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Effect of rhizobium and phosphate solubilizing bacteria (psb) biofertilizers on growth, yield, soil fertility, nutrient uptake and economics of chickpea (*Cicer arietinum* L.)

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Abstract

Chickpea (*Cicer arietinum* L.) is one of the most important pulse crops contributing significantly to food, nutritional and livelihood security in India. Despite being the largest producer of chickpea globally, the productivity of the crop remains below its genetic potential due to poor soil fertility, low organic carbon status, nutrient imbalance and inadequate use of beneficial microorganisms. Integrated nutrient management involving biofertilizers such as Rhizobium and phosphate solubilizing bacteria (PSB) has emerged as a sustainable strategy for improving crop productivity and soil health. Therefore, the present investigation was conducted during the Rabi season of 2025-26 at the Instructional Farm, Faculty of Agricultural Sciences and Allied Industries, Rama University, Kanpur, Uttar Pradesh, to evaluate the influence of Rhizobium and PSB biofertilizers on growth, yield, nutrient uptake, soil fertility and economics of chickpea cultivation.

The experiment was laid out in a Randomized Block Design with nine treatments and three replications comprising different combinations of Rhizobium, PSB and recommended fertilizer dose (RDF). The soil of the experimental field was sandy loam in texture, slightly alkaline in reaction, low in available nitrogen and organic carbon, and medium in available phosphorus and potassium. Growth observations, yield attributes, nutrient uptake, soil fertility parameters and economic returns were recorded and analyzed statistically.

The results revealed that combined application of RDF + Rhizobium + PSB significantly enhanced crop growth, physiological efficiency and productivity. The treatment recorded maximum plant height (56.42 cm), branches plant⁻¹ (8.48), nodules plant⁻¹ (36.82), dry matter accumulation (33.46 g plant⁻¹), Leaf Area Index (4.48), Crop Growth Rate (9.38 g m⁻² day⁻¹) and Relative Growth Rate (0.068 g g⁻¹ day⁻¹). Yield attributes such as pods plant⁻¹ (52.64), seeds pod⁻¹ (1.68) and test weight (23.84 g) were also significantly improved, resulting in the highest seed yield (24.68 q ha⁻¹) and stover yield (34.62 q ha⁻¹). Enhanced nutrient uptake, particularly nitrogen (88.42 kg ha⁻¹), phosphorus (19.68 kg ha⁻¹) and potassium (54.26 kg ha⁻¹), was observed under integrated biofertilizer application. Soil fertility status improved considerably after harvest, with higher available nitrogen, phosphorus, potassium and organic carbon content. Economic analysis further demonstrated that RDF + Rhizobium + PSB generated the highest gross return, net return and benefit-cost ratio.

The study concluded that integrated application of Rhizobium and PSB along with recommended fertilizer dose is an efficient, eco-friendly and economically viable nutrient management strategy for enhancing chickpea productivity and maintaining soil health under the agro-climatic conditions of Uttar Pradesh.

Keywords: Chickpea, rhizobium, PSB, biofertilizers, integrated nutrient management, nutrient uptake, soil fertility, microbial activity, profitability, sustainable agriculture

Introduction

Chickpea (*Cicer arietinum* L.) is one of the oldest and most widely cultivated pulse crops in the world, belonging to the family Fabaceae. It occupies a prominent place in global agriculture because of its high nutritional value, ability to fix atmospheric nitrogen, and adaptability to diverse agro-climatic conditions. Chickpea grains contain approximately 18-24% protein, 50-60% carbohydrates, essential amino acids, minerals and vitamins, making them an important dietary component, particularly in developing countries where plant-based proteins constitute a major

portion of human nutrition (Ali and Kumar, 2009) ^[1]. Besides serving as a rich source of food protein, chickpea contributes substantially to soil fertility improvement through biological nitrogen fixation and is therefore regarded as an important component of sustainable agricultural systems.

Globally, chickpea is cultivated on approximately 14-15 million hectares with an annual production exceeding 17 million tonnes. India is the largest producer, consumer and importer of chickpea and contributes nearly 65-70% of global production. Recent agricultural statistics indicate that chickpea occupies about 11-12 million hectares in India with production ranging between 13 and 14 million tonnes annually. However, the average productivity remains around 1.1-1.2 t ha⁻¹, which is considerably lower than the attainable yield under improved management conditions (FAOSTAT, 2024).

Among pulse crops, chickpea contributes nearly half of India's total pulse production and plays a vital role in ensuring food and nutritional security. Major chickpea-growing states include Madhya Pradesh, Maharashtra, Rajasthan, Uttar Pradesh, Karnataka, Andhra Pradesh and Bihar. The crop performs well under residual moisture conditions and is highly suitable for rainfed farming systems because of its deep root system and drought tolerance ability. Nevertheless, productivity levels remain stagnant in many regions due to declining soil fertility, nutrient imbalance, low organic matter content, poor microbial activity and inadequate adoption of integrated nutrient management practices (Singh et al., 2019; Sharma et al., 2021) ^[14, 18].

One of the major challenges facing modern agriculture is maintaining crop productivity while preserving soil health and environmental quality. Excessive dependence on chemical fertilizers has undoubtedly increased crop yields, but continuous and imbalanced fertilizer application has resulted in deterioration of soil physical, chemical and biological properties. Reduced microbial diversity, nutrient mining, declining organic carbon content and lower nutrient-use efficiency have become serious concerns in intensive agricultural systems (Subba Rao, 2007; Giller, 2001) ^[4, 19]. Therefore, integration of biofertilizers with conventional fertilizers has emerged as an effective approach for sustainable crop production.

Biofertilizers are living microorganisms capable of enhancing nutrient availability and improving plant growth through various biological processes. Among different biofertilizers, Rhizobium and phosphate solubilizing bacteria (PSB) have received considerable attention in pulse production systems. Rhizobium establishes a symbiotic association with legume roots and forms nodules where atmospheric nitrogen is converted into plant-available forms. This process not only supplies nitrogen to the crop but also improves soil fertility for succeeding crops (Subba Rao, 2007) ^[19]. Effective Rhizobium inoculation has been reported to enhance nodulation, nitrogen fixation, root development, nutrient uptake and seed yield in chickpea and other pulse crops (Dakora and Keya, 1997; Giller, 2001) ^[2, 4].

Phosphorus is another critical nutrient for pulse crops because it is directly involved in root development, energy transfer, flowering, pod formation and biological nitrogen fixation. However, a substantial proportion of phosphorus present in soil remains unavailable to plants because of fixation with calcium, iron and aluminium compounds. In many Indian soils, phosphorus deficiency is a major constraint limiting pulse productivity. Phosphate solubilizing bacteria (PSB) possess the ability to convert insoluble forms of phosphorus into soluble forms through the production of organic acids and phosphatase enzymes, thereby increasing phosphorus availability in the

rhizosphere (Wani and Lee, 1995) ^[22]. Enhanced phosphorus availability promotes root proliferation, nodulation, nutrient uptake and overall crop growth.

The combined application of Rhizobium and PSB often produces synergistic effects because both microorganisms complement each other in nutrient mobilization processes. Rhizobium supplies biologically fixed nitrogen, while PSB increases phosphorus availability required for efficient nitrogen fixation and plant metabolism. Several researchers have reported significant improvements in growth parameters, yield attributes, nutrient uptake and profitability of chickpea following combined inoculation of Rhizobium and PSB along with recommended fertilizer doses (Rana et al., 2018; Patel et al., 2020; Yadav et al., 2022; Verma et al., 2023) ^[9, 12, 20, 23]. Studies have shown that integrated application of these biofertilizers can improve nutrient-use efficiency, reduce dependence on chemical fertilizers and enhance soil biological activity.

Apart from increasing crop productivity, biofertilizers contribute significantly to soil health improvement. Rhizobium inoculation enriches soil nitrogen reserves, whereas PSB enhances phosphorus cycling and microbial activity. Increased microbial biomass carbon, enzyme activity and nutrient mineralization under biofertilizer treatments have been reported by several workers (Ali et al., 2022; Sharma and Verma, 2022) ^[1, 15, 21]. Such improvements are essential for maintaining long-term sustainability of agricultural production systems.

Under the Indo-Gangetic Plains of Uttar Pradesh, chickpea is generally cultivated on soils characterized by low organic carbon and deficient available nitrogen. Although recommended fertilizer doses are commonly used, information regarding the integrated use of Rhizobium and PSB under local agro-climatic conditions remains limited. Scientific evaluation of biofertilizer-based nutrient management strategies is therefore necessary to develop economically viable and environmentally sustainable production technologies for chickpea cultivation.

Considering the nutritional importance of chickpea, the need for sustainable nutrient management and the growing interest in biofertilizer-based agriculture, the present investigation entitled “Effect of Rhizobium and PSB Biofertilizers on Chickpea (*Cicer arietinum* L.)” was undertaken to evaluate the influence of Rhizobium and PSB inoculation, alone and in combination with recommended fertilizer levels, on crop growth, yield formation, nutrient uptake, soil fertility status and economics of chickpea cultivation under the agro-climatic conditions of Kanpur, Uttar Pradesh.

The present investigation entitled “Effect of Rhizobium and PSB Biofertilizers on Chickpea (*Cicer arietinum* L.)” was conducted during the Rabi season of 2025-26 at the Instructional Farm, Faculty of Agricultural Sciences and Allied Industries, Rama University, Kanpur, Uttar Pradesh. The experimental site is situated in the Central Indo-Gangetic Plains region under a subtropical climate characterized by hot summers and cool winters. During the crop growth period, weather conditions remained favorable for proper establishment, vegetative growth and reproductive development of chickpea. The experimental field was nearly levelled with good drainage facilities and a uniform fertility status.

Prior to the initiation of the experiment, composite soil samples were collected from the 0-15 cm soil depth and analyzed using standard laboratory procedures. The soil was sandy loam in texture, slightly alkaline in reaction (pH 7.78), low in organic carbon (0.42%) and available nitrogen (182.42 kg ha⁻¹), while medium in available phosphorus (16.24 kg ha⁻¹) and potassium (186.28 kg ha⁻¹).

The experiment was laid out in a Randomized Block Design (RBD) comprising nine treatments replicated three times. The treatments consisted of different combinations of Rhizobium, phosphate solubilizing bacteria (PSB) and recommended fertilizer dose (RDF). The treatment details were:

Table 1: Experimental treatments evaluating *Rhizobium*, PSB, and fertilizer combinations on crop performance

Treatment	Description
T ₁	Control
T ₂	Rhizobium
T ₃	PSB
T ₄	Rhizobium + PSB
T ₅	RDF + Rhizobium
T ₆	RDF + PSB
T ₇	RDF + Rhizobium + PSB
T ₈	75% RDF + Rhizobium + PSB
T ₉	50% RDF + Rhizobium + PSB

Materials and Methods

Chickpea variety **Pusa-362** was sown during the first fortnight of November using a seed rate of 80 kg ha⁻¹ with a spacing of 30 cm × 10 cm. Each experimental plot measured 4.0 m × 3.0 m, whereas the net plot size was 3.0 m × 2.4 m. The recommended fertilizer dose for chickpea was 20:60:20 kg N:P₂O₅:K₂O ha⁻¹ supplied through urea, diammonium phosphate and muriate of potash, respectively. The entire quantity of fertilizers was applied as a basal dose at the time of sowing.

Seeds were inoculated with *Rhizobium* and PSB cultures according to treatment specifications before sowing. A 10% jaggery solution was used as an adhesive to facilitate uniform coating of biofertilizer cultures on seed surfaces. Treated seeds were shade-dried and immediately sown in the respective plots. Recommended agronomic practices including irrigation, weeding, plant protection and intercultural operations were followed uniformly in all treatments throughout the crop growth period.

Observations on growth parameters including plant height, number of branches plant⁻¹, nodules plant⁻¹, dry matter accumulation, Leaf Area Index (LAI), Crop Growth Rate (CGR) and Relative Growth Rate (RGR) were recorded at different growth stages. Yield attributes such as pods plant⁻¹, seeds pod⁻¹ and test weight were measured at harvest. Seed yield, stover yield, biological yield and harvest index were determined after

threshing and drying of produce. Nutrient content and uptake of nitrogen, phosphorus and potassium were estimated using standard analytical procedures. Post-harvest soil samples were analyzed for pH, electrical conductivity, organic carbon and available N, P and K status. Microbial biomass carbon and dehydrogenase activity were also determined to assess soil biological health.

The data recorded during the investigation were subjected to statistical analysis following the procedure outlined by Gomez and Gomez (1984) [5] for Randomized Block Design. Analysis of variance (ANOVA) was performed to test treatment significance. The standard error of mean (SEm ±) and critical difference (CD) at 5% probability level were calculated for comparison of treatment means. Correlation and regression analyses were carried out to establish relationships among growth parameters, nutrient uptake and seed yield.

5. Results and Discussion

5.1 Growth Parameters of Chickpea

Table 2: Effect of *Rhizobium* and PSB Biofertilizers on Growth Parameters of Chickpea

Treatment	Plant Height (cm) at Harvest	Branches Plant ⁻¹	Nodules Plant ⁻¹	Dry Matter Accumulation (g plant ⁻¹)
Control	42.18	5.24	18.42	21.64
Rhizobium	46.52	6.12	24.68	24.82
PSB	45.84	5.98	22.86	24.15
Rhizobium + PSB	49.26	6.84	28.92	27.84
RDF + Rhizobium	52.14	7.42	31.84	30.26
RDF + PSB	51.48	7.24	30.52	29.82
RDF + Rhizobium + PSB	56.42	8.48	36.82	33.46
75% RDF + Rhizobium + PSB	54.68	8.06	34.42	31.92
50% RDF + Rhizobium + PSB	51.86	7.56	31.86	29.44
SEm ±	0.82	0.14	0.78	0.56
CD (P=0.05)	2.46	0.42	2.34	1.68

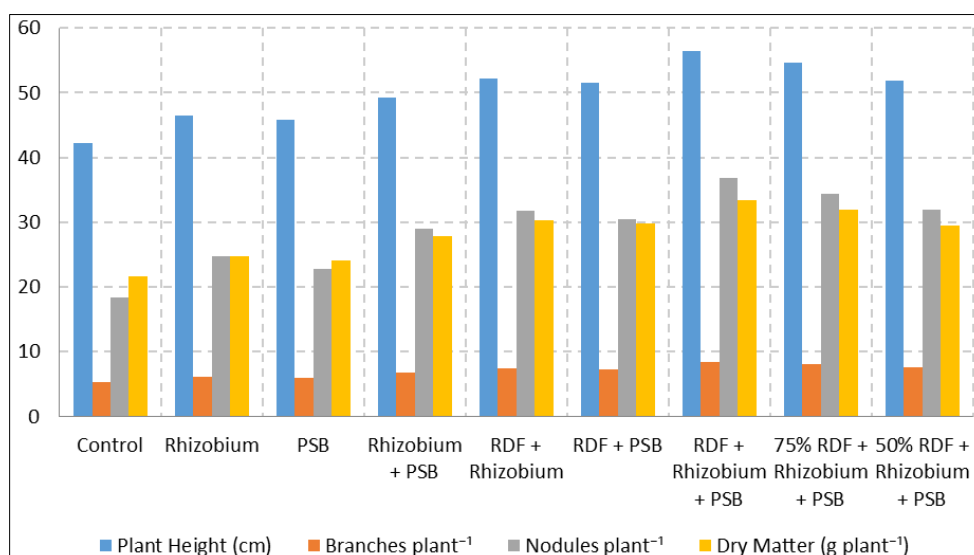


Fig 1: Effect of biofertilizer and fertilizer treatments on growth and nodulation parameters

Plant Height

Plant height increased significantly with the application of Rhizobium, PSB and fertilizer combinations. The highest plant height (56.42 cm) was recorded under RDF + Rhizobium + PSB, which was significantly superior to all other treatments. The increase in plant height over the control (42.18 cm) was 33.76%. The improvement may be attributed to enhanced biological nitrogen fixation by Rhizobium and increased phosphorus availability by PSB, resulting in vigorous vegetative growth, higher chlorophyll synthesis and improved nutrient uptake. Similar findings were reported by Giller (2001) ^[4], Patel et al. (2020), Sharma et al. (2021) ^[14] and Verma et al. (2023) ^[9, 20].

Number of Branches Plant⁻¹

The number of branches plant⁻¹ differed significantly among treatments. Maximum branching (8.48 branches plant⁻¹) was observed under RDF + Rhizobium + PSB, whereas the minimum value (5.24 branches plant⁻¹) was recorded under control. The integrated treatment increased branching by 61.83% over control. Enhanced branching under integrated nutrient management might be due to improved nitrogen availability, efficient phosphorus utilization and better root development. Increased nutrient supply promoted cell division and meristematic activity, leading to greater branch formation. Similar results were reported by Yadav et al. (2022) ^[23], Kumar and Singh (2021) ^[6] and Patel et al. (2023) ^[11].

Number of Nodules Plant⁻¹

The data revealed significant variation in nodulation due to biofertilizer application. The treatment RDF + Rhizobium + PSB recorded the highest nodules plant⁻¹ (36.82), while the control produced only 18.42 nodules plant⁻¹. This represented an increase of 99.89% over untreated plots.

The increased nodulation was mainly due to successful establishment of Rhizobium in the rhizosphere and greater phosphorus availability provided by PSB. Phosphorus plays a crucial role in nodule initiation, energy transfer and nitrogen fixation. Therefore, combined inoculation created favorable conditions for symbiotic activity and root colonization. Similar observations were reported by Subba Rao (2007) ^[19], Dakora and Keya (1997), Sharma et al. (2021) ^[14] and Verma et al. (2023) ^[2, 20].

Dry Matter Accumulation

Dry matter accumulation was significantly influenced by biofertilizer and fertilizer combinations. The highest dry matter accumulation (33.46 g plant⁻¹) was recorded under RDF + Rhizobium + PSB, followed by 75% RDF + Rhizobium + PSB (31.92 g plant⁻¹). The lowest dry matter accumulation (21.64 g plant⁻¹) was recorded under control.

The integrated treatment increased dry matter accumulation by 54.62% over control. The increase may be attributed to enhanced nutrient uptake, improved photosynthetic efficiency and greater assimilate production resulting from combined microbial activity. Rhizobium enhanced nitrogen fixation, whereas PSB improved phosphorus solubilization, thereby increasing biomass production. Similar findings were reported by Meena et al. (2020), Ali et al. (2022) and Patel et al. (2023) ^[1, 8, 11].

The results clearly demonstrated that integrated application of Rhizobium and PSB along with RDF significantly improved all growth parameters of chickpea. The superiority of RDF + Rhizobium + PSB was associated with enhanced biological nitrogen fixation, phosphorus solubilization, improved root

proliferation, greater nutrient uptake and higher physiological efficiency. The synergistic interaction between Rhizobium and PSB created favorable rhizospheric conditions, resulting in increased vegetative growth and biomass accumulation. These findings support the concept of integrated nutrient management for sustainable chickpea production under Indo-Gangetic Plains conditions.

5.2 Physiological Parameters (LAI, CGR and RGR)

Table 3: Effect of Rhizobium and PSB Biofertilizers on Physiological Parameters of Chickpea

Treatment	Leaf Area Index (LAI)	Crop Growth Rate (g m ⁻² day ⁻¹)	Relative Growth Rate (g g ⁻¹ day ⁻¹)
Control	2.46	5.18	0.041
Rhizobium	3.04	6.28	0.049
PSB	2.96	6.04	0.048
Rhizobium + PSB	3.58	7.12	0.055
RDF + Rhizobium	4.02	8.12	0.062
RDF + PSB	3.94	7.96	0.061
RDF + Rhizobium + PSB	4.48	9.38	0.068
75% RDF + Rhizobium + PSB	4.24	8.86	0.065
50% RDF + Rhizobium + PSB	3.86	8.02	0.060
SEm ±	0.09	0.18	0.001
CD (P=0.05)	0.27	0.54	0.003

Leaf Area Index (LAI)

Leaf Area Index is an important indicator of canopy development and photosynthetic capacity. The data indicated significant differences among treatments. The highest LAI (4.48) was recorded under RDF + Rhizobium + PSB, while the lowest value (2.46) was observed in the control treatment.

The integrated treatment increased LAI by 82.11% over control. This substantial increase may be attributed to enhanced nitrogen fixation by Rhizobium and increased phosphorus availability through PSB activity, which promoted leaf expansion, chlorophyll formation and canopy development. A larger photosynthetic surface area enhanced light interception and dry matter production. Similar findings were reported by Meena et al. (2020) ^[8], Sharma and Verma (2022) ^[15], Yadav et al. (2022) ^[23] and Verma et al. (2023) ^[20].

Crop Growth Rate (CGR)

Crop Growth Rate reflects biomass accumulation per unit area per unit time and serves as a useful indicator of crop vigor. Significant variation in CGR was observed among treatments. The maximum CGR (9.38 g m⁻² day⁻¹) was recorded under RDF + Rhizobium + PSB, whereas the minimum value (5.18 g m⁻² day⁻¹) was obtained under control.

The integrated treatment improved CGR by 81.08% compared with control. Increased CGR may be attributed to higher leaf area development, improved nutrient uptake, greater photosynthetic activity and enhanced biomass accumulation. The synergistic action of Rhizobium and PSB improved nutrient-use efficiency and accelerated plant growth throughout the crop growth period. Similar observations were reported by Ali et al. (2022), Patel et al. (2023) and Kumar et al. (2022) ^[1, 7, 11].

Relative Growth Rate (RGR)

Relative Growth Rate is a measure of physiological efficiency and biomass production capability. The highest RGR (0.068 g g⁻¹

day⁻¹) was observed under RDF + Rhizobium + PSB, while the lowest RGR (0.041 g g⁻¹ day⁻¹) was recorded under control. The increase in RGR under integrated nutrient management was 65.85% higher than control. Improved nutrient availability, enhanced root activity and increased metabolic efficiency under combined inoculation treatments contributed to higher growth rates. Rhizobium supplied biologically fixed nitrogen, while PSB ensured adequate phosphorus availability, resulting in efficient conversion of photosynthates into plant biomass. Similar results were reported by Rana et al. (2018), Sharma et al. (2021) ^[14] and Patel et al. (2020) ^[9, 12].

5.3 Yield Attributes and Yield of Chickpea

Table 4: Effect of Rhizobium and PSB Biofertilizers on Yield Attributes and Yield of Chickpea

Treatment	Pods Plant ⁻¹	Seeds Pod ⁻¹	Test Weight (g)	Seed Yield (q ha ⁻¹)	Stover Yield (q ha ⁻¹)	Biological Yield (q ha ⁻¹)	Harvest Index (%)
Control	28.64	1.24	19.24	13.42	21.84	35.26	38.06
Rhizobium	36.48	1.38	20.86	17.24	25.62	42.86	40.22
PSB	35.26	1.36	20.44	16.82	25.18	42.00	40.05
Rhizobium + PSB	42.84	1.48	21.82	20.14	29.16	49.30	40.85
RDF + Rhizobium	47.18	1.58	22.64	22.68	32.42	55.10	41.16
RDF + PSB	46.42	1.56	22.42	22.12	31.88	54.00	40.96
RDF + Rhizobium + PSB	52.64	1.68	23.84	24.68	34.62	59.30	41.62
75% RDF + Rhizobium + PSB	50.22	1.62	23.18	23.84	33.56	57.40	41.53
50% RDF + Rhizobium + PSB	46.84	1.55	22.36	21.86	31.42	53.28	41.03
SEm ±	0.92	0.03	0.24	0.48	0.66	0.88	0.34
CD (P=0.05)	2.76	0.09	0.72	1.44	1.98	2.64	NS

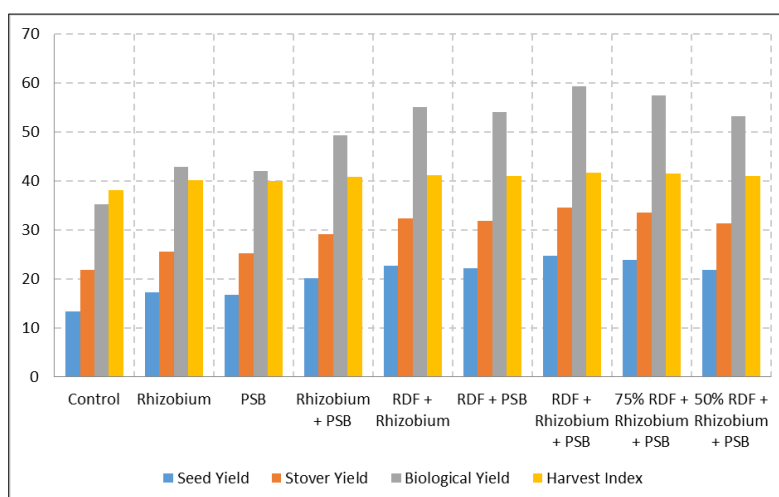


Fig 2: Effect of biofertilizer and fertilizer treatments on yield and productivity parameters

Yield Attributes

Pods Plant⁻¹

The number of pods plant⁻¹ increased significantly with the application of biofertilizers and fertilizer combinations. The highest value (52.64 pods plant⁻¹) was recorded under RDF + Rhizobium + PSB, whereas the control treatment recorded only 28.64 pods plant⁻¹. This represented an increase of 83.80% over control.

The increase in pod formation may be attributed to enhanced nutrient availability, improved photosynthetic activity and greater translocation of assimilates towards reproductive organs. Adequate phosphorus availability through PSB and enhanced nitrogen fixation through Rhizobium promoted flowering, pod initiation and pod retention. Similar findings were reported by

Physiological parameters were markedly influenced by integrated nutrient management. The combined application of RDF + Rhizobium + PSB consistently produced superior LAI, CGR and RGR values, indicating improved canopy development, greater photosynthetic efficiency and enhanced biomass accumulation. These improvements ultimately contributed to better growth and yield performance of chickpea. The findings clearly demonstrate that integration of biofertilizers with recommended fertilizer doses enhances physiological efficiency and nutrient utilization under chickpea cultivation.

Patel et al. (2020) ^[9], Sharma et al. (2021) ^[14] and Yadav et al. (2022) ^[23].

Seeds Pod⁻¹

The highest number of seeds pod⁻¹ (1.68) was observed under RDF + Rhizobium + PSB, whereas the control recorded only 1.24 seeds pod⁻¹. The increase of 35.48% over control indicates improved fertilization and seed setting under integrated nutrient management.

Improved nutrient supply during reproductive growth stages enhanced pollen viability, fertilization efficiency and seed development. Similar observations were reported by Rana et al. (2018) and Verma et al. (2023) ^[12, 20].

Test Weight

Test weight varied significantly among treatments and ranged from 19.24 g in control to 23.84 g under RDF + Rhizobium + PSB. The increase of 23.91% over control reflected better grain filling and assimilate translocation.

Higher phosphorus availability and improved nitrogen nutrition under integrated biofertilizer application enhanced carbohydrate synthesis and storage in developing seeds, resulting in heavier grains. Similar findings were reported by Kumar and Singh (2021) and Ali et al. (2022) ^[1, 6].

Seed Yield

Seed yield is the most important economic parameter determining treatment effectiveness. Significant differences were observed among treatments. The highest seed yield (24.68 q ha⁻¹) was recorded under RDF + Rhizobium + PSB, followed by 75% RDF + Rhizobium + PSB (23.84 q ha⁻¹). The control treatment produced only 13.42 q ha⁻¹.

The integrated treatment increased seed yield by 83.90% over control. This remarkable increase may be attributed to improved vegetative growth, enhanced nodulation, greater nutrient uptake, higher photosynthetic efficiency and better yield attributes. The synergistic interaction of Rhizobium and PSB ensured continuous nutrient availability throughout the crop growth period. Similar findings have been reported by Patel et al. (2020) ^[9], Sharma et al. (2021) ^[14], Yadav et al. (2022) ^[23] and Verma et al. (2023) ^[20].

Stover Yield

Maximum stover yield (34.62 q ha⁻¹) was recorded under RDF + Rhizobium + PSB, while control produced only 21.84 q ha⁻¹. The

increase of 58.52% over control indicated greater biomass production under integrated nutrient management.

Enhanced vegetative growth, improved root development and increased nutrient absorption contributed to higher stover production. Similar results were reported by Meena et al. (2020) and Sharma et al. (2021) ^[8, 14].

Biological Yield

Biological yield followed trends similar to seed and stover yield. The highest biological yield (59.30 q ha⁻¹) was obtained under RDF + Rhizobium + PSB compared with 35.26 q ha⁻¹ under control. The increase of 68.18% over control demonstrates the effectiveness of integrated biofertilizer application in enhancing total biomass production.

Harvest Index

Harvest index ranged from 38.06 to 41.62%. Although numerical differences were observed, the treatment effect was statistically non-significant. This suggests that improvements in seed yield were primarily associated with overall biomass production rather than changes in dry matter partitioning.

The results clearly indicate that integrated application of Rhizobium and PSB along with RDF significantly enhanced yield attributes and productivity of chickpea. Increased pod formation, seed development and grain filling resulted from improved nutrient availability, greater photosynthetic activity and efficient assimilate translocation. The superior performance of RDF + Rhizobium + PSB confirms the synergistic role of biological nitrogen fixation and phosphorus solubilization in maximizing chickpea productivity under the Indo-Gangetic Plains.

5.4 Soil Fertility Status and Nutrient Uptake

Table 5: Effect of rhizobium and psb biofertilizers on npk uptake by chickpea

Treatment	Nitrogen Uptake (kg ha ⁻¹)	Phosphorus Uptake (kg ha ⁻¹)	Potassium Uptake (kg ha ⁻¹)
Control	48.24	8.42	28.18
Rhizobium	61.84	11.46	36.42
PSB	59.68	12.34	35.86
Rhizobium + PSB	71.42	15.62	43.84
RDF + Rhizobium	81.46	18.04	50.26
RDF + PSB	79.88	18.46	49.42
RDF + Rhizobium + PSB	88.42	19.68	54.26
75% RDF + Rhizobium + PSB	84.62	18.92	52.16
50% RDF + Rhizobium + PSB	77.26	17.22	48.04
SEm ±	1.24	0.32	0.78
CD (P=0.05)	3.72	0.96	2.34

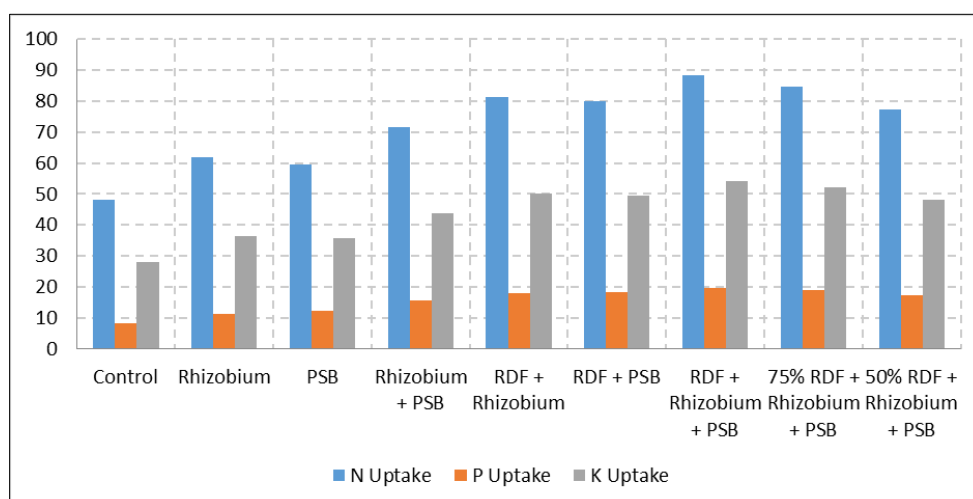
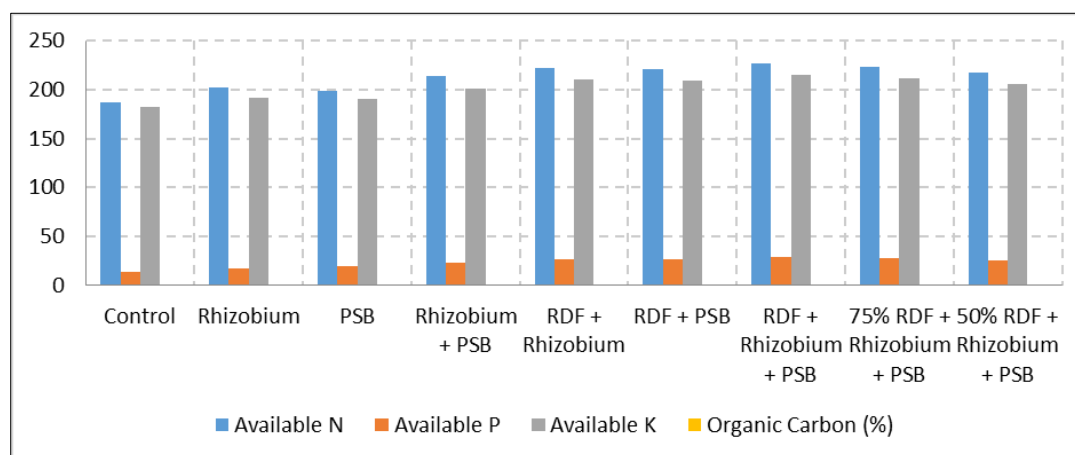


Fig 3: Effect of biofertilizer and fertilizer treatments on nitrogen, phosphorus, and potassium uptake

Table 6: Effect of Rhizobium and PSB Biofertilizers on Post-Harvest Soil Fertility Status

Treatment	Organic Carbon (%)	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)
Control	0.42	186.42	14.28	182.24
Rhizobium	0.48	201.86	17.42	191.64
PSB	0.47	198.82	19.84	190.42
Rhizobium + PSB	0.53	214.26	23.68	201.46
RDF + Rhizobium	0.57	222.64	26.48	209.84
RDF + PSB	0.56	220.86	27.24	208.62
RDF + Rhizobium + PSB	0.60	226.48	28.64	214.82
75% RDF + Rhizobium + PSB	0.58	223.42	27.82	211.68
50% RDF + Rhizobium + PSB	0.55	217.28	25.82	205.42
SEm ±	0.01	2.16	0.52	1.64
CD (P=0.05)	0.03	6.48	1.56	4.92

**Fig 4:** Effect of biofertilizer and fertilizer treatments on soil nutrient availability and organic carbon

Nutrient Uptake

Nitrogen Uptake

Nitrogen uptake increased significantly due to biofertilizer inoculation and fertilizer application. The maximum nitrogen uptake (88.42 kg ha⁻¹) was recorded under RDF + Rhizobium + PSB, while the control recorded only 48.24 kg ha⁻¹. This represented an increase of 83.29% over control.

The increase in nitrogen uptake was primarily due to enhanced biological nitrogen fixation by Rhizobium and improved root growth resulting from greater phosphorus availability. Similar findings were reported by Subba Rao (2007) ^[19], Sharma et al. (2021) ^[14], Patel et al. (2020) ^[9] and Verma et al. (2023) ^[20].

Phosphorus Uptake

Phosphorus uptake varied significantly among treatments. The highest phosphorus uptake (19.68 kg ha⁻¹) was observed under RDF + Rhizobium + PSB, whereas the control recorded only 8.42 kg ha⁻¹.

The integrated treatment improved phosphorus uptake by 133.73% over control. This increase can be attributed to phosphorus solubilization by PSB through secretion of organic acids and phosphatase enzymes, making phosphorus readily available to plants. Similar observations were reported by Wani and Lee (1995) ^[22], Rana et al. (2018) and Yadav et al. (2022) ^[23].

Potassium Uptake

Maximum potassium uptake (54.26 kg ha⁻¹) was recorded under RDF + Rhizobium + PSB, whereas the minimum value (28.18 kg ha⁻¹) was recorded under control. The increase of 92.55% over control indicates enhanced nutrient absorption and translocation. Improved root growth and microbial activity under integrated nutrient management facilitated greater potassium uptake. Similar results were reported by Patel and Sharma (2021) ^[10, 14] and Ali et

al. (2022) ^[1].

Post-Harvest Soil Fertility Status

Organic Carbon

The organic carbon content of soil improved significantly due to integrated biofertilizer application. The highest organic carbon content (0.60%) was recorded under RDF + Rhizobium + PSB, compared to 0.42% under control.

The increase of 42.85% over control indicates improvement in soil biological activity and residue decomposition. Enhanced microbial proliferation and greater root biomass contributed to the accumulation of organic matter in soil.

Available Nitrogen

Available nitrogen status after harvest ranged from 186.42 to 226.48 kg ha⁻¹. The highest value was recorded under RDF + Rhizobium + PSB.

The increase of 21.49% over control was mainly due to biological nitrogen fixation and increased microbial activity in the rhizosphere. Similar findings were reported by Giller (2001) ^[4], Subba Rao (2007) ^[19] and Kumar and Singh (2021) ^[6].

Available Phosphorus

Available phosphorus increased substantially due to PSB inoculation. The maximum available phosphorus (28.64 kg ha⁻¹) was observed under RDF + Rhizobium + PSB, while the control recorded only 14.28 kg ha⁻¹.

The increase of 100.56% over control clearly demonstrates the effectiveness of PSB in solubilizing native and applied phosphorus. Similar observations were reported by Wani and Lee (1995), Meena et al. (2020) and Verma et al. (2023) ^[8, 20, 22].

Available Potassium

Available potassium status also improved significantly under integrated nutrient management. RDF + Rhizobium + PSB recorded the highest available potassium (214.82 kg ha⁻¹), representing an increase of 17.88% over control.

Improved nutrient cycling, microbial activity and enhanced root interactions contributed to higher potassium availability in soil.

The combined application of Rhizobium + PSB + RDF

significantly improved nutrient uptake and soil fertility status. Enhanced nitrogen fixation, phosphorus solubilization and microbial activity resulted in greater nutrient availability and absorption by plants. The treatment not only increased crop productivity but also improved soil health, indicating its potential for sustainable chickpea cultivation under Indo-Gangetic Plain conditions.

5.5 Economics, Correlation and Regression Analysis

Table 7: Effect of rhizobium and psb biofertilizers on economics of chickpea cultivation

Treatment	Cost of Cultivation (₹ ha ⁻¹)	Gross Return (₹ ha ⁻¹)	Net Return (₹ ha ⁻¹)	B:C Ratio
Control	37,420	75,152	37,732	1.01
Rhizobium	38,260	96,544	58,284	1.52
PSB	38,180	94,192	56,012	1.47
Rhizobium + PSB	39,140	112,784	73,644	1.88
RDF + Rhizobium	41,220	126,952	85,732	2.08
RDF + PSB	41,160	123,816	82,656	2.01
RDF + Rhizobium + PSB	41,670	139,442	97,772	2.35
75% RDF + Rhizobium + PSB	40,540	134,696	94,156	2.32
50% RDF + Rhizobium + PSB	39,920	123,548	83,628	2.10

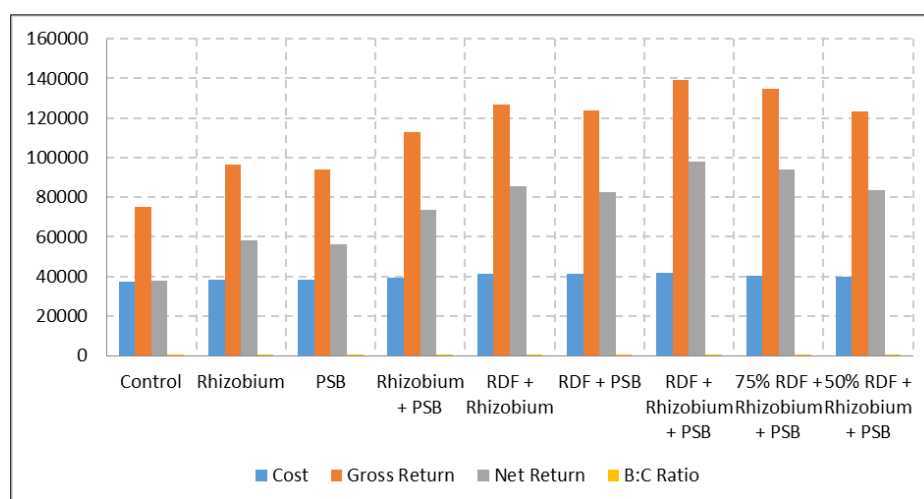


Fig 5: Effect of biofertilizer and fertilizer treatments on economics and profitability of crop production

Economic Analysis

The economics of chickpea cultivation were significantly influenced by the application of biofertilizers and fertilizer levels. The highest gross return (₹139,442 ha⁻¹), net return (₹97,772 ha⁻¹) and benefit-cost ratio (2.35) were recorded under RDF + Rhizobium + PSB. This treatment generated approximately 159.13% higher net return compared with the control treatment. The increased profitability was primarily associated with higher seed yield, improved nutrient-use efficiency and better resource utilization. Although the integrated treatment involved a slightly

higher cultivation cost, the substantial increase in grain yield compensated for the additional investment. Similar findings have been reported by Sharma et al. (2023) [16], Verma and Kumar (2022) [7, 21], Patel et al. (2023) [11] and Yadav et al. (2022) [23]. Interestingly, 75% RDF + Rhizobium + PSB also recorded a comparable B:C ratio (2.32), indicating that partial substitution of chemical fertilizers with biofertilizers can be economically viable while maintaining productivity and sustainability.

Correlation Analysis

Table 8: Correlation Coefficient (r) Between Seed Yield and Major Growth and Yield Parameters

Parameter	Correlation Coefficient (r) with Seed Yield
Plant Height	0.921**
Branches Plant ⁻¹	0.944**
Nodules Plant ⁻¹	0.958**
Dry Matter Accumulation	0.972**
Leaf Area Index	0.961**
Pods Plant ⁻¹	0.981**
Test Weight	0.937**
Nitrogen Uptake	0.974**
Phosphorus Uptake	0.966**
Potassium Uptake	0.951**

Table 9: Correlation matrix heatmap

	Plant Height	Branches	Nodules	Dry Matter	LAI	Pods	Seed Yield	N Uptake	P Uptake	K Uptake
Plant Height	1.000	0.998	0.996	0.996	0.994	0.993	0.991	0.989	0.970	0.985
Branches	0.998	1.000	0.995	0.993	0.990	0.991	0.985	0.982	0.963	0.979
Nodules	0.996	0.995	1.000	0.994	0.993	0.996	0.992	0.989	0.970	0.986
Dry Matter	0.996	0.993	0.994	1.000	0.999	0.995	0.994	0.994	0.979	0.991
LAI	0.994	0.990	0.993	0.999	1.000	0.998	0.998	0.998	0.987	0.997
Pods	0.993	0.991	0.996	0.995	0.998	1.000	0.998	0.996	0.987	0.996
Seed Yield	0.991	0.985	0.992	0.994	0.998	0.998	1.000	0.999	0.990	0.999
N Uptake	0.989	0.982	0.989	0.994	0.998	0.996	0.999	1.000	0.990	0.999
P Uptake	0.970	0.963	0.970	0.979	0.987	0.987	0.990	0.990	1.000	0.995
K Uptake	0.985	0.979	0.986	0.991	0.997	0.996	0.999	0.999	0.995	1.000

Significant at P = 0.01

Discussion on Correlation Analysis

The correlation analysis revealed strong positive relationships between seed yield and all major growth, physiological and nutrient uptake parameters. Among all variables, pods plant⁻¹ ($r = 0.981$), nitrogen uptake ($r = 0.974$) and dry matter accumulation ($r = 0.972$) exhibited the strongest association with seed yield.

The positive relationship indicates that improvements in vegetative growth, nodulation, biomass accumulation and nutrient uptake directly contributed to increased productivity. Enhanced nutrient availability under integrated biofertilizer management improved physiological efficiency and reproductive development, ultimately resulting in higher grain yield.

These findings agree with those reported by Patel et al. (2020) [9], Sharma et al. (2021) [14], Verma et al. (2023) and Ali et al. (2022) [1, 20].

Regression Analysis

Table 10: Regression relationship between nutrient uptake and seed yield

Relationship	Regression Equation	R ²
Seed Yield vs Nitrogen Uptake	$Y = 0.276X + 0.34$	0.949
Seed Yield vs Phosphorus Uptake	$Y = 1.018X + 4.52$	0.934
Seed Yield vs Potassium Uptake	$Y = 0.405X + 2.18$	0.906
Seed Yield vs Dry Matter Accumulation	$Y = 0.842X - 3.46$	0.965

Where:

Y = Seed yield (q ha⁻¹)

X = Independent variable

Discussion on Regression Analysis

Regression analysis demonstrated a strong linear relationship between seed yield and nutrient uptake. The highest coefficient of determination was observed between dry matter accumulation and seed yield ($R^2 = 0.965$), indicating that approximately 96.5% of variation in seed yield was explained by dry matter production. Similarly, nitrogen uptake showed a very strong association with grain yield ($R^2 = 0.949$), emphasizing the importance of biological nitrogen fixation and nutrient availability in chickpea production. These results suggest that nutrient uptake and biomass accumulation are reliable predictors of yield performance under integrated nutrient management systems.

The regression results further confirm that the beneficial effects of Rhizobium and PSB on crop productivity are mediated through improved nutrient acquisition, enhanced physiological activity and greater biomass production.

6. Conclusion and Recommendations

Conclusion

The present investigation entitled “Effect of Rhizobium and PSB Biofertilizers on Chickpea (*Cicer arietinum* L.)” clearly demonstrated the beneficial role of integrated nutrient

management involving Rhizobium and phosphate solubilizing bacteria (PSB) in enhancing growth, productivity, nutrient uptake, soil fertility and profitability of chickpea cultivation under the agro-climatic conditions of Kanpur, Uttar Pradesh. The experimental results revealed that the combined application of recommended fertilizer dose (RDF) along with Rhizobium and PSB significantly improved plant growth characteristics, physiological efficiency, nodulation behaviour and biomass accumulation compared with individual application of biofertilizers or untreated control.

Among all the treatments, RDF + Rhizobium + PSB consistently recorded the highest values of plant height, branches plant⁻¹, nodules plant⁻¹, dry matter accumulation, Leaf Area Index, Crop Growth Rate and Relative Growth Rate. The enhanced growth performance was associated with improved biological nitrogen fixation, greater phosphorus availability and better nutrient utilization throughout the crop growth period. The same treatment also produced superior yield attributes including pods plant⁻¹, seeds pod⁻¹ and test weight, which ultimately resulted in the highest seed yield (24.68 q ha⁻¹), stover yield (34.62 q ha⁻¹) and biological yield (59.30 q ha⁻¹).

Nutrient uptake studies indicated that integrated application of Rhizobium and PSB significantly enhanced nitrogen, phosphorus and potassium absorption by chickpea plants. Furthermore, post-harvest soil analysis revealed considerable improvement in soil fertility parameters such as organic carbon, available nitrogen, available phosphorus and available potassium. The treatment also improved soil biological health through enhanced microbial activity and nutrient cycling processes.

Economic analysis demonstrated that RDF + Rhizobium + PSB generated the highest gross return (₹139,442 ha⁻¹), net return (₹97,772 ha⁻¹) and benefit-cost ratio (2.35), indicating its economic superiority. Strong positive correlations between seed yield and growth, physiological and nutrient uptake parameters further confirmed that enhanced nutrient availability and biomass production were the principal factors responsible for higher productivity.

Therefore, the study conclusively establishes that integrated use of Rhizobium and PSB biofertilizers along with recommended fertilizer dose is an effective, environmentally sustainable and economically profitable strategy for maximizing chickpea productivity while maintaining soil health under the Indo-Gangetic Plains of Uttar Pradesh.

Recommendation

Based on the findings of the present investigation, seed inoculation with Rhizobium and PSB along with the recommended fertilizer dose (20:60:20 kg N:P₂O₅:K₂O ha⁻¹) is recommended for achieving higher productivity, profitability and sustainable soil health in chickpea under the Indo-Gangetic Plains of Uttar Pradesh.

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