

Effect of bioinoculants on soil fertility, phosphate solubilization, and yield enhancement in chickpea (*Cicer arietinum*) under field conditions

Supriya Tomer¹, Priyanka Khati^{2*}, Ramesh Chandra³, Narendra Singh Bhandari⁴, Saurabh Gangola⁵, Jitender Singh⁶

¹Department of Biotechnology, Ch. Charan Singh University, Meerut, 250004, India; supriyamicro@gmail.com (S.T.).

²Crop Production Division, Vivekananda Parvatiya Krishi Anusandhan Sansthan, Almora, 263601, Uttarakhand, India; Priyankakhahti712@gmail.com (P.K.).

³Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, 263145, India.

⁴Faculty of Agricultural Sciences, Shree Guru Gobind Singh Tricentenary University, Chandu-Budhera, Gurugram-Badli Road, Gurugram, Haryana, 122505, India.

⁵Department of Microbiology, Graphic Era Deemed to be University, Dehradun, 248002, India; Sainsaurabh@gmail.com (S.G.).

⁶Department of Microbiology, Ch. Charan Singh University, Meerut, 250004, India.

Abstract: This study evaluates the effectiveness of three phosphate-solubilizing bacteria (PSB): *Lysinibacillus macrolides* (ST-30), *Bacillus cereus* (ST-06), and *Pseudomonas pelleroniana* (N-26), in enhancing soil phosphorus (P) availability, improving chickpea (*Cicer arietinum* PG-186) yield, and optimizing crop economics compared to chemical P-fertilizer. The application of PSB strains significantly increased soil available phosphorus (AP) and nitrogen content. The highest soil P content, with an 89.89% increase over pre-sown soil, and maximum grain yield, at 24.98 q/ha (a 37.57% increase over control), were achieved with the ST-30 strain combined with 20 kg P₂O₅/ha. PSB, especially *Lysinibacillus macrolides* ST-30, proved highly effective, demonstrating superior performance in P-solubilization and yield enhancement compared to chemical fertilizers alone. Integrating PSB ST-30 with 20 kg P₂O₅/ha resulted in the highest net profit of INR 45,453 and the best cost-benefit ratio of 108%, offering a sustainable and economically advantageous alternative to standard chemical fertilization. Notably, the treatment involving PSB ST-30 with 20 kg P₂O₅/ha achieved the highest harvest index of 55.71, comparable to N-26 with 20 kg P₂O₅/ha. These findings suggest that the bioinoculants studied could serve as effective, sustainable alternatives to chemical fertilizers, improving soil health and crop productivity.

Keywords: *Bacillus cereus*, *Bioinoculants*, *Chickpea*, *Lysinibacillus macrolides*, *Phosphate Solubilization*, *Pseudomonas pelleroniana*, *Soil Fertility*, *Yield Enhancement*.

1. Introduction

Chickpeas (*Cicer arietinum* L.), one of the most widely cultivated pulse crops, are a vital source of protein and other nutrients for human consumption. They also enhance soil nitrogen levels through their symbiotic relationship with rhizobial bacteria. Despite their agronomic importance, chickpea yields are often constrained by soil limitations, including low phosphorus availability, which is crucial for energy transfer and overall plant growth. Phosphorus fertilization at 60 kg/ha is sufficient for chickpea cultivation in India. Adequate phosphorus levels positively influence growth, yield, and harvest index. Legumes like chickpeas require more phosphorus than other crop types [1].

Phosphorus, although abundant in soil, is often present in forms unavailable to plants due to soil pH, organic matter, and other factors, leading to deficiency. Dey et al. [2] stated that phosphorus deficiency is a major issue in India and worldwide, with nearly zero deficiency expected by 2025. The

unavailability of phosphorus across the country necessitates the judicious use of phosphate fertilizers. Phosphorus exists in soil or is added in organic and inorganic forms.

According to Sanyal et al. [3], inorganic phosphorus in Indian soil contributes 54% to 84%, which is 16% to 46% of organic phosphorus. The phosphorus requirement in India is met through the addition of various phosphate fertilizers, with the most commonly used being single super phosphate ($\text{Ca}(\text{H}_2\text{PO}_4)_2$) and triple superphosphate ($\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$), both of which utilize rock phosphates. Plants absorb phosphorus mainly in the form of H_2PO_4^- and HPO_4^{2-} ions, known as labile phosphorus, because they are directly absorbed by roots. However, these ions react with surrounding ions, causing their inactivity and preventing their utilization by plants, which necessitates repeated fertilizer applications to roots. A significant portion of applied fertilizers is lost through leaching into groundwater, leading to environmental toxicity. The global demand for sustainable and environmentally friendly agricultural practices has prompted researchers and agronomists to explore innovative strategies to optimize crop productivity while reducing environmental impacts. Among these strategies, the use of plant growth-promoting rhizobacteria (PGPR) has gained considerable attention as a potential alternative to traditional chemical fertilizers. This study provides a comprehensive evaluation of three distinct strains of phosphorus-solubilizing bacteria, PSB ST-30, PSB ST-06, and PSB N-26, in the context of chickpea cultivation. Through extensive field trials, the study aims to assess the individual and combined effects of these PSB strains on soil nutrient status and chickpea yield, comparing their performance with conventional phosphatic fertilizers. The research evaluates the growth-promoting efficiency, phosphate solubilization potential, and overall impact on soil fertility and chickpea yield of three bacterial strains: *Lysinibacillus macrolides* (ST-30), *Bacillus cereus* (ST-06), and *Pseudomonas pelleroniana* (N-26), under field conditions in Pantnagar, Uttarakhand. The hypothesis is that applying these bioinoculants will enhance phosphorus availability, improve nitrogen fixation, and increase chickpea yield compared to conventional fertilizers.

2. Materials and Methods

2.1. Strains and Culture Conditions

Three bacterial strains (ST-30: *Lysinibacillus macrolides*, accession No. KX396054; ST-06: *Bacillus cereus*, accession No. MF496242; and N-26: *Pseudomonas pelleroniana*, accession No. JN055435) were selected for their ability to promote plant growth and solubilize phosphate [4]. They were cultured in nutrient broth at 30°C with continuous shaking for 48 hours. Afterward, the cultures were centrifuged, and the bacterial cell pellets were resuspended in sterile saline for seed and soil application.

2.2. Field Trial Location and Design

The field trial was conducted at the Norman E. Borlaug Crop Research Centre, G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand (altitude: 343.84 m, 29°N latitude, 79.30°E longitude). The climate in this region is subtropical, with annual rainfall ranging from 800 mm to 1,200 mm. Chickpea (*Cicer arietinum* PG-186) was selected for this study due to its significance in regional cropping systems. The trial employed a randomized block design (RBD) with three replicates. Twelve treatments, including bacterial inoculants and chemical fertilizers, were evaluated across thirty-six plots of 8.4 m² each [5].

2.3. Soil Sample Collection

The soil samples for analysis were collected from field experiments on the application of P-solubilizing microbes [5] on chickpea (study in progress). The details of the treatments are shown in Table 1.

Table 1.
Treatment detail in field trial.

No	Treatment	Details
1	T1	Uninoculated control (without PSB and P_2O_5)
2	T2	Uninoculated + 20kg ha ⁻¹ of P_2O_5
3	T3	Uninoculated + 40 kg P_2O_5 ha ⁻¹
4	T4	PSB ST-30 + 0 P_2O_5
5	T5	PSB ST-30 + 20kg ha ⁻¹ of P_2O_5
6	T6	PSB ST-30 + 40kg ha ⁻¹ of P_2O_5
7	T7	PSB N-26 + 0 P_2O_5
8	T8	PSB N-26 + 20kg ha ⁻¹ P_2O_5
9	T9	PSB N-26 + 40kg ha ⁻¹ P_2O_5
10	T10	PSB ST-06 + 0 P_2O_5
11	T11	PSB ST-06 + 20kg ha ⁻¹ P_2O_5
12	T12	PSB ST-06 + 40kg ha ⁻¹ P_2O_5

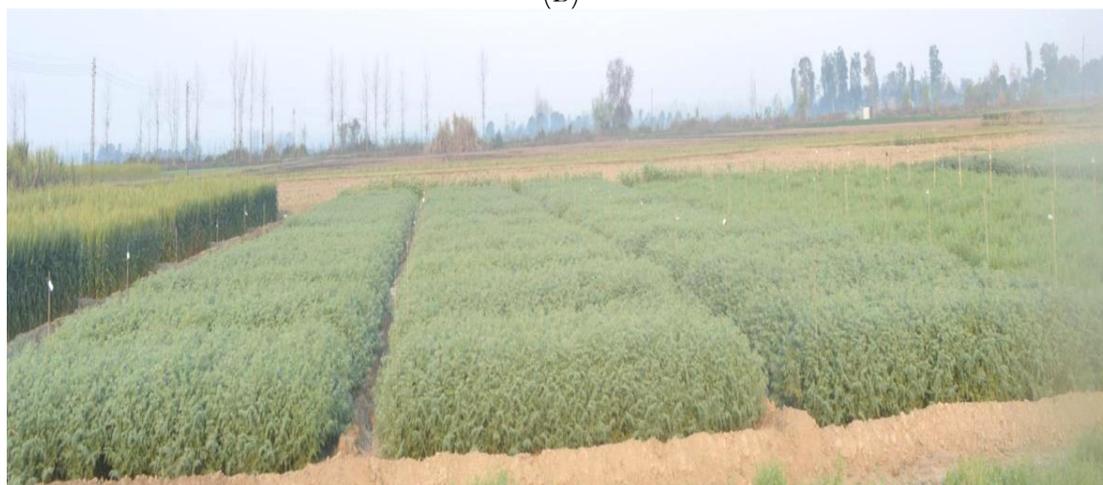
The samples were collected under prescribed conditions and 40 days after sowing (DAS) to compare the effects of treatments before and after sowing on soil status. A field view of the experiment is shown in Figure 1.



(A)



(B)



(C)

Figure 1.

Overview of experimental field at (A) 40, (B) 60, and (C) 75 DAS, respectively.

2.4. Chemical Analysis of Soil Samples

For chemical analysis, soil samples were collected at different intervals, sowing, 40 DAS, 60 DAS, and 75 DAS, and analyzed using the K054 Soil Testing Kit by Himedia Pvt. Ltd., India, for soil pH, oxidizable organic carbon, available potassium, nitrate nitrogen, ammonia nitrogen, and available phosphate. Quantitative phosphorus content was measured using Olson's (NaHCO_3) method, [6], followed by Das et al. [7].

2.5. Impact Assessment of Bioinoculants on Total Straw and Grain Yield

The total straw and grain yield of plants in each treatment plot were used to calculate crop phosphorus economy. The harvest index was then determined. The cost-benefit ratio was compared across all treatments. The entire study was evaluated against standard information for the control treatment, which involved the recommended phosphorus dose and 50% P without PSB inoculation, ensuring consistency in comparison.

Economics of P was calculated as follows:

Treatment number	Cost of production (Rs.)	Return (Rs.)	Net profit Cost of production	(Return –
			<i>S.P (Return)</i>	
			$\text{Cost Benefit Ratio} = \frac{S.P (Return)}{C.P. (Cost of production)}$	

2.6. Statistical Analysis

The analysis was performed in triplicate. All data from the field trial study were analyzed using analysis of variance (ANOVA) with the general linear model procedure (SPSS, ver. 16.0) to identify significant effects of different treatments. Duncan's Multiple Range Test (DMRT) was employed to determine significant differences between individual events ($P \leq 0.05$).

3. Results

3.1. Soil Physicochemical Parameters

The pH of the soil was observed to be slightly lower in most treated samples compared to the control, likely due to organic acids such as gluconic and succinic acids secreted by PSBs for phosphate solubilization. Initially, the soil pH was slightly alkaline at 8.0 ± 0.1 , decreasing to 7.7 ± 0.1 after 40 days after sowing (DAS), and further to 7.6 ± 0.1 at crop maturity, regardless of PSB treatment (Table 2). These findings align with those of Orhan et al. [8] and Das et al. [7]. The initial organic carbon (OC) content ranged from 0.505% to 0.750%, decreasing to 0.30%–0.50% after 75 days in the control and chemical fertilizer treatments, regardless of the amount applied. Conversely, treatments with bio-inoculums N-26 and ST-6 maintained OC levels within the initial range. Notably, the bio-inoculum ST-30 increased OC levels at 75 DAS to 0.750%–1.00%, supporting the growth of other synergistic bacterial populations, which can enhance soil health and fertility.

Table 2.

Soil physico-chemical properties at different time interval. a: as per "K054 soil testing Kit; Himedia Laboratories Pvt Ltd. India.

Treatments	Soil pH	OC b					APH c					APT d				AN e			NN f				
		L	ML	M	MH	H	B	L	M	MH	H	L	M	H	VH	L	M	H	VL	L	M	H	
Presowing	8.0			■				■					■				■			■			
40 DASa																							
T1	7.9			■				■					■				■			■			
T2	8.0			■				■	■				■				■			■			
T3	8.0			■				■	■				■				■			■			
T4	7.7			■	■			■	■				■				■			■	■		
T5	7.8			■	■			■	■				■				■			■	■		
T6	7.9			■	■			■	■				■				■			■	■		
T7	7.8			■	■			■	■				■				■			■	■		
T8	7.9			■	■			■	■				■				■			■	■		
T9	7.9			■	■			■	■				■				■			■	■		
T10	7.8			■	■			■	■				■				■			■	■		
T11	7.9			■	■			■	■				■				■			■	■		
T12	7.9			■	■			■	■				■				■			■	■		
60 DAS																							
T1	8.0			■				■	■				■				■			■			
T2	8.0			■				■	■				■				■			■			
T3	8.0			■				■	■				■				■			■			
T4	7.7			■	■			■	■				■				■			■	■		■
T5	7.7			■	■			■	■				■				■			■	■		■
T6	7.6			■	■			■	■				■				■			■	■		■
T7	7.8			■	■			■	■				■				■			■	■		■
T8	7.9			■	■			■	■				■				■			■	■		■
T9	7.9			■	■			■	■				■				■			■	■		■
T10	7.8			■	■			■	■				■				■			■	■		■
T11	7.9			■	■			■	■				■				■			■	■		■
T12	7.9			■	■			■	■				■				■			■	■		■
75 DAS																							
T1	8.0			■				■	■				■				■			■			
T2	8.0			■				■	■				■				■			■			
T3	8.0			■				■	■				■				■			■			
T4	7.7			■				■	■				■				■			■	■		■
T5	7.7			■				■	■				■				■			■	■		■
T6	7.6			■				■	■				■				■			■	■		■
T7	7.8			■				■	■				■				■			■	■		■
T8	7.9			■				■	■				■				■			■	■		■

T9	7.9																		
T10	7.8																		
T11	7.9																		
T12	7.9																		

Note: Black boxes show respective test results and are the mean of three replicates. b: OC, organic carbon (5 oxidizable organic carbon). L: low (0.1- 0.3); ML: Medium low (0.300-0.500); M: Medium (0.500-0.750); MH: Medium High (0.750-1.00); H: High (1.00-1.50). c: APH, Available phosphate as P₂O₅ (Kg ha⁻¹). B: Blank; L: Low (<22); M: Medium (22-56); MH: Medium High (56-73); H: High (>73). d: APT, Available potassium as K₂O (Kg ha⁻¹). L: Low (>112); M: Medium (112- 280); H: High (280-392); VH: Very High (>393). e: AN, Ammonical nitrogen (Kg ha⁻¹). L: Low (approximately 15); M: Medium (approximately 73); H: High (approximately 202). f: NN, Nitrate nitrogen (Kg ha⁻¹). VL: Very low (approximately 04); L: Low (approximately 10); M: Medium (approximately 20); H: High (approximately 50).

In the case of available phosphorus (APH) at the presown stage, the range was less than 22 kg ha⁻¹, unchanged at 40 DAS in the control. Treatments with 20 and 40 Kg P₂O₅ ha⁻¹ showed slight increases, remaining within 22-56 kg ha⁻¹. Maximum APH increase occurred in plots treated with bio-inoculums (ST-30, ST-6, N-26), rising from 22-56 to 56-73 kg ha⁻¹ after 40 days, maintained up to 60 DAS, then decreasing to 22-56 kg ha⁻¹. Untreated plots' APH remained at 22-56 kg ha⁻¹ until 60 DAS, then decreased below 22 kg ha⁻¹ (Table 2).

The level of available potassium (APT) in the crops was maintained at a medium level (112-280 kg ha⁻¹) throughout the study, regardless of the treatment applied (Table 2).

The nitrogen content of the soil was analyzed in two forms: ammonia N (AN) and nitrate N (NN). An increase in AN levels from ≤ 15 to 16-73 kg ha⁻¹ at 40 DAS was observed in different treated soil samples; however, untreated samples showed no change in AN levels. Similarly, for NN, the absolute control remained constant (≤ 10 kg ha⁻¹) up to 40 DAS and then decreased to ≤ 4 kg ha⁻¹ at 60 and 75 DAS in all chemically treated samples. In contrast, bio-inoculant treatments (ST-30, ST-39, and N-26) showed an increase in NN from ≤ 4 kg ha⁻¹ to 5-10 kg ha⁻¹ at 40 DAS and 10-20 kg ha⁻¹ at 60 and 75 DAS (Table 2). The increase in soil NN content during later stages indicates a lower nitrogen requirement during crop maturity. Frequent nodulation in plants treated with bio-inoculants may be linked to a higher soil nitrogen reservoir.

3.2. P Content of Soil

The phosphorus content of soil samples collected before and after harvesting was compared. In the pre-sown condition, the soil P content was 7.68 ppm, while post-harvest in the absolute control was 6.67 ppm, indicating a 13.15% reduction. Treatment with 20 kg P₂O₅/ha resulted in a 34.03% increase, reaching 10.29 ppm over the pre-sown level. Similarly, applying 40 kg P₂O₅/ha increased P content by 60.63%, reaching 12.34 ppm. The highest soil P level, 14.58 ppm, was recorded in ST-30 with 20 kg P₂O₅/ha, representing an 89.89% increase over pre-sowing soil. ST-30 with 40 kg P₂O₅/ha showed an 87.33% increase, reaching 14.39 ppm. N-26 with 40 kg P₂O₅/ha and N-26 with 20 kg P₂O₅/ha increased soil P by 81.86% and 80.03%, respectively. ST-30 alone increased P by 81.34% to 13.93 ppm, comparable to ST-06 with 40 kg P₂O₅/ha, which increased P by 74.18% to 13.38 ppm. Treatments with N-26 alone and ST-06 alone increased P levels by 61.63% (12.41 ppm) and 56.73% (12.04 ppm), respectively. Additionally, ST-06 combined with 20 kg P₂O₅/ha and 40 kg P₂O₅/ha increased soil P by 59.51% (12.25 ppm) and 81.86% (13.97 ppm), respectively (Table 3).

Table 3.

Effect of PSB (ST-30, N-26, ST-6) on P content of soil (ppm) of *Cicer arietinum* L. var. PG-186.

Treatment	Presowing	Post harvesting	% Increase or decrease in P level of soil
Uninoculated control	7.68	6.67 ± 0.38a	-13.15
20 kg P ₂ O ₅ ha ⁻¹		10.29 ± 0.71b	34.03
40 kg P ₂ O ₅ ha ⁻¹		12.34 ± 1.37bc	60.63
PSB ST-30		13.93 ± 1.47c	81.34
PSB ST-30 + 20 kg P ₂ O ₅ ha ⁻¹		14.58 ± 1.48c	89.89
PSB ST-30 + 40 kg P ₂ O ₅ ha ⁻¹		14.39 ± 0.97c	87.33
PSB N-26		12.41 ± 1.83bc	61.63
PSB N-26 + 20 kg P ₂ O ₅ ha ⁻¹		13.83 ± 1.89c	80.03
PSB N-26 + 40 kg P ₂ O ₅ ha ⁻¹		13.97 ± 2.17c	81.86
PSB ST-6		12.04 ± 1.95bc	56.73
PSB ST-6 + 20 kg P ₂ O ₅ ha ⁻¹		12.25 ± 1.22bc	59.51
PSB ST-6 + 40 kg P ₂ O ₅ ha ⁻¹		13.38 ± 1.76c	74.18
SEm		2.318	

The data were analyzed using SPSS version 16.0. Duncan's multiple-range test was employed. Means ± S.E. are presented. Values in parentheses indicate homogenous subsets with significant

differences ($P \leq 0.05$). Each value represents the mean of three replicates. PSB: phosphate-solubilizing bacteria (1.9×10^8 cfu/seed). Values in brackets show the percentage increase over the control.

3.3. Effect of PSB on Straw Yield

After harvesting, the straw yield and grain yield per hectare of the chickpea crop were calculated. At the time of harvest, the absolute control straw yield was observed at 39.40 q/ha, while the straw yield of the treatment with 20 kg P_2O_5 /ha was recorded at 40.12 q/ha (Figure 2). The harvest index of the absolute control crop was 46.05, which increased to 50.18 in the treatment with 20 kg P_2O_5 /ha. The treatment with 40 kg P_2O_5 /ha resulted in a significant increase in the harvest index compared to the control. This treatment, containing an optimal dose of phosphate fertilizer, achieved a harvest index of 52.47, with a straw yield of 46.71 q/ha. The highest harvest index, 55.71, was obtained in the ST-30 treatment with 20 kg P_2O_5 /ha. The greatest increase in harvest index was observed in the treatment with bio-inoculants N-26 and 20 kg P_2O_5 /ha, which recorded a harvest index of 55.67 and a straw yield of 43.58 q/ha.

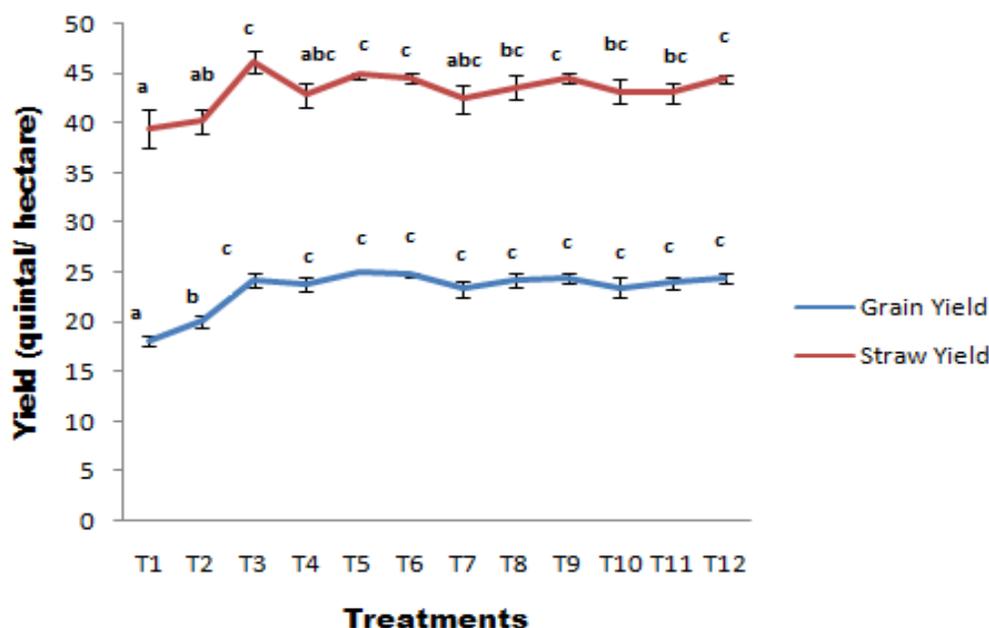


Figure 2. Effect of PSB (ST-30, N-26, and ST-6) on straw and grain yield (q ha⁻¹) at the time of harvesting.

This was followed by ST-30 as a PSB without any additional phosphate fertilizer, with a 55.58 harvest index, and PSB ST-06 along with 20 kg P_2O_5 /ha, achieving a 55.54 harvest index. Treatments containing ST-06 alone and with a blend of 40 kg P_2O_5 /ha showed good harvest indices of 54.30 and 54.83, respectively. The treatment with N-26 combined with 40 kg P_2O_5 /ha resulted in a 54.80 harvest index, with 44.52 q/ha straw harvested. N-26 as the sole phosphate source also yielded promising results, with 42.46 q/ha straw and a 55.03 harvest index (Figure 2).

3.4. Grain Yield

At the time of harvesting, absolute control grain yield was observed at 18.12 q/ha. The treatment with 20 kg P_2O_5 /ha recorded a grain yield of 20.13 q/ha, representing an 11.18% increase over the control. The treatment with 40 kg P_2O_5 /ha resulted in a significant increase in grain yield compared to the control, with a 33.66% rise and a yield of 24.21 q/ha. The highest grain yield of 24.98 q/ha was obtained in the ST-30 treatment with 20 kg P_2O_5 /ha. This treatment showed the greatest percentage

increase of 37.57% over the control. The highest yield was comparable to the treatment containing bio-inoculants ST-30 combined with 40 kg P₂O₅/ha fertilizer, which achieved a 36.46% increase over control with a yield of 24.7 q/ha (Figure 2). The treatment with PSB N-26 along with 40 kg P₂O₅/ha yielded 24.40 q/ha, a 35.10% increase over the control. Treatments containing ST-06 alone and with 20 kg and 40 kg P₂O₅/ha produced grain yields of 23.44, 23.94, and 24.40 q/ha, respectively, with percentage increases over control of 29.41%, 32.19%, and 34.77%. N-26 as a sole phosphate source and combined with 20 kg P₂O₅/ha showed increases of 28.99% and 33.66%, with yields of 23.37 and 24.26 q/ha, respectively. The treatment with ST-30 as a PSB, without additional phosphate fertilizer, also showed promising results, with a yield of 23.78 q/ha and a 31.20% increase over control (Figure 2; supplementary information 1).

3.5. Crop Economics

Crop economics were calculated as per the methods described in Appendix XII. Regarding the economic cost of *Cicer arietinum* var. PG-186, the highest net profit was achieved with the treatment using ST-30 as a PSB and 20 kg P₂O₅/ha, amounting to INR 45,453.33, with a 108% cost-benefit percentage. The next best was ST-30 as a PSB with 40 kg P₂O₅/ha, yielding INR 43,446.67 and a 101% cost-benefit. The cost-benefit percentage was highest at 103% for the treatment with ST-30 as a PSB alone, without additional chemical fertilizers, with a net profit of INR 42,303 (Table 4).

Table 4.

Effect of PSB (ST-30, N-26, ST-6) on cost economy of *Cicer arietinum* L. var. PG-186.

Sl. No.	Treatments	Cost of production (Rs)	Return (Rs.)	Net Profit (Rs.)	Cost Benefit percent
1.	Uninoculated control	40,815	63,408.33±2,059.05a	22,593.33± 2,059.05a	55± 0.05a
2.	20 kg P ₂ O ₅ ha ⁻¹	41,865	70,466.67± 2,136.91b	28,601.67± 2,136.91a	68± 0.05b
3.	40 kg P ₂ O ₅ ha ⁻¹	42,915	84,746.67± 2,456.30c	41,831.67± 2,546.30b	97±0.06c
4.	PSB ST-30	40,915	83,218.33± 2,243.56c	42,303.33± 2,243.56b	103±0.05c
5.	PSB ST-30 + 20 kg P ₂ O ₅ ha ⁻¹	41,965	87,418.33± 488.90c	45,453.33± 488.90b	108±0.01c
6.	PSB ST-30 + 40 kg P ₂ O ₅ ha ⁻¹	43,015	86,461.67± 901.99c	43,446.67± 901.99b	101±0.02c
7.	PSB N-26	40,915	81,783.33± 2829.48c	40,868.33± 2,829.48b	100±0.07c
8.	PSB N-26 + 20 kg P ₂ O ₅ ha ⁻¹	41,965	85,015.00± 2415.07c	43,050.00± 2,415.07b	103±0.06c
9.	PSB N-26 + 40 kg P ₂ O ₅ ha ⁻¹	43,015	85,411.67± 1827.26c	42,396.67± 1,827.26b	99±0.04c
10.	PSB ST-6	40,915	82,040.00± 3479.80c	41,125.00± 3,479.80b	101±0.09c
11.	PSB ST-6+ 20 kg P ₂ O ₅ ha ⁻¹	41,965	83,778.33± 1992.94c	41,813.33± 1,992.94b	100±0.05c
12.	PSB ST-6+ 40 kg P ₂ O ₅ ha ⁻¹	43,015	85,411.67± 0.45c	42,396.67± 1,569.77b	99±0.04c
	SEm		14273734.028	14273734.028	0.008

The data were analyzed using SPSS version 16.0. Duncan's multiple-range test was employed. Means ± S.E. are presented. Values in parentheses denote homogeneous subsets with significant differences ($P \leq 0.05$). Each value represents the mean of three replicates. PSB: phosphate-solubilizing bacteria (1.9×10^8 cfu/seed).

Although the net profit of treatment containing only ST-30 is lower than that of treatment with ST-30 as a PSB and 40 kg P₂O₅/ha, the cost-benefit percentage is noticeably higher in the former due to lower production costs, as it is devoid of expensive chemical-based fertilizers. Net profit in the crop of the absolute control, grown under the same physiological conditions, was INR 22,593. The net profit percentage for the treatment with 20 kg P₂O₅/ha was INR 28,601.67, with a 68% cost-benefit ratio. Treatment with 40 kg P₂O₅/ha resulted in an excellent monetary gain of INR 41,831.67, with a 97% cost-benefit ratio, which is comparable to the treatment containing PSB N-26 along with 20 kg P₂O₅/ha, achieving a monetary gain of INR 43,050 and a 103% cost-benefit ratio. Treatments with ST-06 alone and with a blend of 20 kg and 40 kg P₂O₅/ha were also economically beneficial, with net profits of INR 41,125, INR 41,813.33, and INR 42,396.67, respectively. Treatments with PSB N-26

alone and combined with 40 kg P₂O₅/ha yielded net profits of INR 40,868 (100% cost benefit) and INR 42,396 (99% cost benefit), respectively (Table 4).

This study found that ST-30 is an efficient phosphate-solubilizing bacteria compared to a control crop with no PSB and phosphorus fertilizers. Economically, PSB ST-30 proved more effective than 20 kg P₂O₅/ha. Crops treated with PSB ST-30 and 20 kg P₂O₅/ha outperformed those receiving the recommended 40 kg P₂O₅/ha in agronomical, biochemical, and economic aspects.

3.6. PCA Analysis

All treatments responded positively to the different parameters, except for T1 (control) and T2 (20 kg ha⁻¹ of P₂O₅). High production costs occurred when P₂O₅ was applied at 40 kg ha⁻¹; however, straw yield was maintained with 20 kg ha⁻¹ of P₂O₅ along with various bioinoculants. Microbial inoculants, when used alone, also performed well. Under uninoculated conditions, the minimum phosphatic fertilizer requirement was 40 kg ha⁻¹. When microbial bio-inoculants (PSB ST-30, PSB N-26, and PSB ST-06) were applied, 20 kg ha⁻¹ of P₂O₅ was sufficient to reduce the remaining amount (Figure 3).

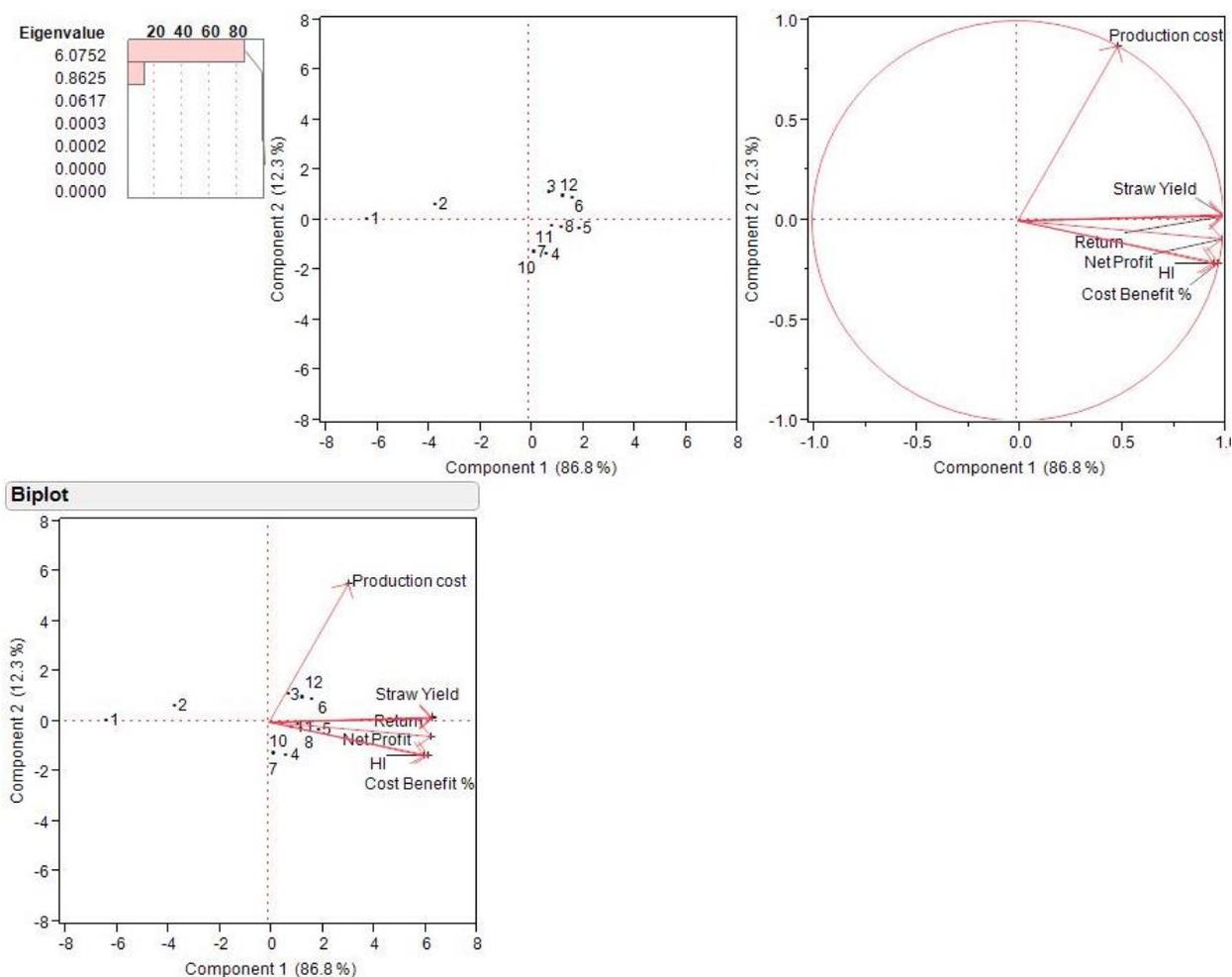


Figure 3.

Principal component analysis Biplot to show the correlation between treatments and parameters studies (production cost, straw yield, grain yield, return, netprofit, HI, and cost benefit percent).

4. Discussion

Along with the organic and inorganic acids secreted by PSBs, different plant exudates and different interactive bacterial activities could also be probable causes of the decrease in pH Fierer and Jackson [9]. Fierer and Jackson [9] reported more diverse bacterial communities in neutral soils than in acidic or alkaline soils [9]. Rhizospheric bacteria are primarily organotrophic; therefore, their growth and proliferation depend on the quantity and quality of available carbon [10]. Similarly, increasing soil organic matter in arable fields can ensure a consistent nutrient supply for crop improvement. Liao et al. [11] also reported that the sustained food supply to the Chinese population was due to an increase in soil organic carbon levels through agricultural intensification.

An increase in soil nutrient levels due to PGPR treatment on organically grown raspberries was observed by Orhan et al. [8]. Similarly, Chen et al. [12] found that PSB accelerated litter decay and nitrate release, enriching soil microbial communities. The references remain unchanged. Rashid et al. [13] also analyzed the impact of plant growth-promoting rhizobacteria on growth enhancement and nutrient bioavailability in soil has been observed to produce positive responses. Correlating with previous research, the application of bio-inoculants (N-26, ST-06, and ST-30) can improve the nutrient status of Himalayan soils. The sample from the absolute control after harvesting showed a reduction in phosphorus levels compared to pre-sown conditions, likely due to plant utilization. Plants require phosphorus from soil to support various metabolic activities during development, emphasizing the importance of adding phosphorus fertilizers, organic or inorganic, from external sources [14]. Many studies have shown that the integrated application of PSB with fertilizers effectively improves soil phosphate content. Singh et al. [15]. Alamzeb and Inamullah [16] also studied PSB's impact on plant P uptake, observing positive results. A similar study was also conducted by Parashar and Sharma [17], who observed that the inoculation of PSB has a positive impact on the growth and yield of Chicken Pea.

Straw yield was positively affected by treatment with N-26 as the sole P source, representing the vegetative biomass of the plant, which imparts strength and influences reproductive growth. The effect of PSB was analyzed and found to be positive on wheat's vegetative and reproductive growth by Cataldi et al. [18]. Several reports indicate that plant growth promotion occurs after inoculation with commercial PGPB, which solubilizes inorganic Pi and mineralizes organic P in soils [19-21]. Results show the positive impact of PSB on yield and related parameters, especially with PSB ST-30. Pulses like chickpea require high doses of phosphorus for growth and maintenance, and PSB such as ST-30 has been identified as a potential bioinoculant to meet this heavy P requirement. Using these PSB can potentially reduce or replace 50-100% of chemical fertilizers. This is supported by studies where vascular arbuscular root inoculants containing *Glomus fasciculatum* served as biofertilizer, reducing fertilizer use in crops such as sugarcane, banana, and others [22]. Similarly, Öksel et al. [23] conducted A study on winter wheat investigated the effects of PGPR on yield, highlighting its positive impact on yield and related parameters. It was shown that PSB ST-30 with 20 kg P₂O₅/ha was more economical than 40 kg P₂O₅/ha. Similarly, Lalrinzuali et al. [24] examined the yield and economics of chickpea (*Cicer arietinum* L.) during the Rabi season. They used biofertilizers such as *Rhizobium* sp. (5 g/kg seed), *Pseudomonas striata* (10 g/kg seed), and PSB (20 g/kg seed), alongside chemical fertilizers at rates of 40, 50, and 60 kg/ha. The highest gross return and benefit ratio was observed with phosphorus at 60 kg/ha combined with PSB (20 g/kg seed). These findings suggest that integrating biofertilizers with optimized phosphorus levels can enhance chickpea yield and economic returns. Prajapati et al. [25] studied the impact of bioinoculants on the yield and profitability of chickpea. Similarly, Prajapati et al. [26] also experimented with chickpea with five levels of phosphorus fertilizers and three levels of phosphorus biofertilizers. Based on this observation, 75% RDP (recommended dose of phosphorus) through SSP (single super phosphate) plus 25% RDP through RP (rock phosphate) (F 4) was comparable to 100% RDP through SSP (F 1). They recommended the integrated use of 75% RDP via SSP and 25% RDP via RP, along with the combined use of AM (arbuscular mycorrhizal fungi) and PSB (phosphate-solubilizing bacteria), for improved chickpea yield. According to Kumar and Singh [27], application of *Rhizobium*, PSB, and 60 kg/ha phosphorus produced the maximum number of grains per

pod (1.93), higher seed yield (1537.20 kg/ha), and straw yield (3195.12 kg/ha). Rhizobium inoculation of seeds may replace costly nitrogen fertilizers and promote sustainable production. Therefore, seed inoculation with an effective rhizobial strain is essential to maintain adequate rhizobial populations in the rhizosphere. The combined application of phosphorus fertilizers and PSB inoculation proved most effective for yield and economic returns [28].

5. Conclusion

In conclusion, the comparative analysis of phosphate solubilizers, specifically *Lysinibacillus macroides* ST-30, *Bacillus cereus* ST-6, and *Pseudomonas pelleroniana* N-26, with chemical fertilizers has provided compelling evidence of the positive impact of phosphate solubilizers on soil phosphorus (P) content and various other soil physicochemical parameters. The results of this study demonstrated a notable increase of 89.89% in soil P content when PSB ST-30 was applied in conjunction with 20 kg P₂O₅ ha⁻¹, surpassing the efficacy of chemical fertilizers. This substantial enhancement in P availability signifies the effectiveness of phosphate solubilizers in promoting a nutrient-rich soil environment. The positive impact on P content is of paramount importance, as phosphorus is a critical nutrient for plant growth and development. In addition to improving soil nutrient status, these strains have proven their efficacy in promoting chickpea growth, with notable achievements in terms of harvest index and economic returns. A comparison between phosphatic fertilizers and PSB underscored the advantages of the latter, revealing that the integration of PSB with chemical fertilizers yielded superior results. These findings have significant implications for sustainable agriculture and offer a viable alternative to traditional fertilization methods. The success of PSB, particularly PSB ST-30, in improving soil status along with chickpea yield and economic returns, signifies a promising avenue for farmers and agronomists seeking environmentally friendly and economically sound practices.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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