering. The field was eventually prepared on October 18, 2023,

using a country plough and laddering. The furrows were covered with soil shortly after the seeds were planted on October 17, 2023. Plant-to-plant distance was 7 cm, line-to-line distance was 30 cm, and replication-to-replication was 1 m. A recommended seed rate of 25 kg ha⁻¹ was used to determine the amount of seed needed for each plot. Plots were treated by applying a specific rate of biofertilizer and phosphorus level. Triple super phosphate (TSP), muriate of potash (MOP), and gypsum were all treated at rates of 40 kg ha⁻¹, 35 kg ha⁻¹, and 45 kg ha⁻¹, respectively.

2.5 Crop husbandry

At 15 and 30 days after sowing (DAS), weeding and thinning were carried out. Since there were no signs of moisture stress during the trial, no irrigation was administered. At 50% pod formation stage, Malathion 57EC g 1.5 L ha⁻¹ was applied to effectively control aphids and pod borers.

2.6 Observation, data collection, and analysis

Five randomly chosen plants from each plot were uprooted prior to harvesting in order to collect data. The remaining plants were harvested in plots, wrapped separately, marked, and transported to the Agronomy Field Laboratory's threshing floor. A variety of data were recorded, including growth data (plant height, number of branches, number of leaves, number of nodules, and shoot and root dry weight at 30, 45, and 60 DAS) and yield data (number of filled and unfilled pods per plant, length of the pod, weight of 1000 seeds, number of seeds/pod, seed yield, stover yield, biological yield, harvest index). The yield data were collected on February 8, 2024. Soil samples were analyzed at the Soil Science Laboratory of the Bangladesh Institute of Nuclear Agriculture (BINA) to determine key chemical properties. Soil pH was measured with a glass electrode pH meter in a 1:2.5 soil–water suspension. Organic carbon content was determined following the Walkley–Black wet oxidation method. Total nitrogen was analyzed by the Kjeldahl digestion method. Available phosphorus was extracted and determined using the Olsen method, suitable for neutral soils. Exchangeable potassium was measured by flame photometry after extraction with 1 N ammonium acetate, and available sulfur was determined by the turbidimetric method using calcium dihydrogen phosphate extraction. Finally, using the MSTAT-C package program, a statistical analysis was conducted on the collected data based on a number of criteria to determine the level of significance. Duncan's Multiple Range Test was used to compare the mean differences (DMRT) (Gomez & Gomez, 1984).

3. Results and Discussion

3.1 Results

3.1.1 Effect of *Rhizobium* and phosphorus on growth parameters

The phosphorus level and *Rhizobium* inoculation had a substantial impact on the growth indicators, which included plant height, number of branches, and number of nodules per plant. At 60 DAS, the tallest plant height with *Rhizobium* inoculation was 65.38 cm, while the plant height without *Rhizobium* inoculation was the shortest (58.02 cm) (Table 1). Similarly, phosphorus application at 20 kg P ha⁻¹ resulted in the tallest plant height (64.39

cm), while the absence of phosphorus at 60 DAS led to the lowest plant height (57.89 cm) at 60 days (Table 1). Furthermore, the maximum number of branches was 5.4 with *Rhizobium* inoculation, and the minimum number was 3.8 without *Rhizobium* inoculation at 60 DAS. No branches were produced at 30 and 45 DAS (Table 2). When 20 and 25 kg P ha⁻¹ of phosphorus were applied at 60 DAS, the greatest number of branches per plant (5.17) was observed (Table 2). In the case of nodules, maximum numbers (50.20) were produced with *Rhizobium* inoculation, and lower numbers (29.00) were produced without *Rhizobium* inoculation at 45 DAS (Table 3). Again, the highest number of nodules was produced (46.17) from 20 kg P ha⁻¹ application at 45 DAS (Table 3). After 45 DAS, the number of nodules gradually declined.

Table 1. Effect of *Rhizobium* inoculation and phosphorus level on plant height of mungbean at different DAS

<i>Rhizobium</i> Inoculation	Plant Height (cm)		
	30 DAS	45 DAS	60 DAS
R ₀	31.33 ^b	52.31 ^b	58.02 ^b
R ₁	32.38 ^a	59.49 ^a	65.38 ^a
Level of significance	**	**	**
CV (%)	6.12	7.06	6.83
Phosphorus level			
P ₁	31.22 ^b	52.89 ^c	57.89 ^d
P ₂	31.56 ^{ab}	53.28 ^c	60.50 ^c
P ₃	32.23 ^a	55.45 ^b	61.78 ^{bc}
P ₄	32.00 ^{ab}	58.95 ^a	64.39 ^a
P ₅	32.28 ^a	58.95 ^a	63.95 ^{ab}
Level of significance	*	**	**
CV (%)	6.12	7.06	6.83

Notes: Means with the same letters within the same column do not differ significantly. ** = Significant at 1% level of probability. R₀ = without *Rhizobium* inoculation (control), R₁ = with *Rhizobium* inoculation, P₁ = No phosphorus, P₂ = 10 kg P ha⁻¹, P₃ = 15 kg P ha⁻¹, P₄ = 20 kg P ha⁻¹, P₅ = 25 kg P ha⁻¹.

3.1.2 Interaction effects of *Rhizobium* and phosphorus on the growth parameters

Rhizobium and phosphorus had an equally substantial interaction effect on plant height, number of branches per plant, and number of nodules per plant. At 60 DAS, the plants treated with *Rhizobium* inoculation and 20 kg ha⁻¹ phosphorus application had the tallest plant height (70.56 cm), while the plant treated with neither had the lowest plant height (56.56 cm) (Table 4). Additionally, 20 kg ha⁻¹ of phosphorus and *Rhizobium* were applied at 60 DAS, resulting in the highest number of branches per plant (6.33) (Table 5). At 45 DAS, the combination of *Rhizobium* and 20 kg ha⁻¹ phosphorus application produced the most nodules per plant (58.33), while the combination of *Rhizobium* and no phosphorus application produced the fewest (20.33) nodules per plant (Table 6).

Table 2. Effect of *Rhizobium* inoculation and phosphorus level on number of branches plant⁻¹ of mungbean at 60 DAS

<i>Rhizobium</i> Inoculation		Number of Branches Plant⁻¹ 60 DAS
R ₀		3.8 ^b
R ₁		5.4 ^a
Level of significance		**
CV (%)		10.68
Phosphorus level		
P ₁		3.83 ^c
P ₂		4.50 ^b
P ₃		4.33 ^{bc}
P ₄		5.17 ^a
P ₅		5.17 ^a
Level of significance		**
CV (%)		10.68

Notes: No branches were produced at 30 and 45 DAS. Means with the same letters within the same column do not differ significantly. ** = Significant at 1% level of probability. R₀ = without *Rhizobium* inoculation (control), R₁ = with *Rhizobium* inoculation, P₁ = No phosphorus, P₂ = 10 kg P ha⁻¹, P₃ = 15 kg P ha⁻¹, P₄ = 20 kg P ha⁻¹, P₅ = 25 kg P ha⁻¹.

Table 3. Effect of *Rhizobium* inoculation and phosphorus on number of nodules plant⁻¹ of mungbean at different DAS

<i>Rhizobium</i> Inoculation	Number of Nodules Plant⁻¹		
	30 DAS	45 DAS	60 DAS
R ₀	14.60 ^b	29.00 ^b	14.87 ^b
R ₁	32.07 ^a	50.20 ^a	25.93 ^a
Level of significance	**	**	**
CV (%)	9.53	8.23	9.88
Phosphorus level			
P ₁	16.83 ^b	30.50 ^d	16.33 ^d
P ₂	19.50 ^b	36.33 ^c	18.83 ^c
P ₃	24.83 ^a	40.17 ^{bc}	20.67 ^{bc}
P ₄	28.17 ^a	46.17 ^a	24.67 ^a
P ₅	27.33 ^a	44.83 ^{ab}	21.50 ^b
Level of significance	**	**	**
CV (%)	9.53	8.23	9.88

Notes: Means with the same letters within the same column do not differ significantly. ** = Significant at 1% level of probability. R₀ = without *Rhizobium* inoculation (control), R₁ = with *Rhizobium* inoculation, P₁ = No phosphorus, P₂ = 10 kg P ha⁻¹, P₃ = 15 kg P ha⁻¹, P₄ = 20 kg P ha⁻¹, P₅ = 25 kg P ha⁻¹.

Table 4. Interaction effect of *Rhizobium* inoculation and phosphorus levels on mungbean plant height at various DAS

<i>Rhizobium</i> Inoculation × Phosphorus Level	Plant Height (cm)		
	30 DAS	45 DAS	60 DAS
R ₀ P ₁	30.78 ^d	50.22 ^{fg}	56.56 ^e
R ₀ P ₂	31.45 ^{cd}	49.45 ^g	58.78 ^{de}
R ₀ P ₃	31.67 ^{b-d}	52.56 ^{ef}	57.78 ^e
R ₀ P ₄	30.78 ^d	54.23 ^{de}	58.22 ^e
R ₀ P ₅	32.00 ^{bc}	55.11 ^{c-e}	58.78 ^{de}
R ₁ P ₁	31.67 ^{b-d}	55.56 ^{b-d}	59.22 ^{de}
R ₁ P ₂	31.67 ^{b-d}	57.11 ^{bc}	62.23 ^{cd}
R ₁ P ₃	32.78 ^{ab}	58.34 ^b	65.78 ^{bc}
R ₁ P ₄	33.22 ^a	63.67 ^a	70.56 ^a
R ₁ P ₅	32.56 ^{a-c}	62.78 ^a	69.11 ^{ab}
Level of significance	*	*	**
CV (%)	6.12	7.06	6.83

Notes: Means with the same letters within the same column do not differ significantly. ** = Significant at 1% level of probability. R₀ = without *Rhizobium* inoculation (control), R₁ = with *Rhizobium* inoculation, P₁ = No phosphorus, P₂ = 10 kg P ha⁻¹, P₃ = 15 kg P ha⁻¹, P₄ = 20 kg P ha⁻¹, P₅ = 25 kg P ha⁻¹.

Table 5. Interaction effects of *Rhizobium* inoculation and phosphorus levels on number of branches plant⁻¹ of mungbean at 60 DAS

<i>Rhizobium</i> Inoculation × Phosphorus Level	Number of Branches Plant ⁻¹
	60 DAS
R ₀ P ₁	3.33 ^f
R ₀ P ₂	3.67 ^{ef}
R ₀ P ₃	3.33 ^f
R ₀ P ₄	4.00 ^{d-f}
R ₀ P ₅	4.67 ^{cd}
R ₁ P ₁	4.33 ^{de}
R ₁ P ₂	5.33 ^{bc}
R ₁ P ₃	5.33 ^{bc}
R ₁ P ₄	6.33 ^a
R ₁ P ₅	5.67 ^{ab}
Level of significance	*
CV (%)	10.68

Notes: No branches were produced at 30 and 45 DAS. Means with the same letters within the same column do not differ significantly. ** = Significant at 1% level of probability. R₀ = without *Rhizobium* inoculation (control), R₁ = with *Rhizobium* inoculation, P₁ = No phosphorus, P₂ = 10 kg P ha⁻¹, P₃ = 15 kg P ha⁻¹, P₄ = 20 kg P ha⁻¹, P₅ = 25 kg P ha⁻¹.

Table 6. Interaction effects of *Rhizobium* inoculation and phosphorus levels on number of nodules plant⁻¹ of mungbean at different DAS

<i>Rhizobium</i> Inoculation x Phosphorus Level	Number of Nodules Plant ⁻¹		
	30 DAS	45 DAS	60 DAS
R ₀ P ₁	10.33 ^e	20.33 ^f	11.67 ^f
R ₀ P ₂	10.33 ^e	28.00 ^{ef}	14.00 ^{ef}
R ₀ P ₃	14.00 ^{de}	30.00 ^e	16.67 ^e
R ₀ P ₄	18.00 ^{cd}	31.33 ^e	16.33 ^e
R ₀ P ₅	20.33 ^c	35.33 ^{de}	15.67 ^e
R ₁ P ₁	23.33 ^{bc}	40.67 ^{cd}	21.00 ^d
R ₁ P ₂	28.67 ^b	44.67 ^{bc}	23.67 ^{cd}
R ₁ P ₃	35.67 ^a	50.33 ^{ab}	24.67 ^{bc}
R ₁ P ₄	36.67 ^a	58.33 ^a	33.00 ^a
R ₁ P ₅	36.00 ^a	57.00 ^a	27.33 ^b
Level of significance	*	*	*
CV (%)	9.53	8.23	9.88

Notes: Means with the same letters within the same column do not differ significantly. ** = Significant at 1% level of probability. R₀ = without *Rhizobium* inoculation (control), R₁ = with *Rhizobium* inoculation, P₁ = No phosphorus, P₂ = 10 kg P ha⁻¹, P₃ = 15 kg P ha⁻¹, P₄ = 20 kg P ha⁻¹, P₅ = 25 kg P ha⁻¹.

3.1.3 Effect of *Rhizobium* and phosphorus on yield parameters

In this study, the rhizobium and phosphorus levels had a substantial impact on the number of filled and unfilled pods. *Rhizobium* inoculation produced the greatest number of full pods (10.27), while rhizobium-free conditions produced the greatest number of unfilled pods. The greatest number of full pods (12.17) was generated at a phosphorus level of 20 kg ha⁻¹. *Rhizobium* inoculation produced the highest pod length (7.41 cm), number of seeds pod⁻¹ (11.17), 1000-seed weight (36.06 g), and seed yield (1.30 t ha⁻¹) (Table 7 and Figure 1). In contrast, 20 kg ha⁻¹ phosphorus application produced the highest pod length (7.41 cm), number of seeds pod⁻¹ (10.60), 1000-seed weight (33.89 g), and seed yield (1.43 t ha⁻¹) (Table 7 and Figure 1).

3.1.4 Interaction effect of *Rhizobium* and phosphorus on the yield parameters

The combination of *Rhizobium* and 20 kg ha⁻¹ phosphorus administration resulted in the highest number of full pods (14.00), pod length (8.00 cm), seeds pod⁻¹ (12.67), 1000-seed weight (38.99 g), and seed yield (1.55 t ha⁻¹) (Table 8 and Figure 2). The lowest number of filled pods (5.67), 1000-seeds weight (30.52) and seed yield (0.90 t ha⁻¹) were recorded for the crop without *Rhizobium* and without phosphorus application (Table 8 and Figure 2).

Table 7. Effect of *Rhizobium* inoculation and phosphorus levels on yield attributes and harvest index of mungbean at harvest

<i>Rhizobium</i> inoculation	Plant Height (cm)	No. of Branches Plant ⁻¹	No. of Filled Pods Plant ⁻¹	No. of Unfilled Pods Plant ⁻¹	Pod Length (cm)	No. of Seeds Pod ⁻¹	Dry Weight Plant ⁻¹ (g)	1000-Seed Weight (g)	Harvest Index (%)
R ₀	59.49 ^b	4.67 ^b	8.40 ^b	1.00	6.38 ^b	8.60 ^b	9.21 ^b	32.44	35.89 ^b
R ₁	66.78 ^a	6.13 ^a	10.27 ^a	0.73	7.41 ^a	10.60 ^a	17.03 ^a	33.89	38.07 ^a
Level of significance	**	**	**	NS	**	**	**	NS	**
CV (%)	5.58	10.63	9.60	5.71	5.88	9.55	6.69	2.94	5.55
Phosphorus level									
P ₁	59.61 ^c	4.50 ^b	6.33 ^c	0.83	6.23 ^c	7.67 ^c	10.87 ^d	30.68 ^c	31.81 ^d
P ₂	61.5 ^{bc}	5.33 ^a	7.33 ^c	1.17	6.68 ^{bc}	8.67 ^{bc}	11.70 ^c	31.79 ^{bc}	35.09 ^c
P ₃	63.22 ^{ab}	5.33 ^a	8.83 ^b	0.83	6.79 ^b	9.33 ^b	13.09 ^b	31.97 ^b	37.45 ^b
P ₄	65.95 ^a	6.00 ^a	12.17 ^a	0.67	7.41 ^a	11.17 ^a	15.07 ^a	36.06 ^a	40.02 ^a
P ₅	65.39 ^a	5.83 ^a	12.00 ^a	0.83	7.37 ^a	11.17 ^a	14.87 ^a	35.33 ^a	40.55 ^a
Level of significance	**	**	**	NS	**	**	**	**	*
CV (%)	5.58	10.63	9.60	5.71	5.88	9.55	6.69	2.94	5.55

Notes: Means with the same letters within the same column do not differ significantly. ** = Significant at 1% level of probability. R₀ = without *Rhizobium* inoculation (control), R₁ = with *Rhizobium* inoculation, P₁ = No phosphorus, P₂ = 10 kg P ha⁻¹, P₃ = 15 kg P ha⁻¹, P₄ = 20 kg P ha⁻¹, P₅ = 25 kg P ha⁻¹.

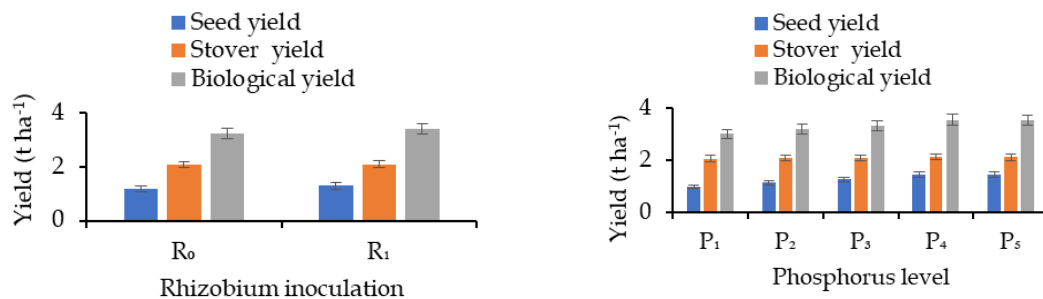
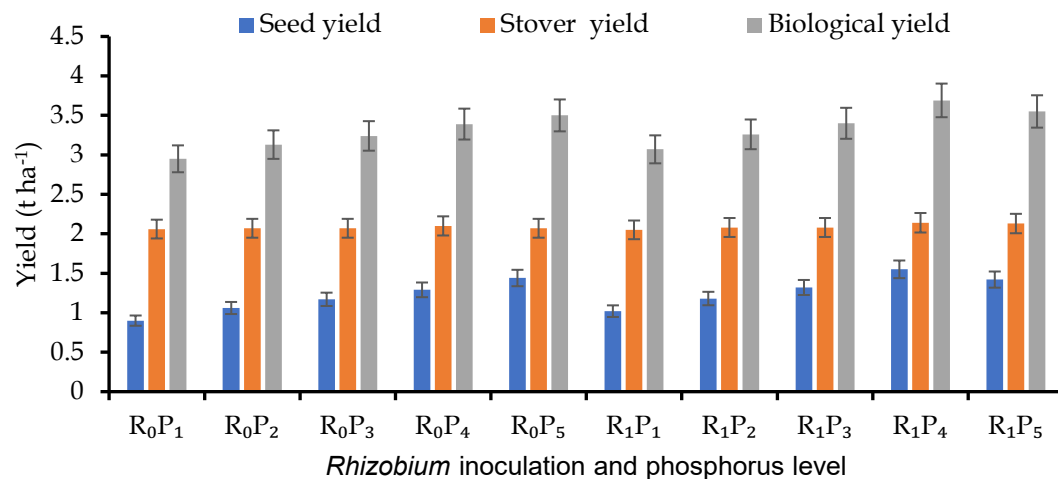
**Figure 1.** Effect of *Rhizobium* inoculation and phosphorus levels on seed, stover and biological yield of mungbean at harvest

Table 8. Interaction effects of *Rhizobium* inoculation and phosphorus levels on yield attributes and harvest index of mungbean at harvest

<i>Rhizobium</i> Inoculation x Phosphorus Level	Plant Height (cm)	No. of Branches Plant ⁻¹	No. of Filled Pod Plant ⁻¹	No. of Unfilled Pod Plant ⁻¹	Pod Length (cm)	No. of Seeds Pod ⁻¹	Dry Weight Plant ⁻¹ (g)	1000- Seed Weight (g)	Harvest Index (%)
R ₀ P ₁	57.78 ^e	3.67 ^f	5.67 ^f	0.67 ^{ab}	5.67 ^e	7.00 ^e	8.09 ⁱ	30.52 ^e	30.36 ^g
R ₀ P ₂	59.00 ^e	5.00 ^{de}	6.33 ^{ef}	1.67 ^a	6.24 ^{de}	7.67 ^e	8.20 ⁱ	31.63 ^{c-e}	33.90 ^f
R ₀ P ₃	59.33 ^e	4.67 ^e	7.67 ^{de}	1.00 ^{ab}	6.17 ^{de}	8.00 ^e	9.09 ^h	31.68 ^{c-e}	36.07 ^e
R ₀ P ₄	60.00 ^e	5.00 ^{de}	10.00 ^c	1.00 ^{ab}	6.73 ^{cd}	9.67 ^{cd}	9.78 ^g	33.13 ^c	38.13 ^d
R ₀ P ₅	61.33 ^{de}	5.00 ^{de}	12.33 ^b	0.67 ^{ab}	7.08 ^{bc}	10.67 ^{bc}	10.87 ^f	35.25 ^b	40.99 ^{ab}
R ₁ P ₁	61.44 ^{de}	5.33 ^{c-e}	7.00 ^{d-f}	1.00 ^{ab}	6.78 ^{cd}	8.33 ^{de}	13.64 ^e	30.85 ^{de}	33.25 ^f
R ₁ P ₂	64.00 ^{cd}	5.67 ^{cd}	8.33 ^d	0.67 ^{ab}	7.11 ^{bc}	9.67 ^{cd}	15.20 ^d	31.96 ^{c-e}	36.29 ^e
R ₁ P ₃	67.11 ^{bc}	6.00 ^{bc}	10.00 ^c	0.67 ^{ab}	7.41 ^{a-c}	10.67 ^{bc}	17.09 ^c	32.25 ^{cd}	38.82 ^{cd}
R ₁ P ₄	71.89 ^a	7.00 ^a	14.00 ^a	0.33 ^b	8.00 ^a	12.67 ^a	20.36 ^a	38.99 ^a	41.91 ^a
R ₁ P ₅	69.44 ^{ab}	6.67 ^{ab}	12.00 ^b	1.00 ^{ab}	7.73 ^{ab}	11.67 ^{ab}	18.87 ^b	35.41 ^b	40.1 ^{bc}
Level of significance CV (%)	*	*	**	*	*	*	**	**	*
	5.58	10.63	9.60	5.71	5.88	9.55	6.69	2.94	5.55

Notes: Means with the same letters within the same column do not differ significantly. ** = Significant at 1% level of probability. R₀ = without *Rhizobium* inoculation (control), R₁ = with *Rhizobium* inoculation, P₁ = No phosphorus, P₂ = 10 kg P ha⁻¹, P₃ = 15 kg P ha⁻¹, P₄ = 20 kg P ha⁻¹, P₅ = 25 kg P ha⁻¹.

**Figure 2.** Interaction effects of *Rhizobium* inoculation and phosphorus levels on seed, stover and biological yield of mungbean at harvest

3.1.5 Regression model for seed yield

The seed yield could be influenced by the yield contributing characteristics of mungbean. The study utilized the regression model to observe the effect of those variables on seed yield. The model's explanatory variable, number of filled pods, alone accounted for about 96% of the variances in grain yield. Similar results were observed in previous studies (El-Badawy & Mehasen, 2012; Bam et al., 2022), which showed that the plant height, number of branches, nodules per plant, number of seed/pod and 1000 seed weight accounted for 30%, 58%, 52%, 55% and 87% of the difference in seed output, respectively (Figure 3). Higher values of the above parameter were recorded with *Rhizobium* inoculation. Although plant height and branch quantity are important characteristics, their impact on seed yield production was less than that of filled pods and 1000 seed weight.

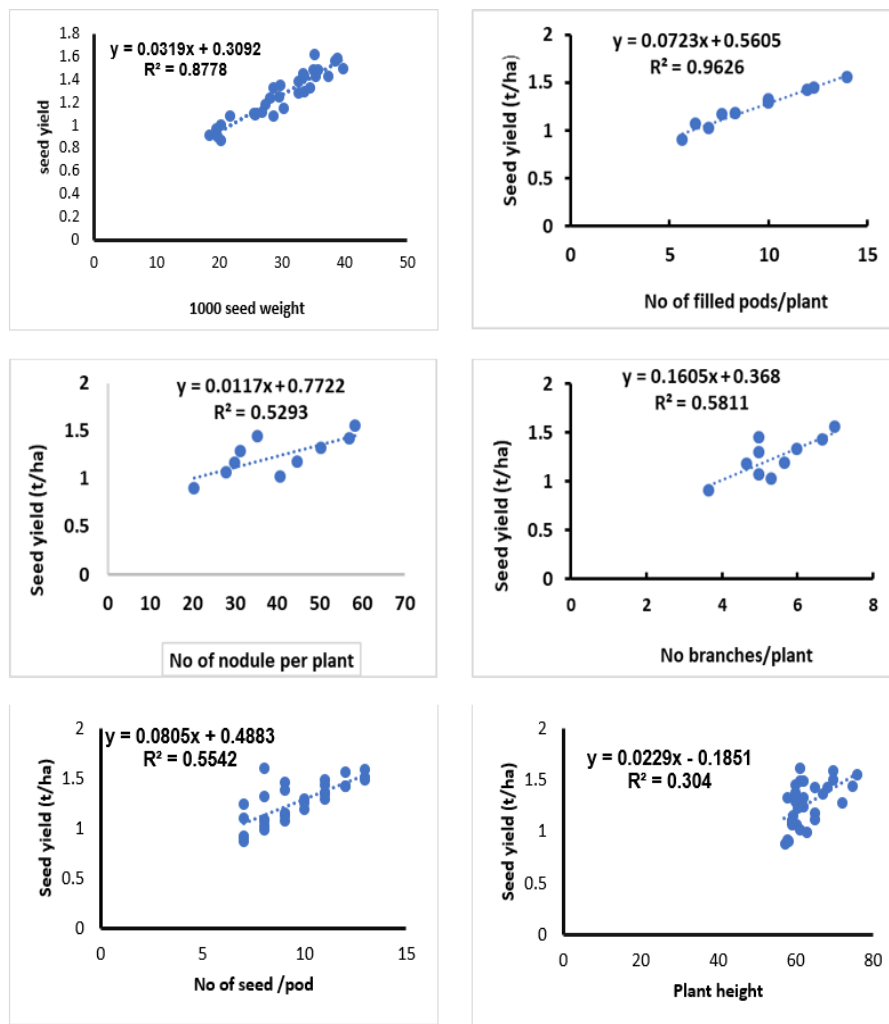


Figure 3. Relationship between seed yield and yield contributing characteristics

3.1.6 Effect of *Rhizobium* and phosphorus on the soil properties

Soil properties such as soil pH (7.28), organic matter (1.55), soil N (0.13%), sulfur (22.90 ppm), potassium (0.08 meq/100g), and phosphorus (19.92 ppm) were found to be maximum under *Rhizobium* inoculation (Table 9). Furthermore, the maximum soil pH (7.37), organic matter (1.51), soil N (0.11%), sulfur (22.25 ppm), and potassium (0.08 meq/100g) were obtained from the application of 20 kg phosphorus per hectare (Table 9).

Table 9. Effect of *Rhizobium* inoculation and phosphorus levels on soil properties

<i>Rhizobium</i> inoculation	Soil pH	Organic Carbon	Soil N (%)	Sulfur (ppm)	Potassium (meq/100g)	Phosphorus (ppm)
Initial Soil	7.10 ^c	1.01 ^b	0.01 ^b	15.01 ^b	0.042 ^c	13.69 ^b
R ₀	7.28 ^a	1.15 ^b	0.04 ^b	16.35 ^b	0.06 ^b	16.51 ^b
R ₁	7.22 ^b	1.55 ^a	0.13 ^a	22.90 ^a	0.08 ^a	19.92 ^a
Significance level	**	**	**	**	**	**
CV (%)	5.08	3.16	7.84	5.55	3.81	3.96
Phosphorus level						
Initial Soil	7.10 ^e	1.01 ^e	0.01 ^f	15.01 ^e	0.042 ^e	13.69 ^f
P ₁	7.37 ^a	1.22 ^d	0.05 ^e	16.85 ^d	0.06 ^d	16.96 ^e
P ₂	7.26 ^b	1.25 ^d	0.07 ^d	18.52 ^c	0.07 ^c	17.12 ^d
P ₃	7.24 ^c	1.32 ^c	0.09 ^c	18.66 ^c	0.07 ^b	18.21 ^c
P ₄	7.25 ^c	1.51 ^a	0.11 ^a	22.25 ^a	0.08 ^a	19.74 ^a
P ₅	7.16 ^d	1.45 ^b	0.10 ^b	21.85 ^b	0.08 ^a	19.04 ^b
Level of significance	**	**	**	**	**	**
CV (%)	5.08	3.16	7.84	5.55	3.81	3.96

Notes: Means with the same letters within the same column do not differ significantly. ** = Significant at 1% level of probability. R₀ = without *Rhizobium* inoculation (control), R₁ = with rhizobium inoculation, P₁ = No phosphorus, P₂ = 10 kg P ha⁻¹, P₃ = 15 kg P ha⁻¹, P₄ = 20 kg P ha⁻¹, P₅ = 25 kg P ha⁻¹.

3.1.7 Interaction effect of *Rhizobium* and phosphorus on soil properties

There was considerable variation observed for soil pH, organic matter, soil nitrogen, sulfur, potassium and phosphorus due to the interaction between *Rhizobium* and phosphorus level. The highest soil pH (7.43), organic carbon (1.83), soil N (0.18%), sulfur (27.21 ppm), and phosphorus (20.71 ppm) were recorded for the combination of *Rhizobium* inoculation and 20 kg ha⁻¹ phosphorus application (Table 10).

Table 10. Interaction effect of *Rhizobium* inoculation and phosphorus levels on soil properties

<i>Rhizobium</i> Inoculation x Phosphorus level	Soil pH	Organic Carbon	Soil N (%)	Sulfur (ppm)	Potassium (meq/100g)	Phosphorus (ppm)
Initial soil	7.10 ⁱ	1.01 ^g	0.01 ⁱ	15.01 ^j	0.042 ^h	13.69 ^k
R ₀ P ₁	7.30 ^c	1.09 ^f	0.03 ^h	15.06 ⁱ	0.05 ^g	14.89 ^j
R ₀ P ₂	7.32 ^b	1.10 ^f	0.04 ^{gh}	16.15 ^h	0.06 ^f	15.03 ⁱ
R ₀ P ₃	7.28 ^d	1.17 ^e	0.05 ^{fg}	15.05 ⁱ	0.06 ^e	16.33 ^h
R ₀ P ₄	7.28 ^d	1.19 ^e	0.05 ^f	17.30 ^g	0.07 ^d	17.37 ^g
R ₀ P ₅	7.22 ^e	1.21 ^e	0.05 ^f	18.20 ^f	0.07 ^{cd}	18.92 ^f
R ₁ P ₁	7.43 ^a	1.35 ^d	0.08 ^e	18.65 ^e	0.07 ^c	19.02 ^e
R ₁ P ₂	7.2 ^{fg}	1.41 ^{cd}	0.1 ^d	20.89 ^d	0.08 ^b	19.21 ^d
R ₁ P ₃	7.19 ^g	1.46 ^c	0.13 ^c	22.26 ^c	0.08 ^b	20.08 ^c
R ₁ P ₄	7.21 ^{ef}	1.83 ^a	0.18 ^a	27.21 ^a	0.08 ^a	20.71 ^a
R ₁ P ₅	7.09 ^h	1.69 ^b	0.16 ^b	25.50 ^b	0.08 ^a	20.56 ^b
Significance level	**	**	**	**	**	**
CV (%)	5.08	3.16	7.84	5.55	3.81	3.96

Notes: Means with the same letters within the same column do not differ significantly. ** = Significant at 1% level of probability. R₀ = without *Rhizobium* inoculation (control), R₁ = with *Rhizobium* inoculation, P₁ = No phosphorus, P₂ = 10 kg P ha⁻¹, P₃ = 15 kg P ha⁻¹, P₄ = 20 kg P ha⁻¹, P₅ = 25 kg P ha⁻¹.

3.2 Discussion

The characteristics of short-duration varieties, better cultivation techniques, and efficient soil management techniques are some of the reasons for the recent rise in mungbean yield. These factors support soil health, which is essential for long-term agricultural output, in addition to increasing yield. The study used a variety of characteristics to assess how *Rhizobium* inoculation, varying phosphorus dosage, and their interactions influenced the yield of mungbean.

A key aspect of phosphorus and *Rhizobium* synergy is the enhanced availability of phosphorus to plants. While phosphorus is abundant in many soils, it often exists in insoluble forms unavailable for plant uptake. *Rhizobium* and associated plant growth-promoting rhizobacteria (PGPR), including phosphate-solubilizing bacteria (PSB), play a vital role in converting these insoluble forms of phosphorus into plant-available forms through mechanisms like the secretion of organic acids and enzymes (Ahammad et al., 2025). This microbial activity directly increases the phosphorus pool accessible to the host legume. Again, phosphorus is necessary for *Rhizobium* to fix nitrogen efficiently, and its availability can encourage root growth, which raises the possibility of nodule formation, and supports the energy needs for nitrogen fixation, both of which have an impact on the rhizobia-legume symbiosis's success.

According to the study, applying 20 kg of phosphorus per hectare and inoculating plants with *Rhizobium* increased plant height. If the soil has moderate to high levels of accessible phosphorus (more than 20 kg P ha⁻¹), the plant will not be able to use the additional phosphorus. Excess phosphorus can cause micronutrients (such as iron and zinc) to become antagonistic, impede root development, inhibit biological nitrogen fixation, and ultimately raise costs and disrupt the soil's stability. The interaction effects of this combination are also favorable to plant height, number of branches, and effective nodules. In mungbean, the use of biofertilizers such as plant growth-promoting rhizobacteria (PGPR) has been shown to increase the plant height, number of branches, and nodules per plant (Bam et al., 2022). Numerous leguminous crops primarily benefit from *Rhizobium* or *Bradyrhizobium* strains, including biofertilizer based on *Rhizobium* or *Bradyrhizobium* (Ikbal et al., 2020). *Rhizobium* soil bacteria have the ability to develop certain structures (called nodules) in legume roots; they serve a crucial biological role in fixing nitrogen, particularly in leguminous plants like mungbean, cowpea, or common beans. These bacteria also generate a large quantity of phytohormones, including indole acetic acid (IAA), which can solubilize phosphorus and encourage plant development (Matse et al., 2020). When compared to absolute control, *Rhizobium* or *Azotobacter* seed inoculation significantly increased plant height, branches per plant, nodule quantity, and the number of effective nodules (Beovides-García et al., 2024). The inoculation even minimizes the dependency on synthetic nitrogen fertilizers while increasing soil fertility through crop rotation with non-legume crops. Therefore, *Rhizobium* plays a pivotal role in mungbean production in terms of environmental friendliness, financial savings and soil health.

Additionally, most studies have shown that phosphorus can increase nitrogenase activity and nodule formation in legume crops (Magadlela et al., 2015; Geletu & Mekonnen, 2018; Pérez-Fernández et al., 2019; Li et al., 2022). Phosphorus is essential for promoting plant growth and development by stimulating new cell production, improving vigor, and optimizing nitrogen utilization and solar energy harvesting. This multifaceted nutrient is essential for various physiological processes, which collectively contribute to improved growth characteristics in plants (Odoom & Ofosu, 2024). Plant height increased by 26.5% when *Rhizobium* and phosphorus were applied together, compared to the control. The reason for the greater rate of *Rhizobium* growth in plants is most likely due to increased nitrogen availability through biological fixation (Terefe et al., 2018). The significance of the application of 20 kg ha⁻¹ phosphorus in mungbean was also supported by Gebremariam and Tesfay (2021), Jamir et al., (2022) and Mbaka et al., (2022). In contrast, low phosphorus levels prevented nodule nitrogen fixing by preventing growth and phosphorus absorption (Magadlela et al., 2016). Nodules were unable to fix nitrogen when phosphorus levels were either too high or too low (Yao et al., 2018). This increase in nodulation, rooting, and growth may be the result of more nodules, which may have fixed nitrogen to supply enough nitrogen and ultimately raise green gram productivity (Singh et al., 2015).

Furthermore, the yield attributing characteristics also suggest a favorable response towards *Rhizobium* inoculation and 20 kg ha⁻¹ phosphorus applications. Phosphorus promotes growth, nodulation, root development, speeds up maturation, and enhances crop yield quality. Biofertilizers promote root development by generating growth-promoting chemicals such as cytokinins, auxins and gibberelins that enhance nodule dry weight, pod length, 1000 seeds weight. The number of seeds per pod of green gram was influenced by different levels of phosphorus (Das, 2016). Since phosphorus can influence the flower and seed formation, thereby enhancing length of pod and quantity of seeds in each pod. It is possible that the higher dry weight was caused by the

plant producing more dry matter as a result of growing taller and having more branches (Venkatarao et al., 2017; Dey et al., 2021). Previous results also suggested that *Rhizobium* strains have a significant effect on the number of pods per plant compared to un-inoculated control (Soe & Yamakawa, 2013; Htwe et al., 2019). Strong plant development and dry matter production enhance blooming, fruiting, and pod formation, all of which increase seed yield (Bam et al., 2022). Additionally, *Rhizobium* inoculation results in increased biological, stover, and seed yield (Htwe et al., 2019). An earlier study also discovered that phosphorus and *Rhizobium* worked together to increase the availability of key nutrients, which in turn improved the yield and harvest index (Geletu & Mekonnen, 2018).

In case of soil properties, the application of *Rhizobium* inoculation and phosphorus improved the soil quality (microbial growth, water and nutrient uptake capacity) (Ma et al., 2024) and properties such as organic carbon, nitrogen, phosphorus and potassium level. Biofertilizer improves the soil properties and soil structure, which then enhances the growth of beneficial microorganisms. It can reduce the damage and pollution of soil caused by excessive chemical use. Different soil properties such as soil pH, organic carbon, soil N, sulfur, phosphorus, and potassium were increased after harvesting. The results in our study were consistent with the findings of Geletu and Mekonnen (2018).

Thus, our future goal is to minimize farmer costing through reducing chemical fertilizer usages. The use of *Rhizobium* inoculation in combination with phosphorus fertilizer has shown potential to reduce dependence on chemical fertilizers, thereby lowering input costs for farmers. Previous research reported that biofertilizer-based management can decrease fertilizer costs by 20-30% while maintaining or enhancing legume yield (Islam et al., 2006; Geletu & Mekonnen, 2018). Therefore, integrating biofertilizers into existing fertilizer management systems could contribute to cost-effective and sustainable mungbean production in Bangladesh.

4. Conclusions

The purpose of the study was to determine how phosphorus application levels and *Rhizobium* inoculation affected Bangladesh's mungbean production. There were three different parameters tested, i.e. growth, yield, and soil parameters. The study results emphasized that biofertilizers were essential for leguminous plants such as mungbean, chickpea, soybean, lentil, black gram, and pea. Their application enhances soil properties, reduces the dependency on chemical fertilizer and ultimately contributes to sustainable agriculture. The application of biofertilizers can also increase plant height, nitrogen fixation, and uptake of other nutrients that can improve the yield performance. Phosphorus helps root growth, energy transfer, flowering and seeds formation that also can enhance the yield performance of mungbean. The suggested dose of phosphorus in Bangladesh is 20 kg per hectare, according to many field trials and research organizations; however, the amount may vary depending on the soil and climate. The recommended dosage of phosphorus varies globally depending on cropping intensity, environmental conditions, and fertility level. On the basis of this experiment, it can be concluded that mungbean production is improved from the combined application of *Rhizobium* and 20 kg ha⁻¹ phosphorus application.

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6. Authors' Contributions

Joysree Paul Tandra: designed and performed the research, collected data and analyzed, and wrote the manuscript; Papon Chandra Paul: designed the research and wrote the manuscript; Md. Rasheduzzaman: analyzed the data, wrote, and edited the manuscript; Md. Rashedur Rahman: designed and supervised the research, edited the manuscript, and coordinated the research; Md. Ekram ul Haque: analyzed the data, designed, supervised, and coordinated the research.

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7. Conflicts of Interest

The authors of this study affirm that they have no financial or personal disputes of interest with any other individuals or groups that would have an undue influence on this work.

References

- Ahammad, T., Islam, M. Z., Islam, M. A., Habib, M., Hossain, M. A., & Khan, M. J. I. (2025). Effects of zinc fertilization on various Mungbean cultivars in the Madhupur tract of Bangladesh. *Journal of Bangladesh Agricultural University*, 23(1), 9-17. <http://dx.doi.org/10.3329/jbau.v23i1.80818>
- Alene, A. A., Raffi, M. M., & Tiruneh, K. J. (2021). Phosphorus use efficiency, yield and nodulation of mung bean (*Vigna radiata* L.) as influenced by the rate of phosphorus and *Rhizobium* strains inoculation in Metema district, Ethiopia. *Journal of Plant Nutrition*, 44(9), 1300-1315. <https://doi.org/10.1080/01904167.2020.1849301>
- Alori, E. T., Glick, B. R., & Babalola, O. O. (2017). Microbial phosphorus solubilization and its potential for use in sustainable agriculture. *Frontiers in Microbiology*, 8, Article 971. <https://doi.org/10.3389/fmicb.2017.00971>
- Arif, H., Amjed, A., Tasneem, K., Ashfaq, A., Zubair, A., & Muhammad, A. (2014). Growth, nodulation and yield components of mung bean (*Vigna radiata*) as affected by phosphorus in combination with rhizobium inoculation. *African Journal of Agricultural Research*, 9(30), 2319-2323. <https://doi.org/10.5897/AJAR11.691>
- Bam, R., Mishra, S. R., Khanal, S., Ghimire, P., & Bhattarai, S. (2022). Effect of biofertilizers and nutrient sources on the performance of mungbean at Rupandehi, Nepal. *Journal of Agriculture and Food Research*, 10, Article 100404. <https://doi.org/10.1016/j.jafr.2022.100404>

- BBS. (2023). *Yearbook of agricultural statistics*. Bangladesh Bureau of Statistics, Statistics and Informatics Division, Ministry of Planning, Government of the People's Republic of Bangladesh.
- Beovides-García, Y., Pérez-Peñaranda², M. C., González-Marrero, I., Rayas-Cabrera, A., Basail-Pérez, M., Santos-Pino, A., Medero-Vega, V. R., & Mok, M. J. A. (2024). Effects of a new *Rhizobium*-based biofertilizer (Fertiliz) on growth and the yield of Cowpea (*Vigna unguiculata* (L.) Walp). *Environmental Analysis and Ecology Studies*, 12(1), Article 000778. <https://doi.org/10.31031/EAES.2024.12.000778>
- Das, S. K. (2016). Effect of phosphorus and sulphur on yield attributes, yield, nodulation and nutrient uptake of green gram [*Vigna radiata* (L.) Wilczek]. *Legume Research*, 40(1), 138-143.
- Dey, S. K., Singh, V., & Tiwari, D. 2021. Effect of phosphorus and sulphur on the growth and yield of summer mungbean (*Vigna radiata* L.). *The Pharma Innovation*, 10(8), 1442-1445.
- Dissanayaka, D. M. S. B., Ghahremani, M., Siebers, M., Wasaki, J., & Plaxton, W. C. (2021). Recent insights into the metabolic adaptations of phosphorus-deprived plants. *Journal of Experimental Botany*, 72(2), 199-223. <https://doi.org/10.1093/jxb/eraa482>
- Dubey, S. N., Singh, R., Kumar, R., & Dubey, S. (2018). Effect of phosphorus and PSB on growth, nodulation and fertility status in different mungbean (*Vigna radiata* L.) varieties and its residual effect on fodder yield of sorghum in indo-gangetic plain zone of India. *International Journal of Agricultural Sciences*, 14(1), 196-201. <https://doi.org/10.15740/HAS/IJAS/14.1/196-201>
- El-Badawy, M. El. M., & Mehasen, S. A. S. (2012). Correlation and path coefficient analysis for yield and yield components of soybean genotypes under different planting density. *Asian Journal of Crop Science*, 4(4), 150-158. <https://doi.org/10.3923/ajcs.2012.150.158>
- Gebremariam, M., & Tesfay, T. (2021). Effect of P application rate and *Rhizobium* inoculation on nodulation, growth, and yield performance of chickpea (*Cicer arietinum* L.). *International Journal of Agronomy*, 2021(1), Article 8845489. <https://doi.org/10.1155/2021/8845489>
- Geletu, T., & Mekonnen, F. (2018). The effect of bio and inorganic fertilizer on yield, nutrient uptake and economics of mungbean (*Vigna radiata* L. Wilczek) varieties in Ethiopia. *Journal of Agriculture and Research*, 3(11), Article 00212. <https://doi.org/10.23880/oajar-16000212>
- Ghafoor, A., Mahmood, K., Najeeb, S., Hussain, S., & Bilal, M. (2023). Influence of *Rhizobium* and phosphorus on growth, yield and quality of mungbean (*Vigna radiata* L.) under arid conditions. *Journal of Animal and Plant Sciences*, 33(1), 107-117.
- Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research* (2nd ed.). John Wiley and Sons.
- Gough, E. C., Owen, K. J., Zwart, R. S., & Thompson, J. P. (2021). Arbuscular mycorrhizal fungi acted synergistically with *Bradyrhizobium* sp. to improve nodulation, nitrogen fixation, plant growth and seed yield of mung bean (*Vigna radiata*) but increased the population density of the root-lesion nematode *Pratylenchus thornei*. *Plant and Soil*, 465(1-2), 431-452. <https://doi.org/10.1007/s11104-021-05007-7>
- Hannan, A., Huda, M. S., Sultana, M., Alam, M. R., & Islam, M. A. (2022). Effects of different levels of phosphorus and bradyrhizobium inocula on the productivity and protein content of mungbean (*Vigna radiata* L. Wilczek). *Open Access Journal of Science*, 5(1), 32-39. <https://doi.org/10.15406/oajs.2022.05.00173>
- Hasan, M., Sultana, S., & Jahan, M. A. (2023). The growth and yield performances of mungbean (*Vigna radiata* L.) as influenced by the use of cow dung and chemical

- fertilizers. *Journal of Bangladesh Academy of Sciences*, 47(1), 61-68. <https://doi.org/10.3329/jbas.v47i1.66025>
- Htwe, A. Z., Moh, S. M., Moe, K., & Yamakawa, T. (2018). Effects of co-inoculation of *Bradyrhizobium japonicum* SAY3-7 and *Streptomyces griseoflavus* P4 on plant growth, nodulation, nitrogen fixation, nutrient uptake, and yield of soybean in a field condition. *Soil Science and Plant Nutrition*, 64(2), 222-229. <https://doi.org/10.1080/00380768.2017.1421436>
- Htwe, A. Z., Moh, S. M., Soe, K. M., Moe, K., & Yamakawa, T. (2019). Effects of biofertilizer produced from *Bradyrhizobium* and *Streptomyces griseoflavus* on plant growth, nodulation, nitrogen fixation, nutrient uptake, and seed yield of mungbean, cowpea, and soybean. *Agronomy*, 9(2), Article 77. <https://doi.org/10.3390/agronomy9020077>
- Hussain, A., Ali, A., Khaliq, T., Ahmad, A., Aslam, Z., & Asif, M. (2014). Growth, nodulation and yield components of mung bean (*Vigna radiata*) as affected by phosphorus in combination with *Rhizobium* inoculation. *African Journal of Agricultural Research*, 9(30), 2319-2323. <https://doi.org/10.5897/AJAR11.691>
- Ikbal, Passricha, N., Saifi, S. K., Sikka, V. K., & Tuteja, N. (2020). Multilegume biofertilizer: a dream. In V. Sharma, R. Salwan, & L. K. T. Al-Ani (Eds.). *Molecular aspects of plant beneficial microbes in agriculture* (pp. 35-45). <https://doi.org/10.1016/B978-0-12-818469-1.00003-1>
- Islam, M. K., Islam, S. M. A., Harun-or-Rashid, M., Hossain, A. F. M. G. F., & Alom, M. M. (2006). Effect of biofertilizer and plant growth regulators on growth of summer mungbean. *International Journal of Botany*, 2(1), 36-41.
- Islam, M. R., Sarker, U., Azam, M. G., Hossain, J., Alam, M. A., Ullah, R., Bari, A., Hossain, N., Sabagh, A. E., & Islam, M. S. (2024). Potassium augments growth, yield, nutrient content, and drought tolerance in mung bean (*Vigna radiata* L. Wilczek.). *Scientific Reports*, 14, Article 9378. <https://doi.org/10.1038/s41598-024-60129-z>
- Jamir, A., Sentimenla, & Gohain, T. (2022). Response of phosphorus and biofertilizers on growth, yield attributes and economic indices of black gram (*Vigna mungo* L. Hepper). *International Journal of Environment and Climate Change*, 12(11), 3793-3801. <https://doi.org/10.9734/ijeccl/2022/v12i111432>
- Kumar, A., Yadav, P., Seema, Kumar, R. R., Kushwaha, A., Rashid, M. H., Tarannum, N., & Chakraborty, S. (2022). Mungbean (*Vigna radiata* (L.) R. Wilczek): Progress in breeding and future challenges. *International Journal of Plant and Soil Science*, 34(3), 50-59. <https://doi.org/10.9734/ijpss/2022/v34i330846>
- Kundu, N. D., Uddin, M. T., Sarkar, M. M. A., Toma, N. I., Rashid, M. M., & Ahmed, S. (2025). Profitability and value addition of mungbean production in Barishal and Patuakhali districts of Bangladesh. *Bangladesh Journal of Nuclear Agriculture*, 38(2), 137-149.
- Li, H., Wang, L., Zhang, Z., Yang, A., & Liu, D. (2022). Effect of phosphorus supply levels on nodule nitrogen fixation and nitrogen accumulation in soybean (*Glycine max* L.). *Agronomy*, 12(11), Article 2802.
- Ma, Y., & Chen, R. (2021). Nitrogen and phosphorus signaling and transport during legume-rhizobium symbiosis. *Frontiers in Plant Science*, 12, Article 683601. <https://doi.org/10.3389/fpls.2021.683601>
- Ma, Y., Suo, Y., Qi, H., Tang, F., & Wang, M. (2024). Effects of *Rhizobium* inoculation on rhizosphere soil microbial communities, physicochemical properties, and enzyme activities in Caucasian clover under field conditions. *Agronomy*, 14(12), Article 2880. <https://doi.org/10.3390/agronomy14122880>

- Magadlela, A., Pérez-Fernández, M. A., Kleinert, A., Dreyer, L. L., & Valentine, A. J. (2016). Source of inorganic N affects the cost of growth in a legume tree species (*Virgilia divaricata*) from the Mediterranean-type Fynbos ecosystem. *Journal of Plant Ecology*, 9(6), 752-761. <https://doi.org/10.1093/jpe/rtw015>
- Magadlela, A., Vardien, W., Kleinert, A., Dreyer, L. L., & Valentine, A. J. (2015). The role of phosphorus deficiency in nodule microbial composition, and carbon and nitrogen nutrition of a native legume tree in the Cape Fynbos ecosystem. *Australian Journal of Botany*, 63(5), 379-386. <https://doi.org/10.1071/BT14216>
- Matse, D. T., Huang, C. H., Huang, Y. M., & Yen, M. Y. (2020). Effects of coinoculation of Rhizobium with plant growth promoting rhizobacteria on the nitrogen fixation and nutrient uptake of *Trifolium repens* in low phosphorus soil. *Journal of Plant Nutrition*, 43(5), 739-752. <https://doi.org/10.1080/01904167.2019.1702205>
- Mbaka, F. K., Ndukhu, H. O., Oloo-abucheli, G. O., & Kiplangat, C. T. (2022). Effect of Rhizobium inoculation and phosphate rock fertilizer application on biomass production, nutrient use efficiency and yield parameters of green gram (*Vigna radiata*). *Asian Journal of Agricultural and Horticultural Research*, 9(2), 47-59. <https://doi.org/10.9734/ajahr/2022/v9i230141>
- Nair, R. M., Schafleitner, R., & Lee, S. H. (2020). The mungbean genome. Springer International Publishing. <https://doi.org/10.1007/978-3-030-20008-4>
- Odoom, A., & Ofori, W. (2024). Role of phosphorus in the photosynthetic dark phase biochemical pathways. In N. A. Anjum, A. Masood, S. Umar, & N. A. Khan (Eds.). *Phosphorus in soils and plants* (pp. 1-16). IntechOpen. <https://doi.org/10.5772/intechopen.112573>
- Pérez-Fernández, M., Míguez-Montero, Á., & Valentine, A. (2019). Phosphorus and nitrogen modulate plant performance in shrubby legumes from the Iberian Peninsula. *Plants*, 8(9), Article 334. <https://doi.org/10.3390/plants8090334>
- Rani, M., Prakash, V., Khan, K., (2016). Response of mungbean [*Vigna radiata* (L.) Wilczek] to phosphorus, sulphur and PSB during summer season. *Agricultural Science Digest*, 36(2), 146-148. <https://doi.org/10.18805/asd.v36i2.10637>
- Seleiman, M. F., Almutairi, K. F., Alotaibi, M., Shami, A., Alhammad, B. A., & Battaglia, M. L. (2020). Nano-fertilization as an emerging fertilization technique: Why can modern agriculture benefit from its use? *Plants*, 10(1), Article 2. <https://doi.org/10.3390/plants10010002>
- Singh, K., Manohar, R. S., Choudhary, R., Yadav, A. K., & Sangwan, A. (2015). Response of different sources and levels of phosphorus on yield, nutrient uptake and net returns on mungbean under rainfed condition. *Agricultural Science Digest*, 35(4), 263-268. <https://doi.org/10.18805/asd.v35i4.6856>
- Soe, K., & Yamakawa, T. (2013). Low-density co-inoculation of Myanmar *Bradyrhizobium yuanningense* MAS34 and *Streptomyces griseoflavus* P4 to enhance symbiosis and seed yield in soybean varieties. *American Journal of Plant Sciences*, 4(9), 1879-1892. <https://doi.org/10.4236/ajps.2013.4.9231>
- Sood, A., Bochalya, R. S., Choudhary, K., Shubham, & Katoch, A. (2023). Effect of biofertilizer and fertility levels on growth characters of mungbean under mid hills of Himachal Pradesh, India. *International Journal of Plant and Soil Science*, 35(20), 1271-1277. <https://doi.org/10.9734/ijpss/2023/v35i203926>
- Tena, W., Wolde-Meskel, E., & Walley, F. (2016). Symbiotic efficiency of native and exotic *Rhizobium* strains nodulating lentil (*Lens culinaris* Medik.) in soils of Southern Ethiopia. *Agronomy*, 6(1), Article 11. <https://doi.org/10.3390/agronomy6010011>
- Terefe, M., Shifa, K., Tilahum, A., Ibrahim, A., Biratu, K., & Bogale, A. (2018). Performance of different mulberry/*Morus* sp./genotypes and their effect on mulberry

- silkworm, *Bombyx mori* (Lepidoptera: Bombycidae). *Journal of Agriculture and Research*, 3(11), Article 000210. <https://doi.org/10.23880/oajar-16000210>
- Venkatarao, C. V., Naga, S. R., Yadav, B. L., Koli, D. K., & Rao, I. J. (2017). Effect of phosphorus and biofertilizers on growth and yield of mungbean [*Vigna radiata* (L.) Wilczek]. *International Journal of Current Microbiology and Applied Sciences*, 6(7), 3992-3997. <https://doi.org/10.20546/ijcmas.2017.607.413>
- Yao, Y., Wu, D., Gong, Z., Zhao, J., & Ma, C. (2018). Variation of nitrogen accumulation and yield in response to phosphorus nutrition of soybean (*Glycine max* L. Merr.). *Journal of Plant Nutrition*, 41(9), 1138-1147. <https://doi.org/10.1080/01904167.2018.1433834>