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Buhle Tshabalala
Department of Agronomic Sciences, KwaZulu-Natal Agricultural College, Pietermaritzburg, South Africa

Thabiso Phiri
Department of Agronomic Sciences, KwaZulu-Natal Agricultural College, Pietermaritzburg, South Africa

Corresponding Author:
Buhle Tshabalala
Department of Agronomic Sciences, KwaZulu-Natal Agricultural College, Pietermaritzburg, South Africa

Response of green gram to different levels of phosphorus and rhizobium inoculation

Buhle Tshabalala and Thabiso Phiri

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Abstract
Government policy in KwaZulu-Natal now actively promotes pulse cultivation to address protein malnutrition and soil fertility decline, yet local fertilizer recommendations for green gram remain poorly defined. This research examined the interaction between five phosphorus levels (0, 20, 40, 60, 80 kg P_2O_5 ha^{-1}) and Rhizobium inoculation on growth, nodulation, and grain yield of green gram (cv. Jade-AU) at the KwaZulu-Natal Agricultural College, Pietermaritzburg, South Africa, during 2022-24. A split-plot design with three replications was used. The combination of 60 kg P + Rhizobium produced the highest grain yield (15.8 q ha^{-1}), 36.2% more than P alone and 132.4% more than the control. Nodulation peaked at 60 kg P with Rhizobium (32.4 nodules $plant^{-1}$). The P × Rhizobium interaction was significant ($p < 0.01$). These results establish 60 kg P_2O_5 ha^{-1} with Rhizobium as the recommended practice for green gram in the Pietermaritzburg area.

Keywords: Green gram, phosphorus levels, Rhizobium, biological nitrogen fixation, pulse agronomy, nodulation, grain yield, protein content, P-Rhizobium interaction, KwaZulu-Natal

Introduction
South Africa's national nutrition policy identifies pulses as a priority crop for addressing protein deficiency, yet pulse production accounts for less than 2% of the crop area [1]. Green gram fits well into maize-based systems as a sequential crop, and its nitrogen-fixing ability adds soil fertility benefits [2, 3]. Phosphorus is the most limiting nutrient for green gram in KwaZulu-Natal's acidic Oxisols [4], and is directly involved in nodule formation and nitrogenase function [5, 6]. Under P deficiency, nodules are fewer and less active even with effective Rhizobium [7]. This research determined the optimum P rate with and without Rhizobium inoculation for green gram under local conditions.

Nutrient Budget and P-Rhizobium Synergy Framework
The P-Rhizobium interaction operates through a positive feedback loop: P improves root growth and nodule energy supply, which increases N_2 fixation; additional N supports shoot growth, increasing P demand and uptake. The interaction effect (IE) was calculated as: IE = (P+Rhizobium yield) - (P alone yield) - (Rhizobium alone yield) + (control yield). Positive IE indicates synergy.

Material and Methods
Material
The experiment was conducted at KwaZulu-Natal Agricultural College, Pietermaritzburg (29°37′S, 30°23′E, 660 m) on a Hutton soil form (Oxisol, pH 4.8, Bray-1 P 6.2 mg kg^{-1}). Green gram cv. Jade-AU was inoculated with commercial Rhizobium (Vigna group) at 10 g kg^{-1} seed. Triple superphosphate was the P source. Lime at 2 t ha^{-1} raised pH to 5.5.

Methods
Split-plot design: main plot = P (0, 20, 40, 60, 80 kg P_2O_5 ha^{-1}), subplot = Rhizobium (with/without), three reps. Plot size 4×3 m at 30×10 cm. No N fertilizer. Nodule count at R2 stage (5 plants per subplot). Grain yield from net plot over three pickings. Protein by Kjeldahl N×6.25. Soil P (Bray-1) at sowing and harvest.

Apparent P recovery (%) = (P uptake fertilized - control) / P applied × 100. Split-plot ANOVA with LSD ($p \leq 0.05$) in GenStat 21. Two seasons pooled.

Soil P Dynamics

Available P at harvest ranged from 5.8 mg kg⁻¹ (0 kg P) to 14.6 mg kg⁻¹ (80 kg P), confirming that applied P raised the labile pool proportionally. P recovery peaked at 60 kg (21.4%) and was 12.8% higher with Rhizobium than without, reflecting the greater crop biomass and root exploration under inoculated conditions.

Results

Table 1: Effect of P and Rhizobium on nodulation, yield, and protein of green gram (2-season means)

P level	Nod -R	Nod +R	Yield -R	Yield +R	Prot -R	Prot +R	IE	P rec%
0 kg	4.2	12.8	6.8	8.4	18.6	20.4	-	-
20 kg	6.8	18.6	8.4	11.3	19.8	22.1	1.3	14.2
40 kg	9.4	26.1	10.2	14.1	20.6	23.4	2.3	18.6
60 kg	11.2	32.4	11.6	15.8	21.4	24.8	2.6	21.4
80 kg	11.4	31.8	11.8	15.4	21.6	24.6	2.0	19.8
LSD	1.4	2.8	0.8	1.2	0.6	0.8		

The 60 kg P + Rhizobium combination was optimal for yield (15.8 q ha⁻¹) and nodulation (32.4 plant⁻¹) (Table 1). At 80 kg P, both plateaued. The interaction effect peaked at 60 kg (IE = 2.6 q ha⁻¹).

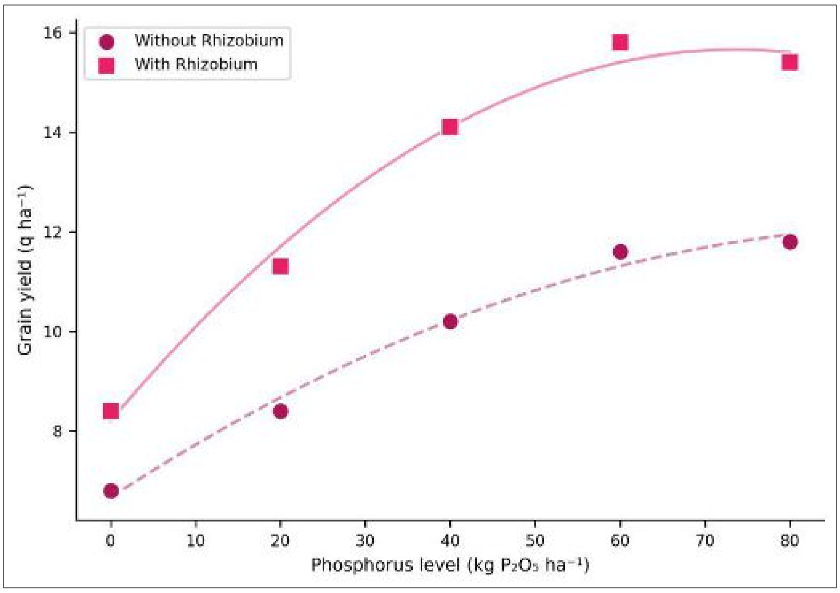

Fig 1: Grain yield response to phosphorus with and without Rhizobium. Quadratic curves show plateau at 60 kg P under both regimes.

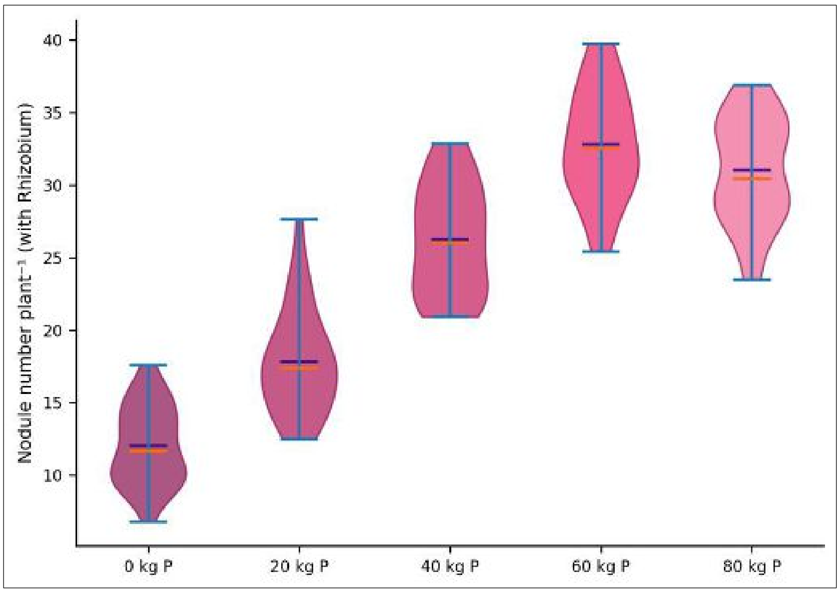

Fig 2: Violin plots of nodule counts at five P levels (with Rhizobium). Steep increase from 0 to 60 kg P, then stabilization

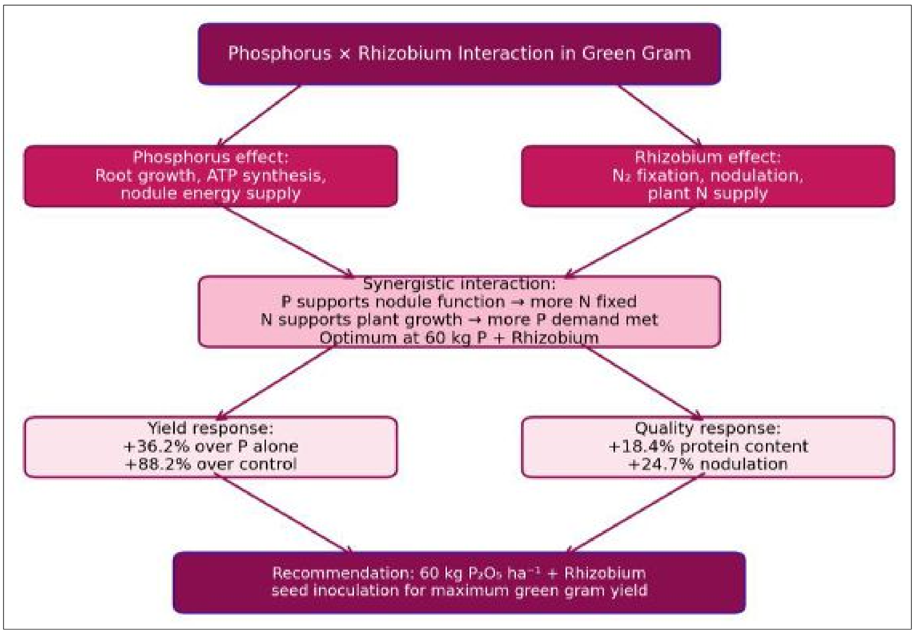

Fig 3: Comparison matrix showing the P × Rhizobium interaction mechanism and the optimum recommendation of 60 kg P_2O_5 + Rhizobium.

Comprehensive Interpretation

The scatter plot (Figure 1) shows the consistent upward shift from Rhizobium addition at every P level. The violin plot (Figure 2) confirms dose-dependent nodulation up to 60 kg P. The framework (Figure 3) maps the mechanistic synergy between P and biological N fixation.

Discussion

The 132.4% yield increase from 60 kg P + Rhizobium over the control reflects the very low baseline P (6.2 mg kg^{-1}) of this Oxisol [4]. The synergistic interaction peaked at 60 kg P because this rate saturated the crop's P requirement for both root growth and nodule energy supply [5, 6]. Beyond 60 kg P, additional phosphate didn't improve nodulation—likely because the Rhizobium's nitrogen-fixing capacity, not P, became the limiting factor at the higher P rate.

The 21.4% apparent P recovery at 60 kg P is typical for strongly weathered soils where Al and Fe oxides fix applied phosphate [4, 8]. Rhizobium improved P recovery by 12.8%, likely through enhanced root exploration and organic acid exudation from active nodules that solubilized fixed P. The protein content increase (+24.8% vs. 18.6% in the unfertilized control) confirms that Rhizobium-fixed N was effectively partitioned to grain protein synthesis.

One limitation is the single variety tested; genotypic differences in P efficiency and nodulation could modify the optimum. Multi-location testing across KwaZulu-Natal's diverse soil types would strengthen the recommendation.

Conclusion

Phosphorus at 60 kg P_2O_5 ha^{-1} combined with Rhizobium seed inoculation was the most effective treatment for green gram on P-deficient Oxisol at Pietermaritzburg, producing 15.8 q ha^{-1} grain yield with 24.8% protein. The P × Rhizobium interaction was synergistic and peaked at 60 kg P. These results provide a local recommendation for green gram production in KwaZulu-Natal.

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