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Conditional effectiveness of an N_2-fixing biofertilizer under nutrient-rich organic and conventional mineral fertilizer systems in calcareous soil of Kabul, Afghanistan

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ABSTRACT

Aim: The aim of the study was to investigate whether the effectiveness of an N_2-fixing biofertilizer is influenced by accompanying fertilizer source and evaluated its effects on the growth, yield and productivity of common bean (*Phaseolus vulgaris* L.).

Materials and Methods: A field experiment was conducted using a randomized complete block design with five fertilizer treatments and three replications. Treatments included an unfertilized control, mineral fertilizer (NPK 100:100:60 kg ha^{-1}), nutrient-rich organic fertilizer (3000 kg ha^{-1}), organic fertilizer combined with biofertilizer and mineral fertilizer combined with biofertilizer. Growth characteristics, yield components, biological yield, grain yield and harvest index were measured. Data were analyzed using analysis of variance, Fisher's least significant difference test, Pearson correlation and simple linear regression.

Results: Fertilizer application significantly improved vegetative growth, yield components, biological yield, and grain yield compared with the unfertilized control. Organic fertilizer alone produced greater vegetative growth and grain yield than mineral fertilizer alone (2.00 vs. 1.82 t ha^{-1}), demonstrating its superior capacity to improve crop performance under nutrient-deficient calcareous soils. In contrast, the response to biofertilizer differed markedly between fertilizer systems. Biofertilizer significantly increased grain yield when combined with mineral fertilizer (2.18 t ha^{-1}) but provided no significant additional benefit when applied together with nutrient-rich organic fertilizer. Pearson correlation analysis revealed strong positive relationships among growth traits and grain yield, with biological yield exhibiting the strongest association with grain yield (r = 0.988, P< 0.001). Linear regression further indicated that biological yield explained 97.6% of the variation in grain yield (R^2 = 0.976, P< 0.001).

Conclusion: It was concluded that the agronomic value of N_2-fixing biofertilizer is determined by the surrounding nutrient environment rather than by inoculation alone. Biofertilizer effectively complements mineral fertilization under relatively nutrient-limited conditions but contributes little when soil fertility has already been enhanced through nutrient-rich organic amendments.

Keywords: *Phaseolus vulgaris* L.; biofertilzer consortium; nutrient-rich organic fertilizer; mineral fertilizer; calcareous soil.

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Introduction

Common bean (*Phaseolus vulgaris* L.) is one of most important grain legumes worldwide, serving as a major source of plant-based protein, dietary fiber, essential vitamins and micronutrients such as iron and zinc, particularly in developing countries where access to animal protein is limited (Beebe, 2012; Broughton et al., 2003). Beyond its nutritional value, common bean contributes to sustainable agriculture through biological nitrogen fixation, crop diversification and improved soil health, making it an important component of resilient farming systems (Broughton et al., 2003). In Afghanistan, where agriculture remains the primary livelihood for much of the rural population, common bean plays a significant role in household food security, nutrition, and income generation; however, its productivity remains substantially below its genetic potential due to widespread soil fertility constraints (FAO, 2023; World Bank, 2024). The predominantly calcareous soils of the country are characterized by high pH, low organic matter, and limited availability of essential nutrients, conditions that restrict crop

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growth and reduce nutrient-use efficiency (Brady & Weil, 2017; Havlin et al., 2014). Consequently, improving soil fertility has become a critical priority for enhancing common bean productivity and supporting sustainable agricultural development in Afghanistan. Nevertheless, achieving efficient nutrient management under these calcareous soil conditions remains a major challenge, raising important questions about the effectiveness of current nutrient management strategies.

Maintaining adequate soil fertility is fundamental for improving common bean productivity, and mineral fertilizers remain the primary strategy for supplying essential nutrients required for crop growth. Their high nutrient concentration and immediate availability enable rapid correction of nutrient deficiencies and substantial yield improvement when applied appropriately (Havlin et al., 2014; Fageria et al., 2011). However, the efficiency of mineral fertilizers is often reduced in calcareous soils because high soil pH limits nutrient availability and increases nutrient losses, thereby lowering fertilizer use efficiency and crop response (Brady & Weil, 2017; Hinsinger, 2001). To overcome these limitations, increasing attention has been directed toward nutrient-rich organic fertilizers, which improve soil organic matter, enhance soil physical and biological properties, and provide a gradual release of nutrients that supports long-term soil fertility (Lal, 2015; Diacono & Montemurro, 2010). More recently, biofertilizers, particularly nitrogen-fixing microbial inoculants, have been promoted as environmentally sustainable inputs capable of enhancing nutrient acquisition, stimulating plant growth, and reducing dependence on synthetic fertilizers (Bhattacharyya & Jha, 2012; Vessey, 2003). Nevertheless, despite their recognized agronomic and environmental benefits, the field performance of N_2-fixing biofertilizers remains inconsistent across different cropping systems and soil conditions, suggesting that their effectiveness is influenced by the surrounding soil and nutrient environment rather than by the inoculant alone.

The effectiveness of N_2-fixing biofertilizers depends on the successful establishment of a symbiotic association between compatible *Rhizobium* species and legume roots, enabling biological nitrogen fixation (BNF), whereby atmospheric nitrogen is converted into plant-available ammonia through the activity of the nitrogenase enzyme (Oldroyd et al., 2011; Mus et al., 2016). Biological nitrogen fixation is an energy-intensive process that requires a continuous supply of ATP to sustain nitrogenase activity and effective symbiotic functioning (Udvardi & Poole, 2013). Consequently, the agronomic performance of N_2-fixing biofertilizers depends not only on the effectiveness of the microbial inoculant but also on the surrounding rhizosphere environment, which governs nutrient availability, microbial activity, and plant physiological processes essential for symbiosis (Vance, 2001; Israel, 1987). Because fertilizer systems differ in the quantity, form, and temporal availability of nutrients supplied to the soil, they can modify the rhizosphere environment and potentially influence the effectiveness of biological nitrogen fixation. Therefore, differences in nutrient availability between fertilizer systems provide a biologically plausible explanation for the contrasting agronomic responses frequently observed with N_2-fixing biofertilizers.

Previous studies have demonstrated that both nutrient-rich organic fertilizers and N_2-fixing biofertilizers can improve soil fertility, crop growth, and grain yield under a wide range of environmental conditions (Diacono & Montemurro, 2010; Bhattacharyya & Jha, 2012; Vessey, 2003). Nevertheless, the agronomic performance of biofertilizers remains highly variable across field conditions, suggesting that their effectiveness is influenced by interactions among soil properties, nutrient availability, and crop management practices rather than by microbial inoculation alone (Bashan et al., 2014; Schütz et al., 2018). Although numerous studies have evaluated organic fertilizers and biofertilizers independently or as components of integrated nutrient management, considerably less attention has been given to understanding why the same N_2-fixing biofertilizer may exhibit contrasting agronomic responses under different fertilizer systems, particularly in calcareous soils. Addressing this knowledge gap is essential for developing more effective and scientifically informed nutrient management strategies that optimize biofertilizer performance under soil conditions where nutrient availability frequently constrains crop productivity.

To address the knowledge gap, the present study investigated the agronomic effectiveness of

an N_2-fixing biofertilizer under contrasting nutrient-rich organic and conventional mineral fertilizer systems in calcareous soil using common bean (*Phaseolus vulgaris* L.) as the test crop. Specifically, the study aimed to evaluate the effects of contrasting fertilizer systems, with and without N_2-fixing biofertilizer, on common bean growth, phenological development, and grain yield, and to determine whether the agronomic response to the biofertilizer depends on the accompanying fertilizer system. Based on the observed responses, the study further sought to interpret the contrasting effectiveness of the biofertilizer in the context of nutrient dynamics and the biological requirements of symbiotic nitrogen fixation. We hypothesized that the agronomic effectiveness of the N_2-fixing biofertilizer is conditional upon the accompanying fertilizer system and that differences in the nutrient environment create distinct rhizosphere conditions that influence crop response under calcareous soil conditions.

Materials and Methods

A field experiment was conducted during the 2025 summer cropping season at the Kabul University Research Farm, Kabul, Afghanistan. Prior to sowing, composite soil samples (0–30 cm) were collected and analyzed at the Soil Laboratory of the Afghanistan Ministry of Agriculture, Irrigation and Livestock (MAIL). The soil was classified as sandy loam with a pH of 7.80, electrical conductivity of 0.259 mS cm^{-1}, cation exchange capacity of 16.4 meq 100 g^{-1} and calcium carbonate content of 12%. It contained 0.9% organic matter, 0.03% total nitrogen, and 1.83 mg kg^{-1} available phosphorus (Table 1).

Table 1. Initial physicochemical properties of the experimental soil (0–30 cm depth) before treatment application

Property	Unit	Value
Soil texture	–	Sandy loam
pH (1:2.5 soil:water)	–	7.80
Electrical conductivity (EC)	mS cm^{-1}	0.259
Cation exchange capacity (CEC)	meq 100 g^{-1}	16.4
Calcium carbonate ($CaCO_3$)	%	12.0
Organic matter	%	0.90
Total nitrogen	%	0.03
Available phosphorus	mg kg^{-1} (ppm)	1.83

Experimental design and crop management

The experiment was arranged in a randomized complete block design (RCBD) with five fertilizer treatments and three replications. Treatments included: (T1) unfertilized control; (T2) conventional mineral fertilizer (NPK at 100:100:60 kg ha^{-1}); (T3) nutrient-rich organic fertilizer (3000 kg ha^{-1}); (T4) nutrient-rich organic fertilizer combined with an N_2-fixing biofertilizer; and (T5) conventional mineral fertilizer combined with the same biofertilizer. The experimental plots measured 4 m^2, with a planting spacing of 50 cm between rows and 15 cm between plants. A local common bean (*Phaseolus vulgaris* L.) cultivar, Talabarfak, was used throughout the study. Seeds assigned to T4 and T5 were inoculated with nitrogen fixing biofertilzer consortium. Immediately before sowing. Mineral fertilizer was applied according to the recommended schedule, while the organic fertilizer was incorporated before planting. All treatments received identical agronomic management, including irrigation, weed control, and pest management.

Data collection: Plant height, number of leaves, number of branches, leaf area index (LAI), number of pods per plant, dry biomass, and grain yield were recorded following standard agronomic procedures. Grain yield was determined from the net plot area and expressed on a hectare basis.

Statistical analysis: Data were analyzed using analysis of variance (ANOVA) for the randomized complete block design in the Statistical Tool for Agricultural Research (STAR Version 2.0.1.). Treatment means were compared using the Least Significant Difference (LSD) test at the 5% significance level ($P \leq 0.05$). Pearson correlation and simple linear regression analyses were performed to examine the relationships between selected growth parameters and grain yield.

Results and Discussion

Effect of fertilizer treatments on vegetative growth:

Fertilizer treatments significantly affected all measured vegetative growth parameters of common bean ($P < 0.05$). Compared with the unfertilized control (T1), all fertilizer treatments improved plant height, leaf production, branch number, and leaf area index (LAI) (Table 2). The combined application of mineral fertilizer and the N_2-fixing biofertilizer (T5) produced the greatest

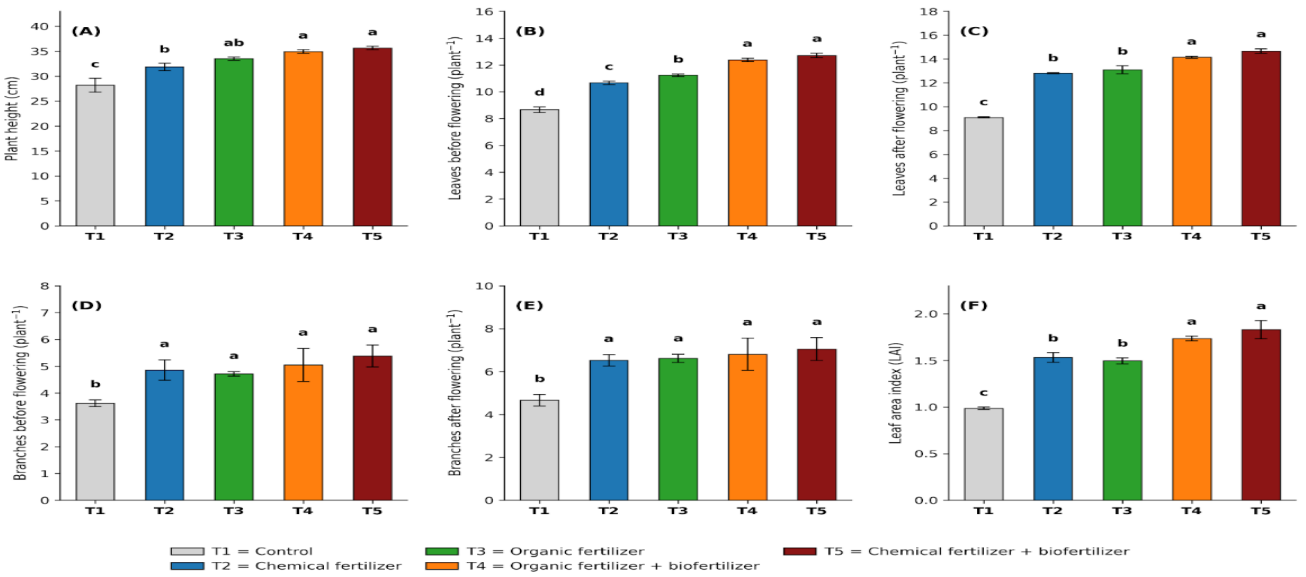


Fig. **1.** Effect of fertilizer treatments on vegetative growth of common bean: (A) plant height, (B) number of leaves before flowering, (C) number of leaves after flowering, (D) number of branches before flowering, (E) number of branches after flowering, and (F) leaf area index. Error bars represent standard errors of the mean (n = 3). Different lowercase letters indicate significant differences among treatments according to Fisher's LSD test ($P \leq 0.05$).

Table 2. Effect of fertilizer treatments on vegetative growth of common bean

Treatment	Plant height (cm)	Leaves before flowering	Leaves after flowering	Branches before flowering	Branches after flowering	Leaf area index
T1 (Control)	28.19 c	14.11 d	10.78 d	3.22 b	4.00 b	1.75 c
T2 (Mineral fertilizer)	31.86 b	17.44 c	14.89 c	4.44 a	5.00 a	2.66 ab
T3 (Organic fertilizer)	33.52 ab	19.11 b	16.78 b	4.67 a	5.33 a	2.36 b
T4 (Organic + biofertilizer)	34.95 a	20.89 a	18.67 a	4.89 a	5.67 a	2.79 a
T5 (Mineral + biofertilizer)	35.67 a	21.11 a	18.89 a	5.00 a	5.89 a	2.86 a
LSD (0.05)	2.52	1.23	1.15	0.71	0.82	0.37
CV (%)	6.27	5.12	5.48	11.38	11.76	10.69

Means followed by different lowercase letters within a column differ significantly at $P \leq 0.05$ according to Fisher's Least Significant Difference (LSD) test.

plant height, leaf number and LAI, although these values were statistically comparable to those obtained with organic fertilizer combined with the biofertilizer (T4). Organic fertilizer alone (T3) consistently resulted in greater vegetative growth than mineral fertilizer alone (T2), whereas branch number showed no significant differences among fertilized treatments. Overall, biofertilizer application enhanced vegetative growth under the mineral fertilizer system, while only limited improvements were observed when combined with organic fertilizer.

Effect of fertilizer treatments on yield components and grain yield

Yield components and grain yield were significantly influenced by fertilizer management ($P < 0.05$), whereas harvest index was not significantly affected (Table 3). The highest number of pods per plant, biological yield, and grain yield were obtained from T5, while the unfertilized control consistently produced the lowest values. Organic fertilizer alone (T3) produced significantly greater biological and grain yields than mineral fertilizer alone (T2). The addition of the N_2-fixing biofertilizer to the mineral fertilizer system (T5) further increased pod number, biomass, and grain yield relative to mineral fertilizer alone. In contrast, combining the same biofertilizer with organic fertilizer (T4) did not produce significant improvements over organic fertilizer alone (T3) for biological yield or grain yield. Harvest index remained statistically similar across all treatments.

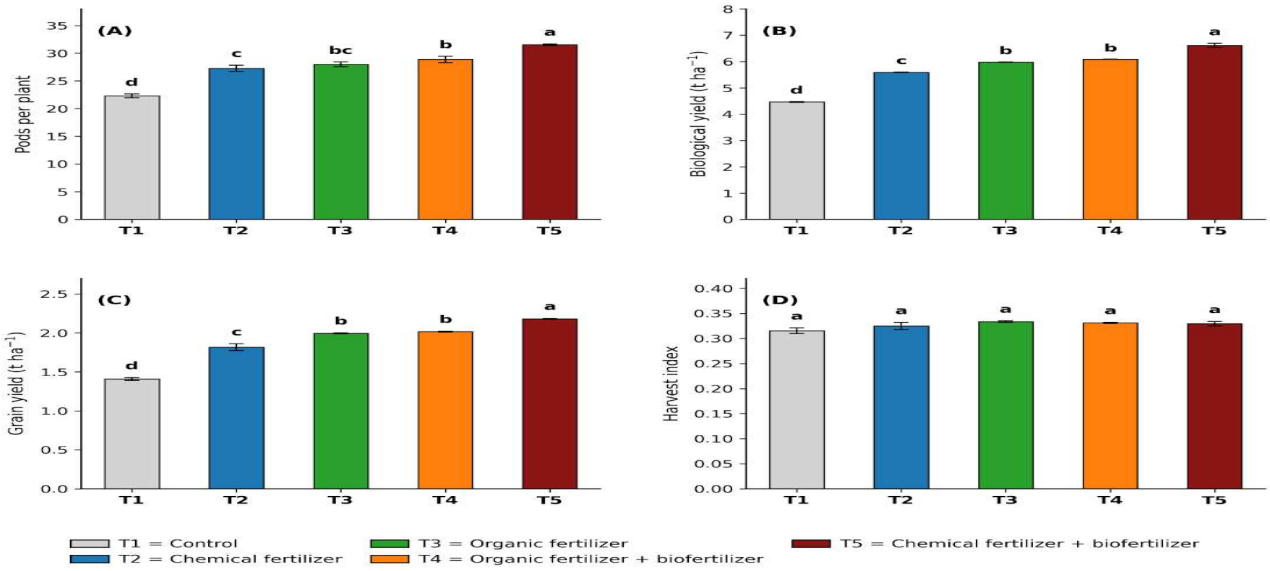


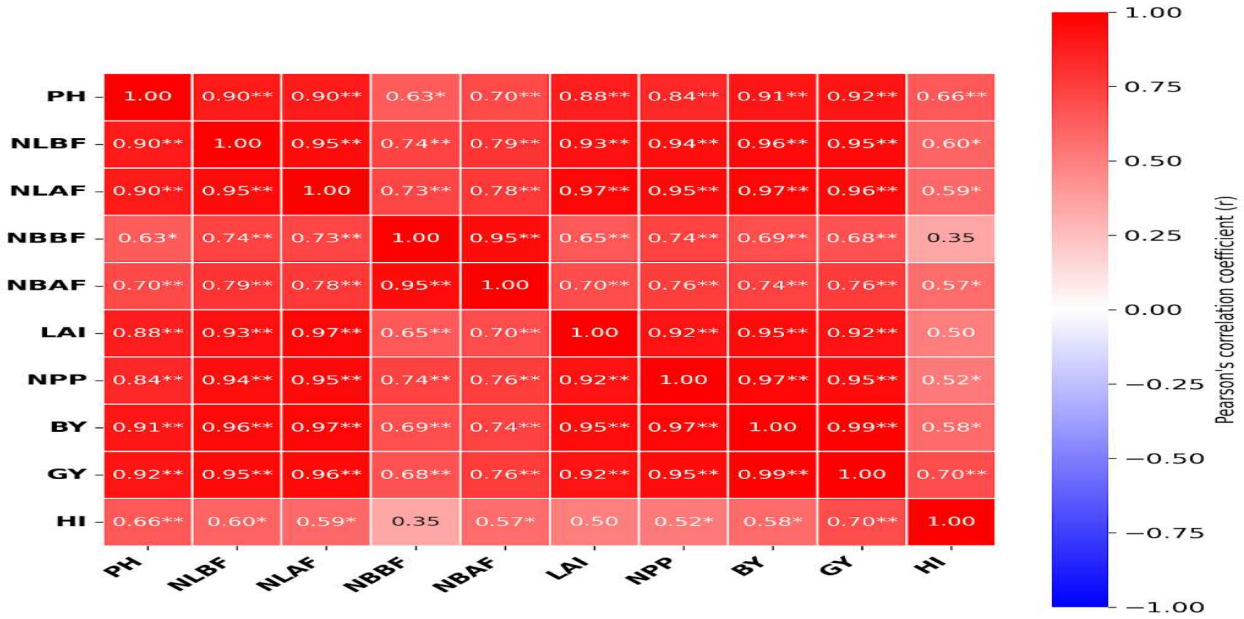
Fig 2. Effect of fertilizer treatments on yield components and grain yield of common bean: (A) pods per plant, (B) biological yield, (C) grain yield, and (D) harvest index. Error bars represent standard errors of the mean (n = 3). Different lowercase letters indicate significant differences among treatments according to Fisher's LSD test (P ≤ 0.05).

Table 3. Effect of fertilizer treatments on yield components and yield of common bean

Treatment	Pods plant^{-1}	Biological yield (t ha^{-1})	Grain yield (t ha^{-1})	Harvest index
T1 (Control)	21.33 d	4.46 c	1.50 c	0.337
T2 (Mineral fertilizer)	25.22 c	5.61 b	1.82 b	0.325
T3 (Organic fertilizer)	28.11 b	6.31 a	2.00 a	0.317
T4 (Organic + biofertilizer)	29.11 b	6.47 a	2.02 a	0.312
T5 (Mineral + biofertilizer)	31.55 a	6.78 a	2.18 a	0.322
LSD (0.05)	2.11	0.54	0.17	NS
CV (%)	6.84	7.26	7.11	5.74

Means followed by different lowercase letters within a column differ significantly at P ≤ 0.05 according to Fisher's Least Significant Difference (LSD) test. NS = not significant.

Fig. 3. Pearson correlation matrix showing the relationships among vegetative growth traits, yield components, and grain yield of common bean under different fertilizer treatments. Correlation coefficients are presented within each cell. Asterisks indicate statistically significant correlations (*P*< 0.05; **P**< 0.01).



Overall treatment response

Across all measured parameters, fertilizer application substantially improved the growth and productivity of common bean compared with the unfertilized control. Organic fertilizer alone consistently outperformed mineral fertilizer alone in both vegetative growth and grain yield. However, contrasting responses were observed following biofertilizer inoculation. The addition of the N_2-fixing biofertilizer significantly enhanced crop performance when combined with mineral fertilizer but provided no additional agronomic benefit when combined with organic fertilizer. This differential response represents the principal finding of the study and forms the basis for the subsequent discussion.

Correlation analysis among growth and yield traits

Pearson correlation analysis revealed significant positive relationships among most measured vegetative growth, yield component, and yield traits (Table 4; Fig. 3). Grain yield exhibited the strongest positive correlation with biological yield ($r = 0.99$, $P< 0.01$), followed by the number of leaves after flowering ($r = 0.96$), number of leaves before flowering ($r = 0.95$), pods per plant ($r = 0.95$), leaf area index ($r = 0.92$), and plant height ($r = 0.92$). Significant positive correlations were also observed between grain yield and the number of branches after flowering ($r = 0.76$), harvest index ($r = 0.70$), and number of branches before flowering ($r = 0.68$). Likewise, biological yield was strongly correlated with most vegetative growth traits and yield components, indicating close associations between crop growth and productivity. In contrast, harvest index showed relatively weaker correlations with the majority of growth traits and was not significantly correlated with the number of branches before flowering. Overall, the correlation analysis demonstrated that improvements in vegetative growth and biomass production were closely associated with enhanced grain yield in common bean.

Linear regression analysis

Simple linear regression identified biological yield as the strongest predictor of grain yield (Table 5; Figure 4). A highly significant positive linear relationship was observed between biological yield and grain yield ($P< 0.0001$), with the fitted regression model explaining 97.6% of the total variation in grain yield ($R^2 = 0.976$). The relationship was described by the equation:

Grain yield = –0.2038 + 0.0485 × Biological yield

indicating that grain yield increased proportionally with increasing biological yield across the experimental treatments. The high coefficient of determination confirmed the close association between biomass accumulation and grain production.

Effect of Fertilizer Source on Common Bean Growth and Productivity

The present study demonstrated that fertilizer source substantially influenced vegetative growth and productivity of common bean. Across almost all measured growth and yield parameters, nutrient-rich organic fertilizer (T3) produced significantly greater responses than chemical fertilizer alone (T2), while the integrated application of chemical fertilizer and biofertilizer (T5) achieved highest overall performance (Fig 1 and 2).

Table 4. Pearson correlation coefficients among vegetative growth traits, yield components, and grain yield of common bean

Trait	PH	NLBF	NLAF	NBBF	NBAF	LAI	NPP	BY	GY	HI
PH	1.000									
NLBF	0.898**	1.000								
NLAF	0.897**	0.953**	1.000							
NBBF	0.634*	0.739**	0.725**	1.000						
NBAF	0.705**	0.794**	0.780**	0.948**	1.000					
LAI	0.876**	0.932**	0.974**	0.655**	0.702**	1.000				
NPP	0.838**	0.945**	0.953**	0.742**	0.757**	0.925**	1.000			
BY	0.909**	0.956**	0.972**	0.693**	0.740**	0.946**	0.971**	1.000		
GY	0.922**	0.954**	0.964**	0.677**	0.758**	0.923**	0.951**	0.988**	1.000	
HI	0.655**	0.604*	0.593*	0.350ns	0.572*	0.503ns	0.517*	0.582*	0.700**	1.000

Abbreviations: PH = Plant height; NLBF = Number of leaves before flowering; NLAF = Number of leaves after flowering; NBBF = Number of branches before flowering; NBAF = Number of branches after flowering; LAI = Leaf area index; NPP = Number of pods per plant; BY = Biological yield (t ha^{-1}); GY = Grain yield (t ha^{-1}); HI = Harvest index.

Note: Pearson correlation coefficients were calculated using plot-level observations (N = 15). and ns indicate significance at $P< 0.05$, $P< 0.01$ and not significant, respectively.

The findings indicated that nutrient availability alone is insufficient to maximize crop productivity, and that improving soil quality through organic amendments can markedly enhance plant growth.

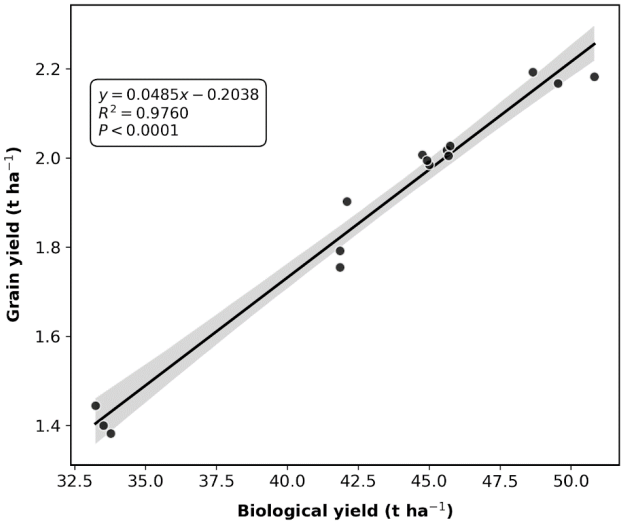


Fig 4. Linear relationship between biological yield and grain yield of common bean. The solid line represents the fitted regression model, and the shaded area indicates the 95% confidence interval.

Table 5. Summary of the simple linear regression model describing the relationship between biological yield and grain yield of common bean.

Parameter	Value
Dependent variable	Grain yield (t ha^{-1})
Independent variable	Biological yield (t ha^{-1})
Regression equation	GY = −0.2038 + 0.0485 × BY
Coefficient of determination (R^2)	0.976
Adjusted R^2	0.974
F-statistic	528.45
P-value	< 0.0001
Number of observations (N)	15

The superior performance of the organic fertilizer treatment can be attributed to the gradual release of nutrients together with improvements in soil physical, chemical, and biological properties. Organic amendments increase soil organic matter, improve aggregation, enhance water-holding capacity, stimulate microbial activity, and increase nutrient retention, thereby providing a more favorable environment for root development and nutrient uptake (Singh et al., 2024; Jiang et al., 2025). Such improvements likely contributed to the greater plant height, leaf production, branching, leaf area index, biomass accumulation, and grain yield observed in the present study. Similar responses have been reported by Ahmadi et al. (2023), who found that organic fertilizer significantly increased common bean growth and yield compared with mineral fertilizer under field conditions.

In contrast, although chemical fertilizer significantly improved crop performance relative to the unfertilized control, its effects remained consistently lower than those of organic fertilizer. Mineral fertilizers provide readily available nutrients but generally do not improve soil structure, microbial activity, or long-term nutrient retention. Consequently, nutrient losses through leaching or reduced nutrient-use efficiency may limit crop performance, particularly in soils with low organic matter such as the experimental soil used in this study. The observed superiority of organic fertilizer therefore highlights the importance of integrating soil fertility improvement with nutrient supply for sustainable common bean production.

Conditional Effectiveness of BiofertilizerUnder Different Fertility Systems

The principal finding of this study was that the effectiveness of the nitrogen-fixing biofertilizer depended strongly on the accompanying fertilizer source. Biofertilizer significantly enhanced vegetative growth, biomass production, and grain yield when combined with chemical fertilizer (T5 compared with T2), whereas its addition to nutrient-rich organic fertilizer (T4 compared with T3) produced no statistically significant improvement. This context-dependent response represents the major contribution of the present study.

The positive response observed under chemical fertilization suggests that biofertilizer effectively complemented mineral nutrient supply by enhancing biological nitrogen fixation and improving plant nutrient acquisition. Similar synergistic interactions between Rhizobium inoculation and mineral fertilizers have been reported in several legume crops, where inoculation increased nodulation, biomass production, and grain yield under moderate soil fertility conditions (Genetu et al., 2021; Fortu et al., 2025). Under such conditions, biological nitrogen fixation supplements mineral nitrogen, resulting in improved nitrogen availability throughout the growing season and greater crop productivity.

Conversely, the absence of additional benefits from biofertilizer in the organic fertilizer treatment suggests that the nutrient-rich organic amendment already provided conditions sufficient to maximize plant growth. Organic fertilizers supply nitrogen gradually while simultaneously improving microbial activity and nutrient cycling, potentially reducing the dependence of common bean on symbiotic nitrogen fixation. Furthermore, organic amendments often support diverse native microbial communities that may compete with introduced inoculant strains for root colonization and nodule occupancy (Mendoza-Suárez et al., 2021). Consequently, the introduced biofertilizer may have contributed little additional benefit beyond that already provided by the organic amendment.

These explanations should, however, be interpreted cautiously because nodulation, nitrogen fixation, soil mineral nitrogen, and microbial community composition were not measured in the present study. Therefore, the proposed mechanisms are supported by previous literature rather than direct experimental evidence. Nevertheless, the consistency between the present findings and previous studies indicates that the agronomic effectiveness of biofertilizers depends largely on the existing soil fertility status and nutrient management strategy.

Relationships Between Growth Traits and Grain Yield

Correlation and regression analyses further clarified the factors associated with grain yield formation. Pearson correlation analysis revealed strong positive relationships among most vegetative growth traits, yield components, and final grain yield (Figure 3). Grain yield exhibited particularly strong positive correlations with biological yield, number of leaves before and after flowering, pods per plant, leaf area index, and plant height, indicating that vigorous vegetative development contributed directly to increased productivity.

Among all measured variables, biological yield showed the strongest association with grain yield ($r = 0.988$), and simple linear regression demonstrated that biological yield explained 97.6% of the total variation in grain yield (Fig 4). This strong relationship suggested that biomass accumulation was the primary determinant of grain production under the experimental conditions. Similar relationships have been reported in common bean and other grain legumes, where greater vegetative growth increases photosynthetic capacity, dry matter accumulation, and assimilate partitioning to reproductive organs, ultimately resulting in higher grain yield.

These statistical analyses complement the treatment comparisons by demonstrating that improvements in vegetative growth translated directly into enhanced grain production. Consequently, management practices that promote biomass accumulation, including balanced nutrient management and appropriate biofertilizer use, are likely to contribute substantially to yield improvement.

Agronomic Implications, Study Limitations, and Future Perspectives

The findings of the study provide important implications for sustainable common bean production in Afghanistan and other regions characterized by low soil fertility. Nutrient-rich organic fertilizer substantially improved crop growth and productivity compared with mineral fertilizer alone, while biofertilizer proved most beneficial when integrated with chemical fertilization. These results suggest that biofertilizer should not be considered a universal substitute for conventional fertilizers but rather as a complementary input whose effectiveness depends on the existing fertility conditions.

From a practical perspective, farmers relying primarily on mineral fertilizers may achieve greater productivity by integrating biofertilizer into their nutrient management programs. Conversely, where sufficient quantities of well-decomposed organic fertilizer are available, additional biofertilizer application may provide limited economic benefit. Such context-specific nutrient management strategies could improve fertilizer-use efficiency while reducing unnecessary production costs and environmental impacts.

Several limitations should be acknowledged. The experiment was conducted at a single location during one growing season, and important physiological variables such as nodulation, biological nitrogen fixation, nutrient uptake, and soil microbial dynamics were not measured. Consequently, the biological mechanisms responsible for the observed treatment responses remain inferential.

Future research should include multi-location and multi-season experiments to validate the consistency of these findings under different

environmental conditions. Studies integrating measurements of nodulation, nitrogen fixation, nutrient uptake, soil microbial communities, and long-term changes in soil fertility would provide a more comprehensive understanding of the mechanisms governing biofertilizer performance. Economic analyses evaluating the cost-effectiveness of integrated nutrient management strategies would also enhance the practical applicability of these findings for farmers.

Conclusions

It was concluded that the agronomic effectiveness of an N_2-fixing biofertilizer is strongly influenced by the accompanying fertilizer system. Nutrient-rich organic fertilizer consistently promoted greater vegetative growth, biological yield, and grain yield than mineral fertilizer alone, confirming the importance of improving soil fertility through organic nutrient inputs under the calcareous conditions of Kabul. However, the biofertilizer exhibited contrasting responses depending on nutrient availability. While inoculation significantly enhanced crop performance when combined with mineral fertilizer, it produced no measurable improvement when applied together with nutrient-rich organic fertilizer. These findings indicate that the response of common bean to biofertilizer is conditional rather than universal.

The strong relationships observed between vegetative growth, biological yield, and grain yield further demonstrate that improvements in biomass production are closely associated with yield formation. The exceptionally strong predictive relationship between biological yield and grain yield highlights biomass accumulation as a key determinant of productivity under different nutrient management strategies.

From an agronomic perspective, these results suggest that biofertilizers should be used strategically in production systems where mineral nutrient availability limits crop growth, whereas their application may offer limited additional benefit in soils already enriched with high-quality organic amendments. Adopting context-specific integrated nutrient management practices that consider the existing soil fertility status can improve fertilizer use efficiency, reduce unnecessary input costs, and enhance the sustainability of common bean production in Afghanistan and other semi-arid regions with similar agroecological conditions.

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