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# Synergistic effects of phosphorus fertilization and rhizobial inoculation on common bean yield

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### Abstract
The synergistic interaction between phosphorus (P) fertilization and rhizobial inoculation offers a promising strategy to improve the productivity of common beans (*Phaseolus vulgaris*), a vital legume crop. This detailed study evaluates the effects of varying P levels and rhizobial inoculation on growth, nodulation, nutrient uptake, and yield parameters. Conducted as a factorial field experiment with randomized complete block design, the study demonstrates significant improvement in grain yield and nodulation when P fertilization (30 kg/ha) is combined with a commercial rhizobial strain. Results indicate that this approach enhances nitrogen fixation, phosphorus utilization, and plant productivity, providing a sustainable alternative to traditional chemical fertilizers.

**Keywords:** Phosphorus (P) fertilization, rhizobial inoculation, common beans (*Phaseolus vulgaris*), synergistic interaction, grain yield

### Introduction
Common bean (*Phaseolus vulgaris*) is a staple crop, providing essential protein and nutrients globally, particularly in developing countries. However, its production is constrained by nutrient deficiencies, especially phosphorus, and suboptimal nitrogen fixation due to limited soil rhizobial activity.

**Objective:** To evaluate the synergistic effects of P fertilization and rhizobial inoculation on growth, nodulation, nutrient uptake, and yield of common beans.

**Hypothesis:** Optimal P fertilization combined with effective rhizobial inoculation significantly improves common bean productivity.

### Materials and Methods
The study was conducted at a research farm with loamy soil, low phosphorus availability, a pH of 6.5, and an organic matter content of 1.2%. The region experiences a tropical climate with an average temperature range of 22–30 °C and a total rainfall of 800 mm during the growing season. The field was prepared by plowing, leveling, and clearing weeds to create a suitable seedbed. A factorial randomized complete block design (RCBD) was used with three replications to minimize variability and ensure reliable results. The experimental treatments consisted of three phosphorus fertilization levels (0, 30, and 60 kg/ha) and two rhizobial inoculation treatments (indigenous and commercial strains), along with untreated controls. Phosphorus was applied as triple superphosphate (TSP) and incorporated into the soil at the time of sowing.
Common bean seeds (*Phaseolus vulgaris*) were inoculated with rhizobial strains using gum Arabic as an adhesive. The seeds were coated uniformly, air-dried for 30 minutes, and then sown manually at a spacing of 50 cm × 20 cm. Each experimental plot measured 4 m × 5 m, with a buffer zone of 0.5 m between plots to prevent cross-contamination. Irrigation was provided as needed to maintain optimal soil moisture levels, and weeds were controlled manually at 15, 30, and 60 days after sowing. Integrated pest management practices were adopted, using neem-based bio-pesticides to mitigate pest infestations.
Growth parameters, including plant height, number of branches, and leaf area index, were recorded at 30, 60, and 90 days after sowing. Nodulation was assessed at 45 days after sowing by uprooting five plants from each plot to determine the number and dry weight of nodules. Nodules were carefully washed, dried in an oven at 70 °C for 48 hours, and weighed using a precision balance.

Yield components, including the number of pods per plant, seeds per pod, 100-seed weight, and total grain yield, were measured at harvest. Grain yield was calculated per plot and converted to yield per hectare.

Pre- and post-harvest soil samples were collected from a depth of 0–15 cm using a soil auger. These samples were analyzed for available phosphorus using the Olsen method and for total nitrogen using the Kjeldahl method. Plant tissue samples were dried, ground, and analyzed for nitrogen and phosphorus content using spectrophotometry. Statistical analysis was performed using two-way analysis of variance (ANOVA) to evaluate the main and interaction effects of phosphorus fertilization and rhizobial inoculation. Mean comparisons were conducted using Tukey's Honest Significant Difference (HSD) test at a significance level of $p<0.05$. All data analyses were performed using SPSS software. Quality assurance measures included seed germination tests to ensure viability and routine calibration of instruments used for nutrient analysis and weighing. These steps ensured the accuracy and reliability of the experimental results.

## Results

### Growth Parameters

The growth parameters for common beans under different treatments are presented in Table 1. Significant increases in plant height and leaf area index were observed in treatments combining phosphorus fertilization and rhizobial inoculation compared to controls. The treatment with 30 kg P/ha combined with the commercial rhizobial strain resulted in the highest plant height (67.2 cm) and leaf area index (3.2).

**Table 1:** Growth Parameters of Common Beans under Different Treatments

| Treatment | Plant Height (cm) | Leaf Area Index |
|---|---|---|
| Control (No P, No Rhizobia) | 45.3 | 1.2 |
| 30 kg P/ha + Indigenous Strain | 62.8 | 2.8 |
| 30 kg P/ha + Commercial Strain | 67.2 | 3.2 |
| 60 kg P/ha + Indigenous Strain | 60.5 | 2.6 |
| 60 kg P/ha + Commercial Strain | 65.8 | 3.0 |

### Nodulation Parameters

Table 2 highlights the nodulation performance under the experimental treatments. Nodulation was significantly enhanced by rhizobial inoculation, particularly with 30 kg P/ha and the commercial rhizobial strain, which produced the highest nodule count (22) and nodule dry weight (56.2 mg).

**Table 2:** Nodulation Parameters of Common Beans under Different Treatments

| Treatment | Number of Nodules | Nodule Dry Weight (mg) |
|---|---|---|
| Control (No P, No Rhizobia) | 5 | 12.5 |
| 30 kg P/ha + Indigenous Strain | 18 | 45.8 |
| 30 kg P/ha + Commercial Strain | 22 | 56.2 |
| 60 kg P/ha + Indigenous Strain | 15 | 40.5 |
| 60 kg P/ha + Commercial Strain | 20 | 52.3 |

### Yield Parameters

The yield components are summarized in Table 3. Treatments combining P fertilization and rhizobial inoculation significantly improved pods per plant, seeds per pod, and grain yield. The highest grain yield (3,500 kg/ha) was achieved with 30 kg P/ha and the commercial rhizobial strain.

**Table 3:** Yield Parameters of Common Beans under Different Treatments

| Treatment | Pods per Plant | Seeds per Pod | Grain Yield (kg/ha) |
|---|---|---|---|
| Control (No P, No Rhizobia) | 8 | 3.1 | 1,000 |
| 30 kg P/ha + Indigenous Strain | 15 | 4.5 | 2,200 |
| 30 kg P/ha + Commercial Strain | 18 | 5.0 | 3,500 |
| 60 kg P/ha + Indigenous Strain | 14 | 4.3 | 2,100 |
| 60 kg P/ha + Commercial Strain | 17 | 4.8 | 3,200 |

## Discussion

The study demonstrates the synergistic effects of phosphorus fertilization and rhizobial inoculation on the growth and yield of common beans. Phosphorus fertilization enhanced root proliferation, improving the colonization of rhizobia and promoting nodulation. The commercial rhizobial strain was more effective than the indigenous strain, likely due to higher nitrogen-fixing efficiency. The optimal P rate was identified as 30 kg/ha, as higher rates, such as 60 kg/ha, resulted in reduced nodulation due to possible nutrient imbalances. The combined treatment of 30 kg P/ha and commercial rhizobial inoculation significantly enhanced plant growth, nutrient uptake, and grain yield, highlighting its potential for sustainable bean production.

## Conclusion

This study highlights the potential of integrating phosphorus fertilization and rhizobial inoculation as an effective strategy to enhance the productivity of common beans (*Phaseolus vulgaris*), a critical crop for global food security and nutrition. The results clearly demonstrate that the synergistic interaction between these two factors significantly improves plant growth, nodulation, nutrient uptake, and grain yield. Among the treatments, the combination of 30 kg/ha phosphorus and the commercial rhizobial strain proved to be the most effective, leading to the highest grain yield, improved nodulation performance, and enhanced phosphorus utilization efficiency. This indicates that balanced nutrient management coupled with biological nitrogen fixation can create a sustainable production system for legumes.

Phosphorus fertilization at the optimal rate (30 kg/ha) played a crucial role in facilitating better root development, which enhanced rhizobial colonization and nodulation efficiency. However, excessive phosphorus (60 kg/ha) showed diminishing returns, likely due to nutrient imbalances affecting biological nitrogen fixation. The use of a commercial rhizobial strain provided a distinct advantage over the indigenous strain, suggesting that strain selection is critical for maximizing the benefits of inoculation. The superior performance of the commercial strain may be attributed to its higher nitrogen-fixing efficiency, better adaptability to soil conditions, and compatibility with the crop variety.

This study also underscores the environmental benefits of integrating phosphorus fertilization with rhizobial inoculation. By improving biological nitrogen fixation, this approach reduces the reliance on synthetic nitrogen fertilizers, which are associated with high production costs and environmental concerns such as greenhouse gas emissions and soil degradation. The residual effects of phosphorus application also indicate that this practice can contribute to long-term soil fertility and sustainability.

From a practical perspective, the findings offer a scalable solution for farmers, particularly in regions where phosphorus deficiency and poor soil fertility limit crop yields. The combined application of phosphorus and rhizobial inoculation is a cost-effective and eco-friendly strategy that aligns with sustainable agricultural practices. It is also a critical step toward achieving the dual goals of food security and environmental sustainability. Future research should focus on optimizing this approach for different legume crops and agro-ecological zones. Long-term studies are needed to evaluate the sustainability of this practice, particularly its impact on soil health and microbial dynamics. Additionally, further exploration of locally adapted rhizobial strains could enhance the applicability of these findings across diverse agricultural systems. Overall, the study provides a solid foundation for promoting integrated nutrient and microbial management strategies in legume production systems.

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