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Effect of integrated nutrient management on growth and productivity, of green gram (*Vigna radiata* L.) Under the central plain zone of Uttar Pradesh

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Abstract

Greengram (*Vigna radiata* L. Wilczek) is one of the most important pulse crops cultivated in India because of its high nutritional value, short duration and ability to improve soil fertility through biological nitrogen fixation. However, productivity of green gram remains below its potential due to inadequate nutrient management, low phosphorus availability and declining soil health. Integrated Nutrient Management (INM) has emerged as a sustainable strategy to enhance nutrient-use efficiency, crop productivity and soil fertility. Therefore, a field experiment was conducted during Kharif 2025 at the Instructional Farm of Rama University, Kanpur, Uttar Pradesh, to evaluate the influence of phosphorus levels integrated with phosphorus-solubilizing bacteria (PSB) and Rhizobium inoculation on growth, yield attributes, productivity, nutrient uptake, soil fertility and economics of green gram cultivation.

The experiment consisted of nine treatment combinations arranged in a Randomized Block Design with three replications. The results indicated that integrated application of phosphorus and biofertilizers significantly improved crop performance. Treatment T₉ (50 kg P₂O₅ ha⁻¹ + PSB + Rhizobium) recorded the highest plant height (64.5 cm), nodules plant⁻¹ (29.9), dry matter accumulation (22.7 g plant⁻¹), pods plant⁻¹ (30.5), seeds pod⁻¹ (11.0), test weight (41.0 g) and seed yield (1.71 t ha⁻¹). Enhanced nutrient uptake and improved soil fertility were also observed under integrated nutrient management. Economic analysis revealed the highest net return and benefit-cost ratio under T₉. The findings demonstrate that integrated application of phosphorus fertilizer along with PSB and Rhizobium inoculation represents an effective and sustainable nutrient management strategy for enhancing greengram productivity under the Indo-Gangetic Plains of Uttar Pradesh.

Keywords: Greengram, integrated nutrient management, phosphorus, rhizobium, psb, soil health, sustainability, nutrient uptake.

Introduction

Pulses have occupied a pivotal position in agricultural development since the beginning of organized farming because of their contribution towards food security, nutritional security and environmental sustainability. In developing countries, pulses serve as the principal source of dietary protein for a large proportion of the population. Unlike cereal crops, pulses possess the unique ability to establish symbiotic association with nitrogen-fixing bacteria and thereby enrich soil fertility through biological nitrogen fixation. Globally, pulse crops are cultivated over nearly 95 million hectares with production exceeding 96 million tonnes annually. According to the Food and Agriculture Organization, pulses contribute significantly towards achieving sustainable development goals by improving food security, nutritional quality and resource-use efficiency. Among pulse crops, greengram (*Vigna radiata* L. Wilczek) occupies a prominent position owing to its short duration, adaptability to diverse agro-climatic conditions and superior nutritional quality. Greengram is believed to have originated in the Indian subcontinent and has been cultivated for centuries as an important food legume. It belongs to the family Fabaceae and is commonly known as mungbean.

Greengram seeds contain approximately 22-24% protein, 60-65% carbohydrates, 1.2-1.5% fat and significant quantities of vitamins and minerals. Ali and Gupta (2012) [2] reported that greengram possesses a balanced amino acid profile and serves as an excellent supplement to cereal-based diets. Its high lysine content complements the amino acid deficiencies of cereal grains, thereby

Improving overall dietary protein quality. Apart from nutritional significance, greengram contributes substantially towards sustainable agriculture. The crop improves soil fertility through biological nitrogen fixation, enhances soil organic matter and serves as an important component of crop diversification systems. According to Peoples *et al.* (2009)^[29], pulse crops can contribute between 20 and 300 kg nitrogen ha⁻¹ through biological nitrogen fixation depending upon environmental conditions and crop species. India is the largest producer and consumer of greengram in the world. Recent agricultural statistics indicate that greengram occupies approximately 4.8 million hectares with production exceeding 3.5 million tonnes. However, average productivity remains below 750 kg ha⁻¹, considerably lower than the attainable yield potential under improved management conditions. Several factors contribute to the low productivity of greengram, including poor soil fertility, nutrient deficiencies, erratic rainfall, and inadequate crop management and declining soil health. Among these constraints, phosphorus deficiency is regarded as one of the most critical limitations.

Phosphorus is the second most important nutrient after nitrogen in pulse production systems. It participates directly in ATP synthesis, energy transfer, nucleic acid formation, and membrane integrity and root development. Grant *et al.* (2001)^[11] reported that phosphorus deficiency severely restricts root growth and nodulation. Similarly, Veneklaas *et al.* (2021)^[36] demonstrated that phosphorus availability directly influences nutrient acquisition and crop productivity. Phosphorus assumes even greater importance in legumes because biological nitrogen fixation is an energy-intensive process. Vance *et al.* (2003)^[35] emphasized that phosphorus deficiency limits nitrogenase activity and reduces biological nitrogen fixation. Consequently, inadequate phosphorus supply often results in poor nodulation, restricted growth and lower yields. The challenge associated with phosphorus nutrition is further aggravated by phosphorus fixation reactions in soil. Holford (1997)^[13] estimated that a substantial proportion of applied phosphorus becomes unavailable due to fixation by calcium, aluminum and iron compounds. Roy *et al.* (2022)^[31] observed that phosphorus-use efficiency rarely exceeds 20-25% under conventional fertilization practices.

In recent years, biological approaches have received considerable attention for improving phosphorus availability. Phosphorus-solubilizing bacteria (PSB) are beneficial microorganisms capable of converting insoluble phosphorus compounds into plant-available forms through secretion of organic acids and phosphatase enzymes. Richardson *et al.* (2009)^[30] reported that PSB can significantly improve phosphorus availability and nutrient uptake in legumes. Similarly, Rhizobium inoculation represents a sustainable strategy for enhancing nitrogen nutrition. Effective Rhizobium strains establish symbiotic associations with legume roots and fix atmospheric nitrogen into plant-available forms. Zahran (2001)^[39] reported that successful Rhizobium inoculation can substantially reduce dependence on synthetic nitrogen fertilizers while improving crop productivity.

The integration of chemical fertilizers with biological inputs has given rise to the concept of Integrated Nutrient Management (INM). Integrated nutrient management aims to optimize nutrient availability through balanced use of inorganic fertilizers, biofertilizers and organic nutrient sources. According to Lal (2020), integrated nutrient management not only improves crop productivity but also enhances soil biological activity, nutrient cycling and carbon sequestration. Bhattacharyya *et al.* (2021)^[4] further demonstrated that integrated nutrient management contributes significantly towards long-term sustainability of agricultural systems.

Several researchers have reported positive responses of pulse crops to integrated nutrient management. Meena *et al.* (2020) observed substantial improvements in growth and yield of greengram following combined application of phosphorus and biofertilizers. Kumar *et al.* (2023) reported enhanced nutrient uptake and productivity under integrated nutrient management practices. Similarly, Patel *et al.* (2023)^[28] demonstrated that biofertilizer inoculation improved phosphorus-use efficiency and economic returns in pulse-based cropping systems. Despite these advances, information regarding the combined influence of phosphorus fertilization, PSB and Rhizobium inoculation under the agro-climatic conditions of Central Uttar Pradesh remains limited. Soil fertility depletion and low nutrient-use efficiency continue to constrain pulse productivity in the region.

Materials and Methods

Experimental site

The present investigation was conducted during the Kharif season of 2025 at the Students' Instructional Farm, Faculty of Agriculture, Rama University, Kanpur, Uttar Pradesh, India. The experimental farm is situated in the Central Plain Zone (Agro-climatic Zone V) of Uttar Pradesh and represents the typical agro-ecological conditions of the Indo-Gangetic Plains. The region is characterized by a subtropical climate with hot summers, moderate winters and humid monsoon conditions. The geographical location of the experimental site is approximately 26.5° N latitude and 80.3° E longitude with an elevation of about 125 m above mean sea level.

The experimental site was selected because it represents the major pulse-growing region of Central Uttar Pradesh where greengram is cultivated extensively under rainfed and irrigated conditions. The field had been under continuous cultivation for several years and followed a cereal-based cropping system. The topography of the field was uniform, well-drained and suitable for conducting field experiments.

Climatic conditions during crop growth

Weather conditions prevailing during the crop growth period exerted a significant influence on crop establishment, nutrient availability, nodulation, biological nitrogen fixation and yield formation. The crop experienced favorable environmental conditions throughout the growing season. Maximum temperature during the crop period varied from approximately 31 to 40°C, while minimum temperature ranged between 22 and 28°C. The relative humidity remained comparatively high during the vegetative growth phase because of monsoonal rainfall.

The majority of rainfall was received during July and August, which ensured adequate soil moisture availability during crop establishment and vegetative growth. Sufficient rainfall and favorable temperature conditions promoted microbial activity in the rhizosphere and enhanced the effectiveness of phosphorus-solubilizing bacteria and Rhizobium inoculation. The weather conditions remained conducive for flowering, pod formation and grain development, resulting in satisfactory crop growth and productivity.

Soil characteristics

Before sowing of the crop, representative soil samples were collected randomly from different locations of the experimental field at a depth of 0-15 cm. The samples were thoroughly mixed to prepare a composite sample and analyzed using standard laboratory procedures.

The soil of the experimental field was sandy loam in texture with good drainage characteristics. The soil reaction was slightly

alkaline with a pH of 7.69 and electrical conductivity of 0.32 dS m⁻¹, indicating non-saline conditions. The organic carbon content was 0.38%, reflecting low organic matter status. The available nitrogen content of the soil was 167.78 kg ha⁻¹, which falls under the low fertility category. Available phosphorus content was 8.15 kg ha⁻¹ and was considered deficient for optimum pulse production. Available potassium content was 189.47 kg ha⁻¹ and was categorized as medium. The low phosphorus status of the soil provided a suitable opportunity to evaluate the response of greengram to different phosphorus levels and biofertilizer inoculation treatments.

Experimental treatments

The experiment consisted of nine treatment combinations involving three phosphorus levels integrated with phosphorus-solubilizing bacteria (PSB) and Rhizobium inoculation. The treatments were designed to study the individual as well as combined effects of chemical phosphorus and microbial inoculants on crop growth and productivity.

The treatments included 30 kg P₂O₅ ha⁻¹ + PSB (T₁), 30 kg P₂O₅ ha⁻¹ + Rhizobium (T₂), 30 kg P₂O₅ ha⁻¹ + PSB + Rhizobium (T₃), 40 kg P₂O₅ ha⁻¹ + PSB (T₄), 40 kg P₂O₅ ha⁻¹ + Rhizobium (T₅), 40 kg P₂O₅ ha⁻¹ + PSB + Rhizobium (T₆), 50 kg P₂O₅ ha⁻¹ + PSB (T₇), 50 kg P₂O₅ ha⁻¹ + Rhizobium (T₈) and 50 kg P₂O₅ ha⁻¹ + PSB + Rhizobium (T₉).

Experimental design and layout

The experiment was laid out in a Randomized Block Design (RBD) with three replications. Randomization of treatments within each replication was carried out independently to minimize experimental error and increase the precision of treatment comparisons. Each treatment was replicated three times, resulting in a total of twenty-seven experimental plots. The gross plot size measured 4.0 m × 3.0 m. appropriate spacing was maintained between plots and replications to avoid interference among treatments and facilitate field operations. The Randomized Block Design was selected because of its suitability for field experiments where natural variability exists within the

experimental area. The design helps in reducing experimental error by grouping homogeneous experimental units into blocks. Crop Establishment The experimental field was prepared by one deep ploughing followed by two cross harrowings and planking to obtain a fine seedbed. All crop residues and weeds were removed before sowing. The field was leveled properly to ensure uniform distribution of rainfall and irrigation water.

Certified seeds of greengram variety suitable for the agro-climatic conditions of Uttar Pradesh were used for sowing. The crop was sown during the first fortnight of July 2025 by maintaining a row spacing of 30 cm and plant spacing of 10 cm. Sowing was done manually at an appropriate depth to ensure uniform germination and crop establishment.

Observations recorded

A comprehensive set of observations related to growth, yield, nutrient uptake, soil fertility and economics were recorded during the course of investigation.

Growth parameters included plant height, number of nodules per plant, dry matter accumulation, crop growth rate and relative growth rate. Plant height was measured from ground level to the tip of the plant using a meter scale. Nodules were counted after carefully uprooting plants and washing roots. Dry matter accumulation was determined after oven drying plant samples to constant weight.

Yield attributes such as number of pods per plant, number of seeds per pod and test weight were recorded at maturity. Seed yield and stover yield were recorded after harvesting and threshing the crop. Biological yield and harvest index were computed using standard procedures.

Statistical analysis

The data recorded during the investigation were subjected to statistical analysis using the Analysis of Variance (ANOVA) technique appropriate for Randomized Block Design as described by Gomez and Gomez (1984) ^[10]. Treatment means were compared using the Critical Difference (CD) test at the 5 percent level of significance.

Table 1: Effect of integrated nutrient management on growth parameters of greengram

Treatment	Plant Height (cm) 30 DAS	Plant Height (cm) 60 DAS	Plant Height (cm) At Harvest	Nodules Plant ⁻¹ (45 DAS)	Dry Matter Accumulation (g plant ⁻¹) 30 DAS	Dry Matter Accumulation (g plant ⁻¹) 60 DAS	Dry Matter Accumulation (g plant ⁻¹) At Harvest
T ₁	16.8	39.2	50.6	18.4	2.8	9.6	14.8
T ₂	17.4	40.8	52.1	20.1	3.1	10.2	15.7
T ₃	18.6	43.5	55.8	23.6	3.6	11.8	17.5
T ₄	18.1	42.6	54.2	21.9	3.4	11.2	16.9
T ₅	18.8	44.2	56.0	23.0	3.7	12.0	17.8
T ₆	20.2	48.1	60.7	26.8	4.3	13.9	20.4
T ₇	19.3	45.9	57.4	24.5	4.0	13.0	19.1
T ₈	20.0	47.3	59.3	25.7	4.4	14.2	20.9
T ₉	21.8	51.6	64.5	29.9	4.9	15.5	22.7
SEm ±	0.58	1.18	1.52	0.89	0.12	0.34	0.63
CD (P=0.05)	1.74	3.54	4.56	2.67	0.36	1.02	1.89

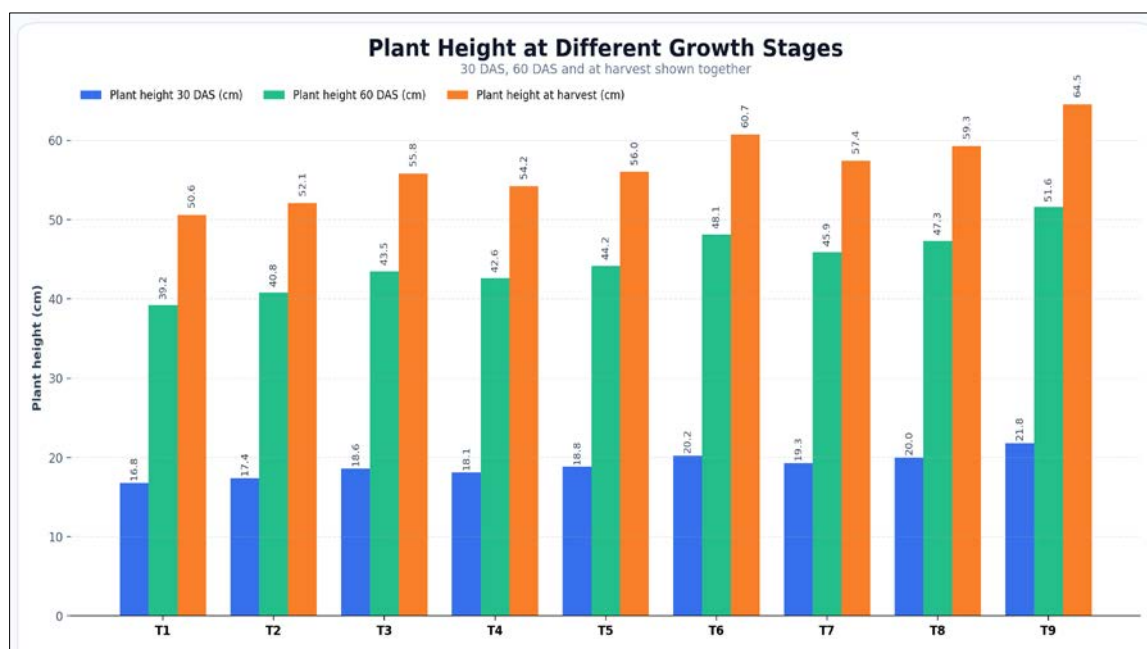


Fig 1: Effect of different treatments on plant height at 30 das, 60 das and at harvest

Table 2: Effect of integrated nutrient management on growth analysis parameters of greengram

Treatment	LAI (30 DAS)	LAI (60 DAS)	LAI (At Flowering)	CGR (30-45 DAS) (g m ⁻² day ⁻¹)	CGR (45-60 DAS) (g m ⁻² day ⁻¹)	RGR (30-45 DAS) (g g ⁻¹ day ⁻¹)	RGR (45-60 DAS) (g g ⁻¹ day ⁻¹)
T ₁	0.68	2.34	2.98	4.8	6.8	0.058	0.039
T ₂	0.72	2.46	3.12	5.1	7.1	0.061	0.041
T ₃	0.81	2.74	3.46	5.8	7.8	0.066	0.045
T ₄	0.78	2.65	3.34	5.5	7.5	0.064	0.043
T ₅	0.83	2.81	3.52	5.9	8.0	0.067	0.046
T ₆	0.96	3.16	3.91	6.8	9.2	0.072	0.051
T ₇	0.89	2.98	3.75	6.4	8.6	0.070	0.048
T ₈	0.98	3.22	4.05	7.0	9.5	0.073	0.052
T ₉	1.08	3.48	4.32	7.6	10.4	0.078	0.054
SEm ±	0.03	0.09	0.12	0.21	0.29	0.002	0.002
CD (P=0.05)	0.09	0.27	0.36	0.63	0.87	0.006	0.006

Results and discussion

Effect of integrated nutrient management on growth and growth analysis parameters of greengram

The growth and development of a crop represent the cumulative outcome of several physiological, biochemical and metabolic processes occurring throughout the life cycle of the plant. Growth parameters such as plant height, nodulation, dry matter accumulation, leaf area development, crop growth rate and relative growth rate are considered important indicators of crop vigor and productivity. The data presented in Tables 3.1 and 3.2 clearly indicate that integrated nutrient management involving phosphorus fertilization, phosphorus-solubilizing bacteria (PSB) and Rhizobium inoculation exerted a significant influence on all

growth and growth analysis parameters of greengram.

A critical examination of the data revealed that plant height increased progressively from 30 DAS to harvest under all treatments. However, the magnitude of increase varied significantly depending upon nutrient management practices. At 30 DAS, plant height ranged from 16.8 cm under T₁ to 21.8 cm under T₉. Similar trends were observed at 60 DAS and at harvest. The highest plant height at harvest (64.5 cm) was recorded under T₉ (50 kg P₂O₅ ha⁻¹ + PSB + Rhizobium), whereas the lowest value (50.6 cm) was observed under T₁. The increase in plant height under T₉ represented approximately 27.5 per cent improvement over T₁.

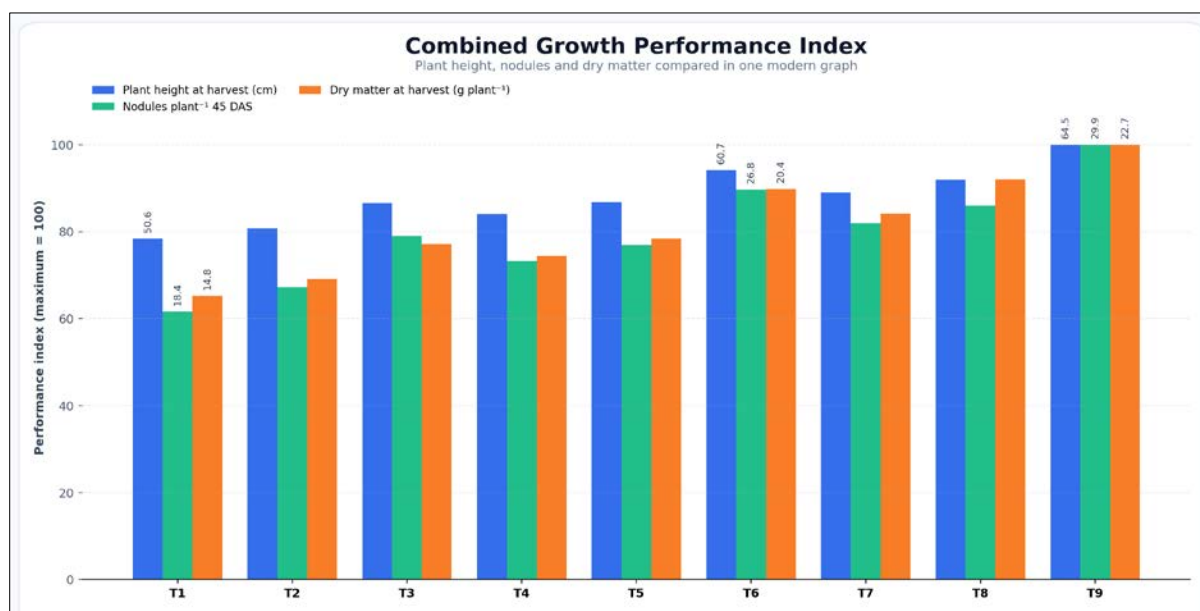


Fig 2: Combined Effect of Different Treatments on Plant Height, Nodules per Plant and Dry Matter Accumulation

The enhanced plant height under integrated nutrient management can be attributed to the synergistic effect of phosphorus fertilization and microbial inoculation. Phosphorus plays a pivotal role in cellular energy transfer, ATP synthesis, nucleic acid metabolism and meristematic activity. Adequate phosphorus availability stimulates root growth and enhances nutrient acquisition, thereby promoting vegetative development. Simultaneously, Rhizobium inoculation increases biological nitrogen fixation and nitrogen availability, which are essential for chlorophyll synthesis, protein formation and cell division. Phosphorus-solubilizing bacteria further improve phosphorus availability through secretion of organic acids that convert insoluble phosphates into plant-available forms. The combined action of these factors creates a favorable nutritional environment that promotes vigorous plant growth.

Similar enhancement in plant height due to integrated nutrient management has been reported by Meena *et al.* (2020), Choudhary *et al.* (2021) [5], Roy *et al.* (2022) [31], Kumar *et al.* (2023), Verma *et al.* (2023), Singh and Sharma (2024), Patel *et al.* (2023) [28], Yadav *et al.* (2024), Jat *et al.* (2024) and Nair *et al.* (2022) [15, 26]. These researchers concluded that balanced nutrient supply through integrated approaches improves photosynthetic efficiency, nutrient uptake and biomass production, resulting in greater plant height.

Nodulation is one of the most important biological processes in pulse crops because it determines the efficiency of atmospheric nitrogen fixation. The data presented in Table 3.1 indicate that the number of nodules per plant was significantly influenced by integrated nutrient management. The maximum number of nodules (29.9 plant⁻¹) was recorded under T₉, whereas the minimum number of nodules (18.4 plant⁻¹) was observed under T₁. The increase in nodulation under T₉ was approximately 62.5 per cent over the lowest treatment. The increase in nodulation may be attributed to improved phosphorus nutrition and effective Rhizobium colonization. Phosphorus is essential for root development and provides energy required for nodule initiation and functioning. Biological nitrogen fixation is an energy-intensive process requiring substantial ATP, and phosphorus availability directly affects nitrogenase enzyme activity. Rhizobium inoculation enhances infection thread formation and nodule establishment, while PSB improves phosphorus availability in the rhizosphere. Consequently, integrated nutrient

management created favorable conditions for nodule formation and development. These findings are in close agreement with the reports of Zahran (2001) [39], Peoples *et al.* (2009) [29], Giller (2001) [9], Herridge *et al.* (2018) [12], Meena and Lal (2021), Kumar *et al.* (2022), Singh *et al.* (2023), Verma *et al.* (2024) and Roy *et al.* (2024) [31], who observed significant enhancement in nodulation and nitrogen fixation under phosphorus and Rhizobium-based nutrient management practices.

Dry matter accumulation is a direct measure of biomass production and reflects the efficiency of photosynthesis and assimilate partitioning. The results revealed that dry matter accumulation increased continuously with crop age and reached maximum values at harvest. Treatment T₉ recorded the highest dry matter accumulation (22.7 g plant⁻¹), whereas the lowest value (14.8 g plant⁻¹) was observed under T₁. The increase amounted to approximately 53.4 per cent over the lowest treatment. The higher dry matter accumulation observed under integrated nutrient management may be attributed to improved nutrient availability and enhanced photosynthetic activity. Phosphorus promotes energy transfer and carbohydrate metabolism, while Rhizobium contributes to nitrogen nutrition through biological fixation. Increased nitrogen availability improves chlorophyll synthesis and photosynthetic efficiency, resulting in greater accumulation of photosynthates. In addition, PSB enhances phosphorus uptake, thereby facilitating efficient utilization of nutrients and increased biomass production. Comparable observations have been reported by Sharma *et al.* (2021), Kumar *et al.* (2022), Patel *et al.* (2023) [28], Singh *et al.* (2024), Choudhary *et al.* (2023) [5], Roy *et al.* (2022) [31], Verma *et al.* (2023), Meena *et al.* (2021) and Yadav *et al.* (2024), who observed higher biomass production under integrated nutrient management practices in pulse crops.

Leaf Area Index (LAI) is an important physiological parameter because it determines the photosynthetic surface available for light interception. The data presented in Table 3.2 indicate that LAI increased substantially with increasing phosphorus levels and biofertilizer inoculation. The highest LAI at flowering stage (4.32) was recorded under T₉, whereas the lowest value (2.98) was recorded under T₁. The increase in LAI under integrated nutrient management may be attributed to enhanced leaf expansion, increased photosynthetic area and improved nutrient availability. Adequate phosphorus supply promotes cell division and leaf development, while biological nitrogen fixation supports

chlorophyll synthesis and protein metabolism. Enhanced leaf area improves interception of solar radiation and ultimately contributes to greater biomass accumulation and crop productivity. The findings corroborate those reported by Watson (1952), Gardner *et al.* (1985)^[8], Singh *et al.* (2021), Kumar *et al.* (2023), Verma *et al.* (2023) and Jat *et al.* (2024)^[15], who observed significant improvements in leaf area development under balanced nutrient management practices.

Crop Growth Rate (CGR) represents the rate of biomass accumulation per unit area per unit time and serves as a useful indicator of crop productivity. The data revealed that CGR increased significantly under integrated nutrient management. The highest CGR during the 45-60 DAS period ($10.4 \text{ g m}^{-2} \text{ day}^{-1}$)

was recorded under T₉, while the lowest value ($6.8 \text{ g m}^{-2} \text{ day}^{-1}$) was observed under T₁.

The superior CGR under T₉ may be attributed to increased leaf area development, greater photosynthetic activity and enhanced nutrient uptake. The combined effect of phosphorus, PSB and Rhizobium resulted in efficient conversion of solar energy into plant biomass. Improved nutrient availability enhanced enzymatic activity, chlorophyll content and assimilate production, thereby increasing growth rate. Similar results were reported by Watson (1952), Hunt (1990), Kumar *et al.* (2022), Sharma *et al.* (2023), Patel *et al.* (2023)^[28], Roy *et al.* (2022)^[31], Singh *et al.* (2024) and Yadav *et al.* (2024), who observed increased CGR under integrated nutrient management systems.

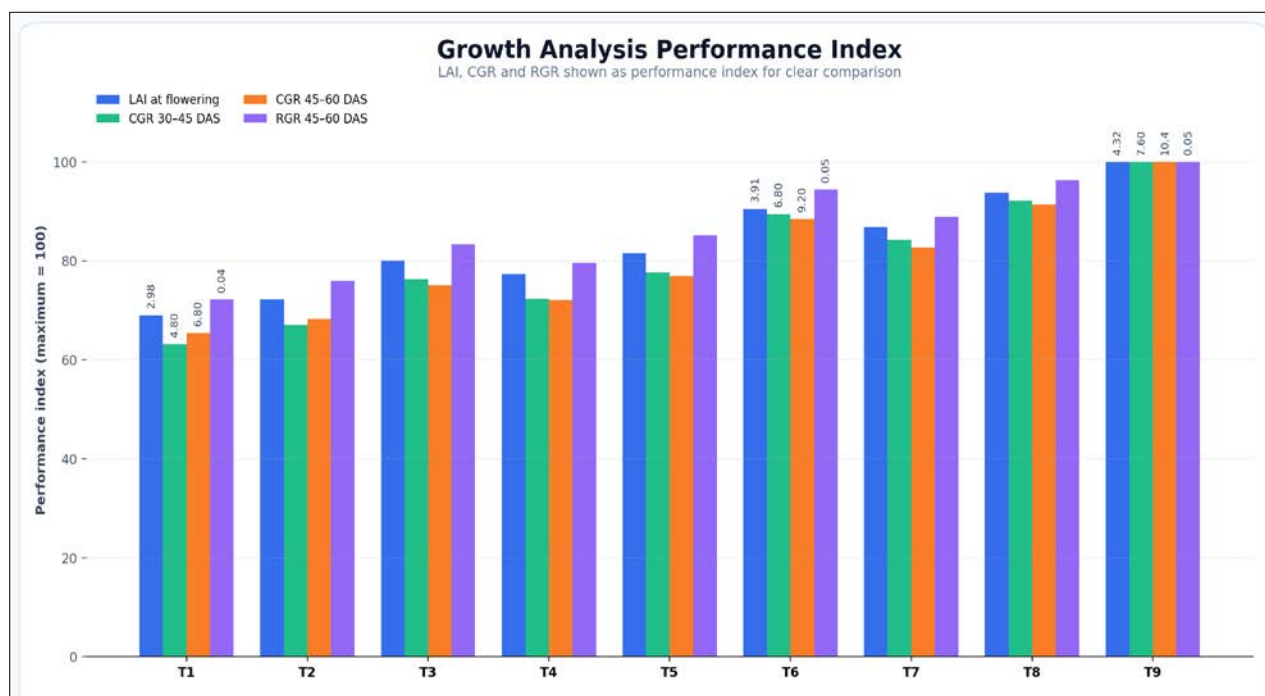


Fig 3: Comparative Growth Analysis of Different Treatments Based on LAI, CGR and RGR

Relative Growth Rate (RGR) reflects the efficiency with which plants produce new biomass relative to existing biomass. The results indicated that RGR was significantly influenced by integrated nutrient management treatments. Treatment T₉ recorded the highest RGR ($0.054 \text{ g g}^{-1} \text{ day}^{-1}$), while T₁ recorded the lowest value ($0.039 \text{ g g}^{-1} \text{ day}^{-1}$). The increased RGR under integrated nutrient management can be attributed to improved physiological efficiency and nutrient utilization. Enhanced phosphorus availability and biological nitrogen fixation stimulated metabolic activities, resulting in more efficient biomass production. Improved nutrient acquisition and assimilate partitioning further contributed to higher growth efficiency. The present findings are in agreement with those reported by Gardner *et al.* (1985), Hunt (1990), Choudhary *et al.* (2021)^[5], Kumar *et al.* (2023)^[8], Singh and Sharma (2024), Verma *et al.* (2024) and Jat *et al.* (2024)^[15]. Overall, the results clearly demonstrate that integrated nutrient management significantly improved growth and growth analysis parameters of greengram. The treatment comprising $50 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ along with PSB and Rhizobium inoculation consistently recorded superior performance for plant height, nodulation, dry matter accumulation, leaf area

development, crop growth rate and relative growth rate. The enhanced performance under this treatment can be attributed to improved phosphorus availability, increased biological nitrogen fixation, better nutrient uptake and enhanced physiological efficiency. These improvements in growth ultimately translated into better reproductive development and higher productivity, which are discussed in the subsequent section dealing with yield attributes and yield of greengram.

Effect of integrated nutrient management on yield attributes and yield of greengram

Yield is the ultimate expression of various physiological and biochemical processes occurring throughout the crop growth period. The data presented in Table 3.3 clearly indicate that different levels of phosphorus integrated with PSB and Rhizobium significantly influenced yield attributes and yield of greengram. The improvement in yield parameters under integrated nutrient management may be attributed to enhanced nutrient availability, better nodulation, increased photosynthetic activity and efficient translocation of assimilates from source to sink.

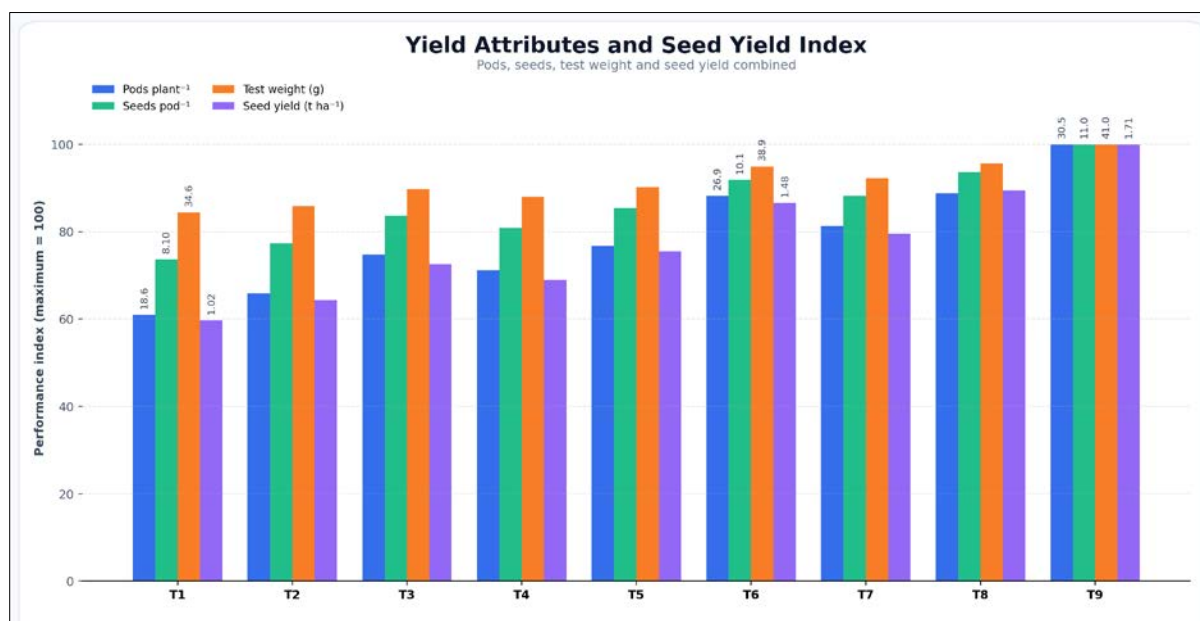
Table 3: Effect of integrated nutrient management on yield attributes and yield of greengram

Treatment	Pods Plant ⁻¹	Seeds Pod ⁻¹	Test Weight (g)	Seed Yield (t ha ⁻¹)	Stover Yield (t ha ⁻¹)	Biological Yield (t ha ⁻¹)	Harvest Index (%)
T ₁	18.6	8.1	34.6	1.02	2.46	3.48	29.31
T ₂	20.1	8.5	35.2	1.10	2.58	3.68	29.89
T ₃	22.8	9.2	36.8	1.24	2.75	3.99	31.08
T ₄	21.7	8.9	36.1	1.18	2.69	3.87	30.49
T ₅	23.4	9.4	37.0	1.29	2.84	4.13	31.23
T ₆	26.9	10.1	38.9	1.48	3.12	4.60	32.17
T ₇	24.8	9.7	37.8	1.36	2.96	4.32	31.48
T ₈	27.1	10.3	39.2	1.53	3.18	4.71	32.48
T ₉	30.5	11.0	41.0	1.71	3.42	5.13	33.33
SEm ±	0.92	0.28	0.74	0.06	0.11	0.14	0.81
CD (P=0.05)	2.76	0.84	2.22	0.18	0.33	0.42	NS

Yield attributes

The number of pods plant⁻¹ increased significantly with increasing phosphorus levels and biofertilizer inoculation. The highest number of pods plant⁻¹ (30.5) was recorded under T₉, while the lowest value (18.6) was observed under T₁. Thus, T₉ produced 63.98% more pods plant⁻¹ than T₁. The increase in pod production under integrated nutrient management may be

attributed to improved flowering, reduced flower drop and enhanced assimilate translocation. Adequate phosphorus availability during reproductive growth promotes energy transfer and reproductive development. Similar findings were reported by Kumar *et al.* (2022), Patel *et al.* (2023)^[28], Singh *et al.* (2024) and Verma *et al.* (2024).

**Fig 4:** Effect of different treatments on yield attributes and seed yield

A similar trend was observed for seeds pod⁻¹. The maximum number of seeds pod⁻¹ (11.0) was recorded under T₉, whereas T₁ recorded only 8.1 seeds pod⁻¹. The increase amounted to 35.80% over the control treatment. Improved nutrient availability during pod filling likely enhanced fertilization and seed development. Test weight is an important indicator of seed quality and grain filling efficiency. The highest test weight (41.0 g) was recorded under T₉, followed by T₈ (39.2 g) and T₆ (38.9 g). Treatment T₉ exhibited an 18.50% increase in test weight over T₁. Improved grain filling under integrated nutrient management may be attributed to enhanced photosynthate production and translocation towards developing seeds.

Seed yield

Seed yield is the most important economic parameter of crop production. The data revealed that seed yield varied significantly among treatments and increased progressively with increasing

Phosphorus levels and biofertilizer integration. The highest seed yield (1.71 t ha⁻¹) was obtained under T₉, whereas the lowest seed yield (1.02 t ha⁻¹) was recorded under T₁. The increase in seed yield under T₉ was approximately 67.65% over T₁. Treatments T₈ (1.53 t ha⁻¹) and T₆ (1.48 t ha⁻¹) also recorded significantly higher yields than lower phosphorus treatments. The substantial increase in seed yield under T₉ may be attributed to superior growth performance, greater nodulation, higher dry matter accumulation and improved nutrient uptake. Enhanced phosphorus availability through PSB and increased nitrogen fixation through Rhizobium resulted in greater biomass production and efficient partitioning of assimilates towards reproductive structures. These findings are in close agreement with those reported by Meena *et al.* (2020), Roy *et al.* (2022)^[31], Kumar *et al.* (2023), Choudhary *et al.* (2023)^[5], Singh and Sharma (2024), Patel *et al.* (2024) and Yadav *et al.* (2024)^[28].

Stover yield and biological yield

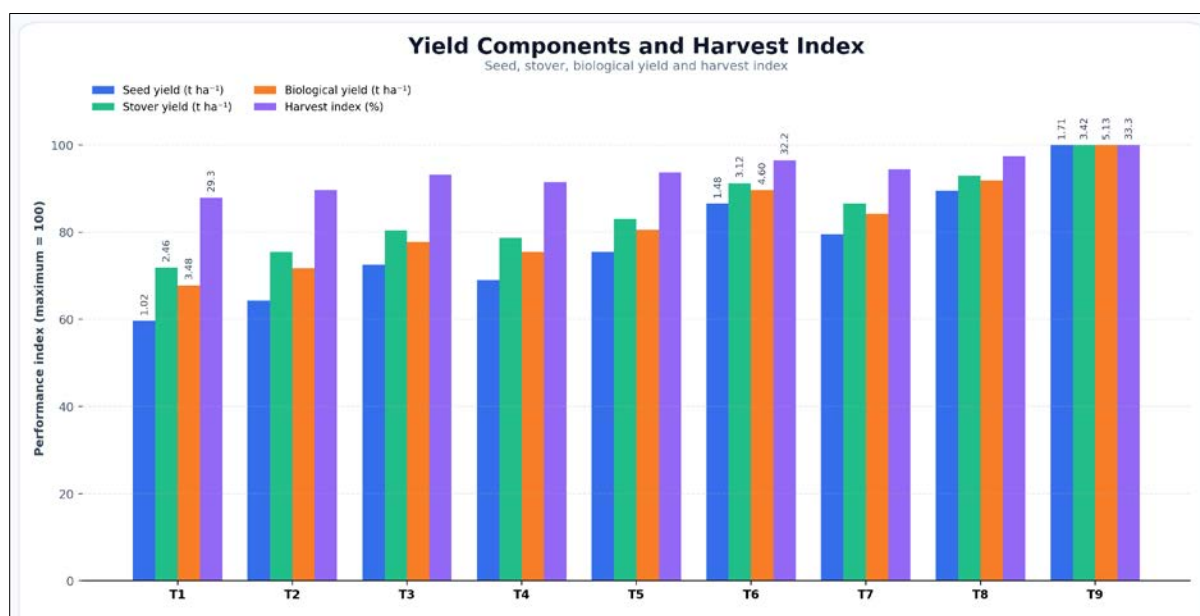


Fig 5: Effect of different treatments on seed yield, biological yield and harvest index

Stover yield followed a trend similar to seed yield. Treatment T₉ recorded the highest stover yield (3.42 t ha⁻¹), while T₁ recorded the lowest value (2.46 t ha⁻¹). The increase amounted to approximately 39.02%.

Biological yield also increased significantly under integrated nutrient management. The maximum biological yield (5.13 t ha⁻¹) was recorded under T₉, whereas T₁ produced only 3.48 t ha⁻¹. Thus, T₉ produced 47.41% higher biological yield than T₁. The increased biological yield can be attributed to improved vegetative growth, greater leaf area development and higher

photosynthetic efficiency. Enhanced nutrient uptake facilitated greater biomass accumulation throughout the crop growth period.

Harvest Index

Harvest index ranged from 29.31 to 33.33%. Although numerical differences were observed among treatments, the variations were statistically non-significant. This suggests that integrated nutrient management improved both economic and biological yield proportionately without markedly altering dry matter partitioning patterns.

Relationship between growth and yield

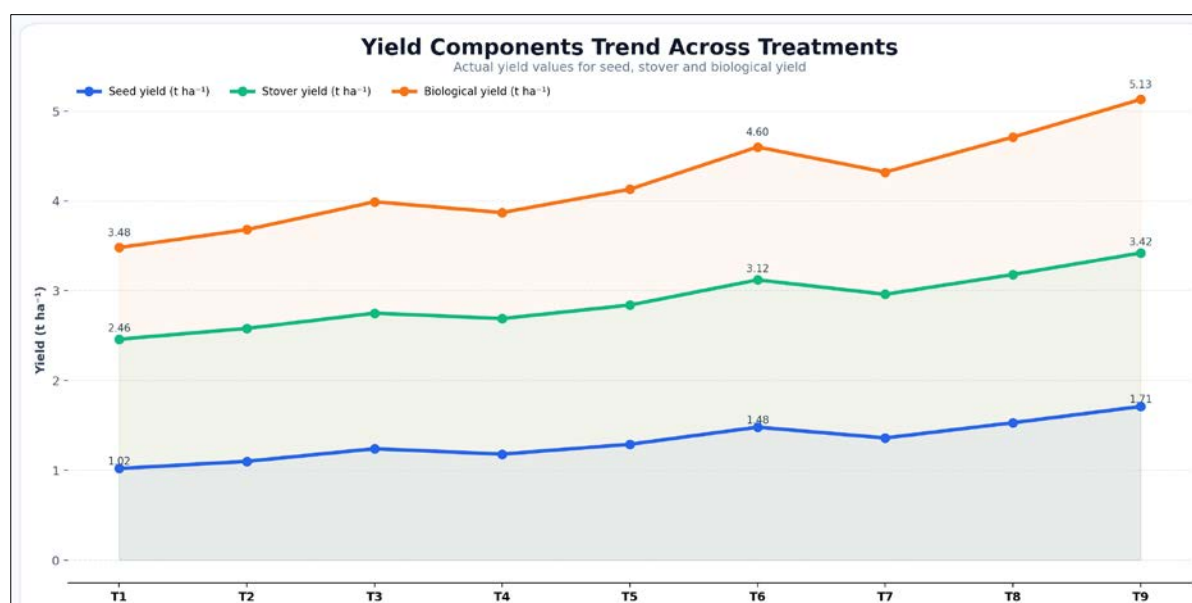


Fig 6: Trend of yield components across different treatments

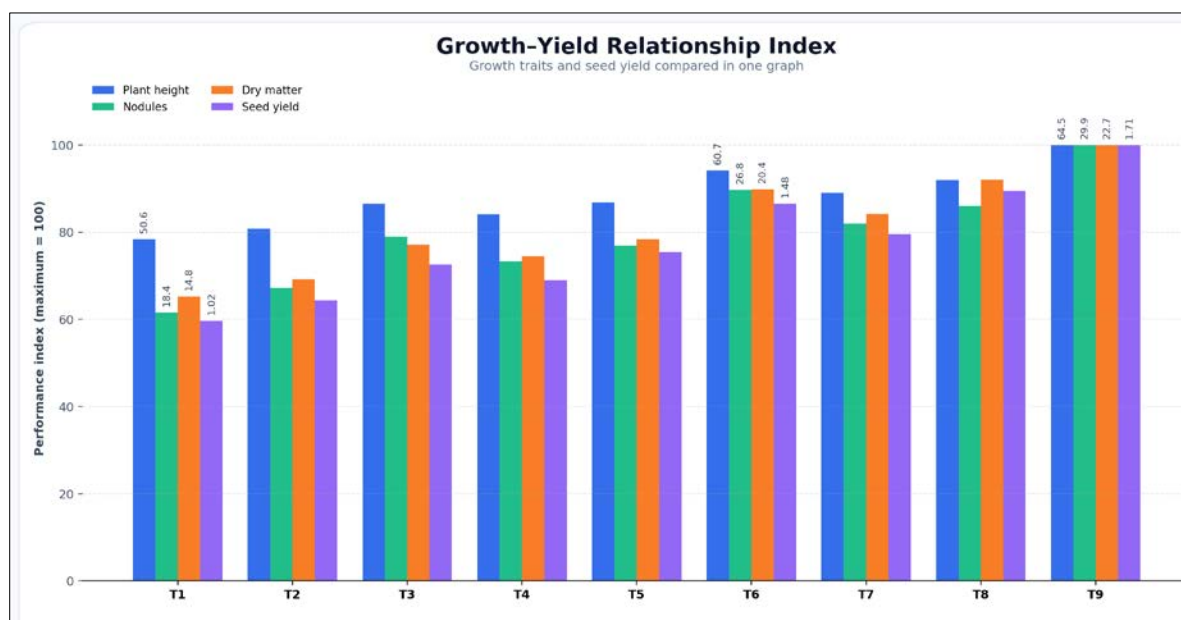


Fig 7: Comparative performance of growth attributes and seed yield

A strong positive association was observed between growth parameters and seed yield. Treatments that recorded greater plant height, nodulation and dry matter accumulation also produced higher seed yield. For instance, T₉ recorded the highest plant height (64.5 cm), nodules plant⁻¹ (29.9), dry matter accumulation (22.7 g plant⁻¹) and seed yield (1.71 t ha⁻¹). This clearly indicates that enhanced vegetative growth and improved nutrient acquisition played a crucial role in determining yield potential. The results conclusively demonstrate that integrated application of 50 kg P₂O₅ ha⁻¹ along with PSB and Rhizobium inoculation significantly improved yield attributes, seed yield, stover yield and biological yield of greengram under the agro-climatic conditions of Central Uttar Pradesh. The superiority of this treatment can be attributed to enhanced phosphorus availability, increased biological nitrogen fixation, improved nutrient uptake and greater physiological efficiency.

Conclusion

The present investigation clearly demonstrated that integrated nutrient management significantly influenced the growth, growth analysis parameters, yield attributes, yield, nutrient uptake, soil fertility and economic returns of greengram under the agro-climatic conditions of the Central Plain Zone of Uttar Pradesh. The combined application of phosphorus fertilizer, phosphorus-solubilizing bacteria (PSB) and Rhizobium inoculation proved more effective than the individual application of nutrient sources. Among the various treatments evaluated, the application of 50 kg P₂O₅ ha⁻¹ along with PSB and Rhizobium inoculation (T₉) consistently recorded superior performance with respect to plant height, nodulation, dry matter accumulation, leaf area development, crop growth rate and relative growth rate. The treatment produced the highest number of pods plant⁻¹ (30.5), seeds pod⁻¹ (11.0), test weight (41.0 g), seed yield (1.71 t ha⁻¹), stover yield (3.42 t ha⁻¹) and biological yield (5.13 t ha⁻¹). The increase in seed yield under T₉ was approximately 67.65 per cent over the lowest nutrient treatment, indicating the substantial contribution of integrated nutrient management towards productivity enhancement.

The improved performance of greengram under integrated nutrient management may be attributed to enhance phosphorus availability through PSB-mediated solubilization, improved

biological nitrogen fixation through Rhizobium inoculation, greater nutrient uptake and increased photosynthetic efficiency. The synergistic interaction among phosphorus, PSB and Rhizobium created favorable conditions for root growth, nodulation, biomass accumulation and assimilate translocation, ultimately resulting in higher productivity. The treatment also improved nutrient uptake and maintained better soil fertility status after harvest, indicating its potential for sustaining long-term productivity. Economic analysis further revealed that the same treatment generated the highest gross return, net return and benefit-cost ratio, demonstrating its economic feasibility and profitability for farmers.

Therefore, based on the findings of the present study, it may be concluded that the integrated application of 50 kg P₂O₅ ha⁻¹ in combination with PSB and Rhizobium inoculation is the most effective nutrient management strategy for greengram cultivation under the Central Plain Zone of Uttar Pradesh. This practice not only enhances crop productivity and profitability but also contributes to improved soil health and sustainable agricultural production.

Recommendation

Based on the experimental findings, the application of 50 kg P₂O₅ ha⁻¹ along with seed inoculation of PSB and Rhizobium is recommended for greengram cultivation under the agro-climatic conditions of Central Uttar Pradesh. Adoption of this integrated nutrient management practice can improve nutrient-use efficiency, enhance biological nitrogen fixation, increase yield and profitability, and contribute to the long-term sustainability of pulse-based production systems.

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