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Integrated phosphorus, rhizobium, Vermicompost, and biostimulant management enhances growth, nodulation, yield, and grain quality of chickpea (*Cicer Arietinum* L)

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Abstract

A field experiment was conducted to evaluate the effect of phosphorus levels integrated with *Rhizobium* inoculation, vermicompost and bio-stimulant application on growth, nodulation, yield attributes and grain quality of chickpea (*Cicer arietinum* L.). The experiment consisted of eleven treatments involving different phosphorus levels (30, 45 and 60 kg P₂O₅ ha⁻¹) combined with *Rhizobium*, vermicompost and bio-stimulant under randomized block design conditions. The results indicated significant improvement in growth, nodulation, yield and quality parameters under integrated nutrient management treatments compared with the control. Among the treatments, T₁₁ (60 kg P₂O₅ + *Rhizobium* + Vermicompost + Bio-stimulant) recorded the highest plant height (58.6 cm) and dry matter accumulation (34.41 g plant⁻¹) at harvest. The same treatment also produced the maximum number of nodules plant⁻¹ (50.4), fresh nodule weight (328 mg plant⁻¹) and dry nodule weight (101.2 mg plant⁻¹). Yield attributes including branches plant⁻¹ (9.1), pods plant⁻¹ (54.8), grains pod⁻¹ (1.48) and test weight (27.6 g) were significantly enhanced under integrated treatments. Quality parameters were also markedly improved, with T₁₁ recording the highest seed nitrogen (3.64%), phosphorus (0.46%), potassium content (0.98%), protein content (22.8%) and protein yield (634 kg ha⁻¹). The study concluded that integrated application of phosphorus with *Rhizobium*, vermicompost and bio-stimulant significantly improves growth, productivity and grain quality of chickpea under field conditions.

Keywords: Biological nitrogen fixation, Dry matter accumulation, Grain nutritional quality, Sustainable agriculture, Nutrient use efficiency

1. Introduction

Chickpea (*Cicer arietinum* L.) is one of the most important pulse crops cultivated in arid and semi-arid regions of the world and serves as a major source of dietary protein, carbohydrates, vitamins and minerals for human nutrition (Singh & Chahal, 2020) [20]. India is the largest producer of chickpea globally, contributing substantially to world pulse production (Kumar *et al.*, 2024) [14]. During 2024-25, chickpea occupied about 9.38 million hectares with a production of 11.97 million tonnes and an average productivity of 1199 kg ha⁻¹ (Govt. of India, MoAFW, 2025). Despite its agricultural and nutritional significance, chickpea productivity in India remains below its genetic potential due to poor soil fertility, nutrient imbalance and cultivation under marginal conditions (Patra & Coumar, 2023) [19].

Among essential nutrients, phosphorus is considered one of the most critical limiting factors in chickpea production. Phosphorus plays a vital role in root development, photosynthesis, energy transfer and symbiotic nitrogen fixation (Buddhi Charana *et al.*, 2022; Khan *et al.*, 2023) [2, 13]. Adequate phosphorus availability enhances nodulation and improves nitrogen fixation efficiency in legumes (Silva *et al.*, 2023). Since biological nitrogen fixation is an energy-intensive process, sufficient phosphorus supply is necessary for proper nodule functioning and crop growth (Mishra *et al.*, 2024) [16]. Recent metabolomic and physiological studies have further highlighted the importance of nutrient-mediated stress adaptation and plant physiological regulation under integrated crop management systems (Gautam *et al.*, 2024; Gautam *et al.*, 2025a) [6, 7, 9]. However, Phosphorus availability in soil is often restricted due to fixation into insoluble forms, resulting in poor phosphorus use efficiency (Silva *et al.*, 2023; Xing *et al.*, 2025) [23]. Integrated nutrient

management involving inorganic fertilizers, biofertilizers and organic amendments has emerged as a sustainable strategy to improve nutrient availability and crop productivity. Rhizobium inoculation enhances biological nitrogen fixation and nitrogen availability to plants (Abd-Alla *et al.*, 2023) ^[1], while vermicompost improves soil structure, microbial activity and nutrient mineralization (Mulatu & Bayata, 2024; Yang *et al.*, 2024) ^[17, 25]. Studies involving biologically active compounds and microbial interactions have demonstrated their positive role in enhancing plant growth, nutrient acquisition and stress resilience (Gautam *et al.*, 2025b; Gautam *et al.*, 2025c) ^[6, 7]. Similarly, bio-stimulants containing phytohormones and amino acids improve nutrient uptake, metabolic activity and stress tolerance in crops (Johnson *et al.*, 2024; del Pozo Valdés, 2023) ^[3, 11]. Recent studies have also emphasized the importance of plant-microbe interactions in improving crop performance and sustainable agricultural productivity (Gautam *et al.*, 2025d; Gautam *et al.*, 2026) ^[6, 7, 8].

The combined application of phosphorus, Rhizobium, vermicompost and bio-stimulants may create a synergistic effect in the rhizosphere, resulting in improved nutrient availability, enhanced nodulation, better growth and improved grain quality of chickpea. However, information regarding the integrated effect of these inputs on growth, nodulation, yield attributes and quality parameters of chickpea under Indo-Gangetic plain conditions remains limited. Therefore, the present investigation was undertaken to evaluate the effect of different phosphorus levels integrated with Rhizobium inoculation, vermicompost and bio-stimulant application on growth, dry matter accumulation, nodulation, yield attributes, seed nutrient content, protein content and protein yield of chickpea under field conditions.

2. Materials and methods

2.1 Experimental site, plant material and treatments

A field experiment was conducted during the rabi season to evaluate the effect of phosphorus levels, Rhizobium, vermicompost and bio-stimulants on growth, nodulation, yield and quality attributes of chickpea (*Cicer arietinum* L.). The experiment was carried out using chickpea variety JG-312, a high-yielding, wilt-resistant desi cultivar widely adapted to central Indian agro-climatic conditions.

The experiment comprised eleven treatments involving different phosphorus levels alone and in combination with Rhizobium, vermicompost and bio-stimulants. The treatments included: T₁ - absolute control; T₂ - recommended dose of fertilizer (20:40:20 kg ha⁻¹ N:P₂O₅:K₂O); T₃ - 30 kg P₂O₅ ha⁻¹ + Rhizobium; T₄ - 30 kg P₂O₅ ha⁻¹ + vermicompost; T₅ - 45 kg P₂O₅ ha⁻¹ + Rhizobium; T₆ - 45 kg P₂O₅ ha⁻¹ + vermicompost; T₇ - 60 kg P₂O₅ ha⁻¹ + Rhizobium; T₈ - 60 kg P₂O₅ ha⁻¹ + vermicompost; T₉ - 45 kg P₂O₅ ha⁻¹ + Rhizobium + vermicompost; T₁₀ - 45 kg P₂O₅ ha⁻¹ + Rhizobium + vermicompost + Myco f. UNO (soil application) + liquid bio-stimulant (seed treatment); and T₁₁ - 60 kg P₂O₅ ha⁻¹ + Rhizobium + vermicompost + Myco f. UNO (soil application) + liquid bio-stimulant (seed treatment).

2.2 Experimental design and crop management

The experiment was laid out in a Randomized Block Design (RBD) with three replications comprising a total of 33 plots. The gross plot size was maintained at 4.0 m × 3.0 m, whereas observations were recorded from a net plot area of 3.2 m × 2.2 m to minimize border effects. A spacing of 40 cm × 20 cm was maintained between rows and plants, respectively, using a seed

rate of 80 kg ha⁻¹. Standard agronomic and crop management practices were followed throughout the crop growth period.

2.3 Growth, nodulation and yield observations

Growth observations were recorded periodically at different growth stages and at harvest using randomly selected representative plants from each plot. Plant height was measured from the soil surface to the terminal growing point using a graduated scale, while the number of branches per plant was determined by counting both primary and secondary branches. Dry matter accumulation was estimated after oven drying plant samples at 70°C until constant weight was obtained.

Root nodulation studies were conducted at active nodulation stages by carefully uprooting plants with intact root systems. Nodules were separated after washing the roots thoroughly with water. Nodule count, fresh weight and dry weight of nodules were recorded and expressed on a per-plant basis. Dry weight of nodules was determined after oven drying at 60°C until constant weight.

Yield attributes including number of pods per plant, grains per pod and test weight were recorded at harvest. Pods from selected plants were counted manually, while grains per pod were determined from randomly selected mature pods. Test weight was recorded as the weight of 100 healthy and well-filled seeds using a precision electronic balance.

2.4 Quality analysis

Protein content in grain and straw was estimated through nitrogen determination using the Micro-Kjeldahl method and calculated using a conversion factor of 6.25 following AOAC (1960).

$$\text{Protein content (\%)} = \text{Nitrogen content (\%)} \times 6.25$$

Protein yield was calculated by multiplying protein content with the corresponding grain or straw yield.

$$\text{Protein yield (}\frac{\text{kg}}{\text{ha}}\text{)} = \frac{\text{Protein content (\%)} \times \text{Yield (}\frac{\text{kg}}{\text{ha}}\text{)}}{100}$$

2.5 Statistical analysis

The experimental data were subjected to analysis of variance (ANOVA) appropriate for Randomized Block Design (RBD). Treatment means were compared using the Critical Difference (CD) test at 5% probability level wherever the treatment effects were found significant.

3. Results

3.1 Effect of phosphorus, rhizobium, vermicompost and bio-stimulant on plant height of chickpea

The effect of different phosphorus levels integrated with Rhizobium, vermicompost and bio-stimulant application on plant height of chickpea was found to be significant at all growth stages (Table 1; Fig. 1). Plant height increased progressively from 30 DAS to harvest under all treatments, indicating continuous vegetative development throughout the crop growth period.

At 30 DAS, the lowest plant height was recorded in the absolute control (T₁) with 12.9 cm, whereas the maximum plant height was observed in T₁₁ (60 kg P₂O₅ + Rhizobium + Vermicompost + Bio-stimulant) with 18.7 cm, which was closely followed by T₁₀ (18.4 cm) and T₉ (18.1 cm). Similar trends were observed at subsequent growth stages. At 60 DAS, treatment T₁₀ recorded the highest

plant height (36.1 cm), followed by T₁₁ (35.6 cm), while the control treatment exhibited the minimum value (24.7 cm). The superiority of integrated nutrient management treatments became more pronounced during later growth stages. At 90 DAS, the maximum plant height was recorded under T₁₀ (51.3 cm), followed by T₁₁ (50.6 cm) and T₉ (48.9 cm), whereas the control treatment maintained the lowest value (35.6 cm). Similarly, at 120 DAS and harvest, T₁₁ produced the highest plant height of 57.2 cm and 58.6 cm, respectively, which was statistically superior to most treatments. The integrated application of phosphorus with Rhizobium, vermicompost and bio-stimulant consistently enhanced plant height over sole phosphorus or individual bio-input treatments.

Among the individual bio-input treatments, Rhizobium

inoculation generally performed better than vermicompost at corresponding phosphorus levels. Increasing phosphorus dose from 30 to 60 kg P₂O₅ ha⁻¹ also resulted in a gradual increase in plant height across all growth stages. The interaction plot further demonstrated a steady increase in plant height with crop age and highlighted the superior performance of integrated treatments, particularly T₁₀ and T₁₁ (Fig. 1).

The enhanced plant height under integrated nutrient management treatments may be attributed to improved nutrient availability, enhanced biological nitrogen fixation, better root development and improved physiological activity resulting from the combined action of phosphorus, Rhizobium, vermicompost and bio-stimulant application.

Table 1: Effect of phosphorus levels, Rhizobium, vermicompost and bio-stimulant on plant height (cm) of chickpea at different growth stages

Treatment	30 DAS	60 DAS	90 DAS	120 DAS	Harvest
T1 - Absolute Control	12.9±0.92	24.7±1.74	35.6±2.28	40.8±2.76	41.7±2.83
T2 - RDF (20:40:20)	14.5±1.01	27.4±1.95	40.1±2.42	44.6±2.94	45.8±3.02
T3 - 30 kg P ₂ O ₅ + Rhizobium	15.6±1.08	29.2±2.07	41.4±2.56	46.8±3.05	47.5±3.11
T4 - 30 kg P ₂ O ₅ + Vermicompost	15.2±1.04	28.5±2.01	42.0±2.61	47.3±3.11	48.1±3.18
T5 - 45 kg P ₂ O ₅ + Rhizobium	16.8±1.14	30.9±2.18	44.7±2.79	49.2±3.24	50.6±3.30
T6 - 45 kg P ₂ O ₅ + Vermicompost	16.1±1.11	30.1±2.14	43.3±2.72	48.5±3.18	49.3±3.25
T7 - 60 kg P ₂ O ₅ + Rhizobium	17.4±1.18	32.0±2.27	46.5±2.96	51.6±3.46	52.7±3.52
T8 - 60 kg P ₂ O ₅ + Vermicompost	16.9±1.16	31.3±2.22	47.1±3.02	52.4±3.51	53.5±3.57
T9 - 45 kg P ₂ O ₅ + Rhizobium + Vermicompost	18.1±1.23	33.8±2.39	48.9±3.18	54.7±3.64	55.9±3.70
T10 - 45 kg P ₂ O ₅ + Rhizobium + Vermicompost + Bio-stimulant	18.4±1.26	36.1±2.60	51.3±3.38	56.9±3.79	58.0±3.84
T11 - 60 kg P ₂ O ₅ + Rhizobium + Vermicompost + Bio-stimulant	18.7±1.28	35.6±2.56	50.6±3.34	57.2±3.82	58.6±3.88
SEm (±)	0.41	0.82	1.12	1.46	1.5
CD (P = 0.05)	1.21	2.4	3.28	4.27	4.38

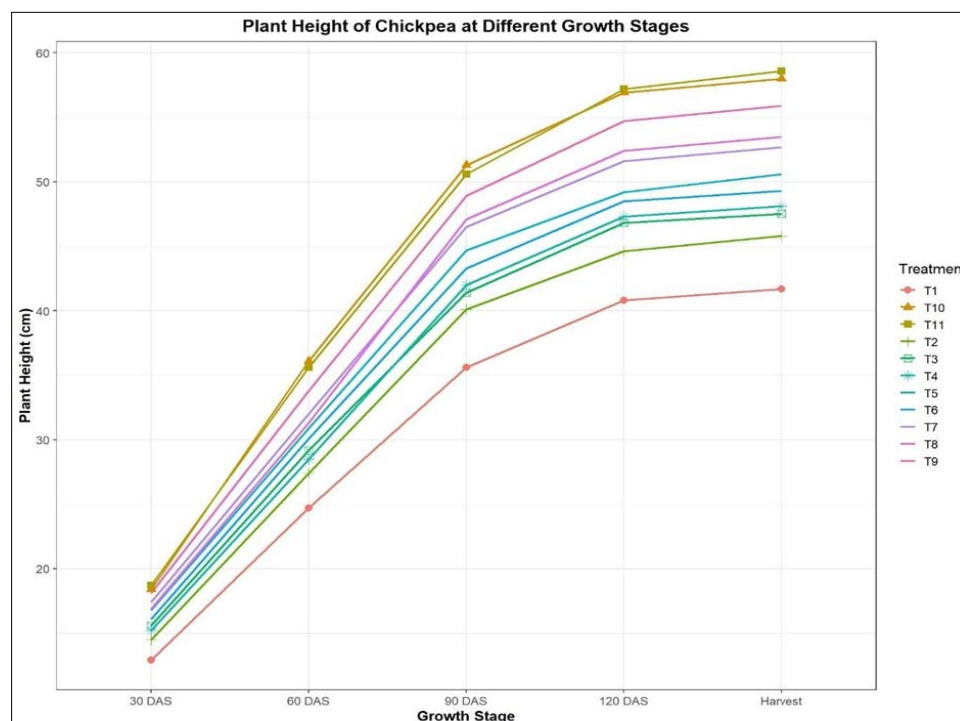


Fig 1: Effect of phosphorus levels, Rhizobium, vermicompost and bio-stimulant on plant height (cm) of chickpea at different growth stages

3.2 Effect of phosphorus, rhizobium, vermicompost and bio-stimulant on dry matter accumulation of chickpea

The accumulation of dry matter in chickpea was significantly influenced by different phosphorus levels in combination with Rhizobium, vermicompost and bio-stimulant application at all growth stages (Table 2; Fig. 2). Dry matter accumulation increased progressively from 30 DAS to harvest under all

treatments, reflecting continuous biomass production throughout crop development.

At 30 DAS, the lowest dry matter accumulation was observed in the absolute control (T₁) with 1.82 g plant⁻¹, whereas the highest value was recorded under T₁₁ (60 kg P₂O₅ + Rhizobium + Vermicompost + Bio-stimulant) with 3.12 g plant⁻¹, closely followed by T₁₀ (3.05 g plant⁻¹) and T₉ (2.98

g plant⁻¹). Similar treatment effects were maintained at subsequent growth stages. At 60 DAS, maximum dry matter accumulation was recorded in T₁₀ (10.48 g plant⁻¹), followed by T₁₁ (10.21 g plant⁻¹), while the control treatment showed the minimum accumulation (5.74 g plant⁻¹).

The differences among treatments became more pronounced during later crop growth stages. At 90 DAS, T₁₀ produced the highest dry matter accumulation (23.11 g plant⁻¹), followed by T₁₁ (22.63 g plant⁻¹) and T₉ (20.84 g plant⁻¹), whereas T₁ recorded the minimum value (11.92 g plant⁻¹). Likewise, at 120 DAS and harvest, T₁₁ recorded the highest dry matter accumulation of 32.18 and 34.41 g plant⁻¹, respectively, which remained significantly superior over most treatments. The integrated application of phosphorus with Rhizobium, vermicompost and bio-stimulant consistently enhanced biomass accumulation compared with sole phosphorus application or individual bio-input treatments.

Among the individual bio-input treatments, Rhizobium inoculation generally resulted in greater dry matter accumulation than vermicompost at corresponding phosphorus levels. Furthermore, increasing phosphorus levels from 30 to 60 kg P₂O₅ ha⁻¹ substantially improved dry matter production throughout crop growth. The interaction plot clearly illustrated the progressive increase in dry matter accumulation with crop age and emphasized the superior performance of integrated nutrient management treatments, particularly T₁₀ and T₁₁ (Fig. 2).

The increased dry matter accumulation under integrated nutrient management treatments may be attributed to enhanced nutrient uptake, improved nodulation and biological nitrogen fixation, better root proliferation and increased photosynthetic efficiency resulting from the combined effects of phosphorus, Rhizobium, vermicompost and bio-stimulant application.

Table 2: Effect of phosphorus levels, Rhizobium, vermicompost and bio-stimulant on dry matter accumulation (g plant⁻¹) of chickpea at different growth stages (30, 60, 90, 120 DAS and at harvest)

Treatment	30 DAS	60 DAS	90 DAS	120 DAS	At Harvest
T1 - Absolute Control	1.82±0.14	5.74±0.41	11.92±0.93	17.83±1.46	19.24±1.58
T2 - RDF (20:40:20)	2.14±0.16	6.83±0.49	14.37±1.10	21.05±1.72	22.68±1.85
T3 - 30 kg P ₂ O ₅ + Rhizobium	2.36±0.18	7.21±0.53	15.46±1.20	22.14±1.79	23.72±1.93
T4 - 30 kg P ₂ O ₅ + Vermicompost	2.28±0.17	7.05±0.52	15.88±1.24	22.57±1.86	24.10±1.96
T5 - 45 kg P ₂ O ₅ + Rhizobium	2.63±0.20	8.04±0.60	17.42±1.38	24.86±2.03	26.63±2.17
T6 - 45 kg P ₂ O ₅ + Vermicompost	2.51±0.19	7.86±0.58	16.84±1.33	24.11±1.96	25.79±2.10
T7 - 60 kg P ₂ O ₅ + Rhizobium	2.82±0.22	8.73±0.66	18.92±1.50	26.95±2.19	28.74±2.33
T8 - 60 kg P ₂ O ₅ + Vermicompost	2.71±0.21	8.45±0.64	19.31±1.53	27.62±2.26	29.41±2.39
T9 - 45 kg P ₂ O ₅ + Rhizobium + Vermicompost	2.98±0.23	9.37±0.72	20.84±1.65	29.74±2.42	31.63±2.58
T10 - 45 kg P ₂ O ₅ + Rhizobium + Vermicompost + Bio-stimulant	3.05±0.24	10.48±0.82	23.11±1.86	31.96±2.61	33.94±2.76
T11 - 60 kg P ₂ O ₅ + Rhizobium + Vermicompost + Bio-stimulant	3.12±0.24	10.21±0.79	22.63±1.81	32.18±2.64	34.41±2.79
SEm (±)	0.07	0.26	0.58	0.92	0.97
CD (P = 0.05)	0.21	0.76	1.69	2.7	2.84

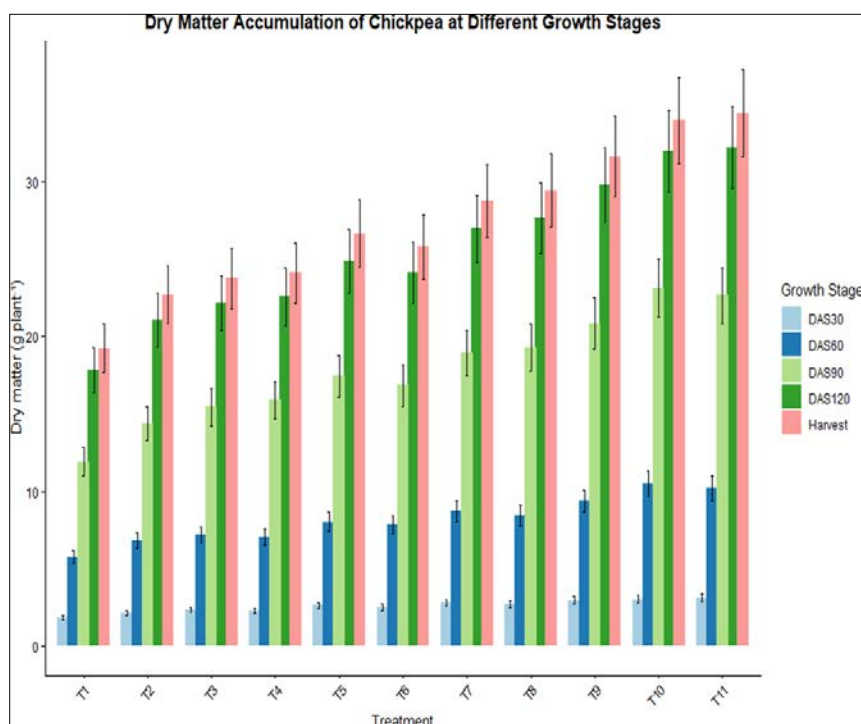


Fig 2: Effect of phosphorus levels, Rhizobium, vermicompost and bio-stimulant on dry matter accumulation (g plant⁻¹) of chickpea at different growth stages

3.3 Effect of phosphorus levels, rhizobium, vermicompost and bio-stimulant on growth, nodulation and yield attributes of chickpea

The growth, nodulation and yield attributes of chickpea were

significantly influenced by different phosphorus levels in combination with Rhizobium inoculation, vermicompost and bio-stimulant application (Table 3; Fig. 3). Integrated nutrient management treatments exhibited substantial improvement in

vegetative growth, nodulation characteristics and reproductive parameters over the control and sole fertilizer treatments.

Among the treatments, the highest number of branches plant⁻¹ was recorded in T₁₁ (60 kg P₂O₅ + Rhizobium + Vermicompost + Bio-stimulant) with 9.1 branches plant⁻¹, which was closely followed by T₁₀ (8.9 branches plant⁻¹) and T₉ (8.3 branches plant⁻¹). In contrast, the absolute control (T₁) produced the minimum number of branches (4.3 plant⁻¹). The combined application of phosphorus and bio-inputs markedly enhanced vegetative branching compared with individual nutrient treatments.

Nodulation parameters were also significantly improved by integrated nutrient management practices. The maximum number of nodules plant⁻¹ was recorded under T₁₁ (50.4 nodules plant⁻¹), followed by T₁₀ (49.1 nodules plant⁻¹) and T₉ (45.2 nodules plant⁻¹), whereas the control treatment recorded the minimum value (18.6 nodules plant⁻¹). Similar trends were observed for fresh and dry weight of nodules. Treatment T₁₁ produced the highest fresh weight (328 mg plant⁻¹) and dry weight of nodules (101.2 mg plant⁻¹), closely followed by T₁₀ with 319 and 98.6 mg plant⁻¹, respectively. The enhanced nodulation observed under integrated treatments indicated improved root colonization and biological nitrogen fixation activity.

Yield attributes were also significantly affected by the treatments. The maximum number of pods plant⁻¹ was recorded in T₁₁ (54.8

pods plant⁻¹), followed by T₁₀ (53.6 pods plant⁻¹) and T₉ (49.7 pods plant⁻¹), while the control treatment recorded the minimum number of pods (22.4 plant⁻¹). Likewise, grains pod⁻¹ and test weight showed a significant increasing trend with integrated phosphorus and bio-input application. The highest grains pod⁻¹ (1.48) and test weight (27.6 g) were observed in T₁₁, followed by T₁₀ with 1.46 grains pod⁻¹ and 27.1 g test weight. The lowest values for these parameters were recorded under the control treatment.

Among the individual bio-input treatments, Rhizobium inoculation generally performed better than vermicompost at corresponding phosphorus levels for most growth and nodulation parameters. Increasing phosphorus levels from 30 to 60 kg P₂O₅ ha⁻¹ also resulted in substantial enhancement of nodulation and yield attributes. The clustered column plots and heatmap further illustrated the superiority of integrated nutrient management treatments, particularly T₁₀ and T₁₁, which consistently formed a distinct high-performing cluster for all measured traits (Fig. 3). The improvement in growth, nodulation and yield parameters under integrated nutrient management treatments may be attributed to enhanced phosphorus availability, improved microbial activity, increased biological nitrogen fixation, better nutrient uptake and improved physiological efficiency resulting from the synergistic interaction of phosphorus, Rhizobium, vermicompost and bio-stimulant application.

Table 3: Effect of phosphorus levels, rhizobium, vermicompost and bio-stimulant on growth, nodulation and yield attributes of chickpea

Treatment	Branches plant ⁻¹	Nodules plant ⁻¹	Fresh weight of nodules (mg plant ⁻¹)	Dry weight of nodules (mg plant ⁻¹)	Pods plant ⁻¹	Grains pod ⁻¹	Test weight (g)
T ₁ - Absolute Control	4.3±0.36	18.6±1.45	114±8.7	35.1±2.8	22.4±1.78	1.12±0.09	19.8±1.52
T ₂ - RDF (20:40:20)	5.2±0.42	23.1±1.79	141±10.6	42.3±3.3	26.7±2.04	1.18±0.09	21.3±1.63
T ₃ - 30 kg P ₂ O ₅ + Rhizobium	5.9±0.47	30.2±2.32	185±14.1	56.2±4.4	30.5±2.31	1.23±0.10	22.4±1.72
T ₄ - 30 kg P ₂ O ₅ + Vermicompost	5.7±0.45	28.4±2.18	176±13.4	53.1±4.1	29.2±2.21	1.21±0.10	22.0±1.69
T ₅ - 45 kg P ₂ O ₅ + Rhizobium	6.8±0.54	35.4±2.71	226±17.2	68.7±5.3	35.8±2.68	1.30±0.10	23.6±1.81
T ₆ - 45 kg P ₂ O ₅ + Vermicompost	6.5±0.52	33.6±2.58	214±16.3	65.2±5.0	34.1±2.57	1.28±0.10	23.1±1.78
T ₇ - 60 kg P ₂ O ₅ + Rhizobium	7.5±0.59	39.6±3.02	255±19.4	77.8±6.0	41.3±3.05	1.35±0.11	24.5±1.87
T ₈ - 60 kg P ₂ O ₅ + Vermicompost	7.2±0.57	38.1±2.91	247±18.8	75.1±5.8	39.8±2.94	1.33±0.11	24.2±1.85
T ₉ - 45 kg P ₂ O ₅ + Rhizobium + Vermicompost	8.3±0.65	45.2±3.43	289±21.9	89.4±6.8	49.7±3.62	1.41±0.11	25.8±1.97
T ₁₀ - 45 kg P ₂ O ₅ + Rhizobium + Vermicompost + Bio-stimulant	8.9±0.69	49.1±3.71	319±24.1	98.6±7.5	53.6±3.91	1.46±0.12	27.1±2.04
T ₁₁ - 60 kg P ₂ O ₅ + Rhizobium + Vermicompost + Bio-stimulant	9.1±0.71	50.4±3.82	328±24.8	101.2±7.7	54.8±3.98	1.48±0.12	27.6±2.08
SEm (±)	0.31	1.24	9.6	3.2	1.48	0.04	0.58
CD (P = 0.05)	0.91	3.62	28.1	9.3	4.32	0.12	1.69

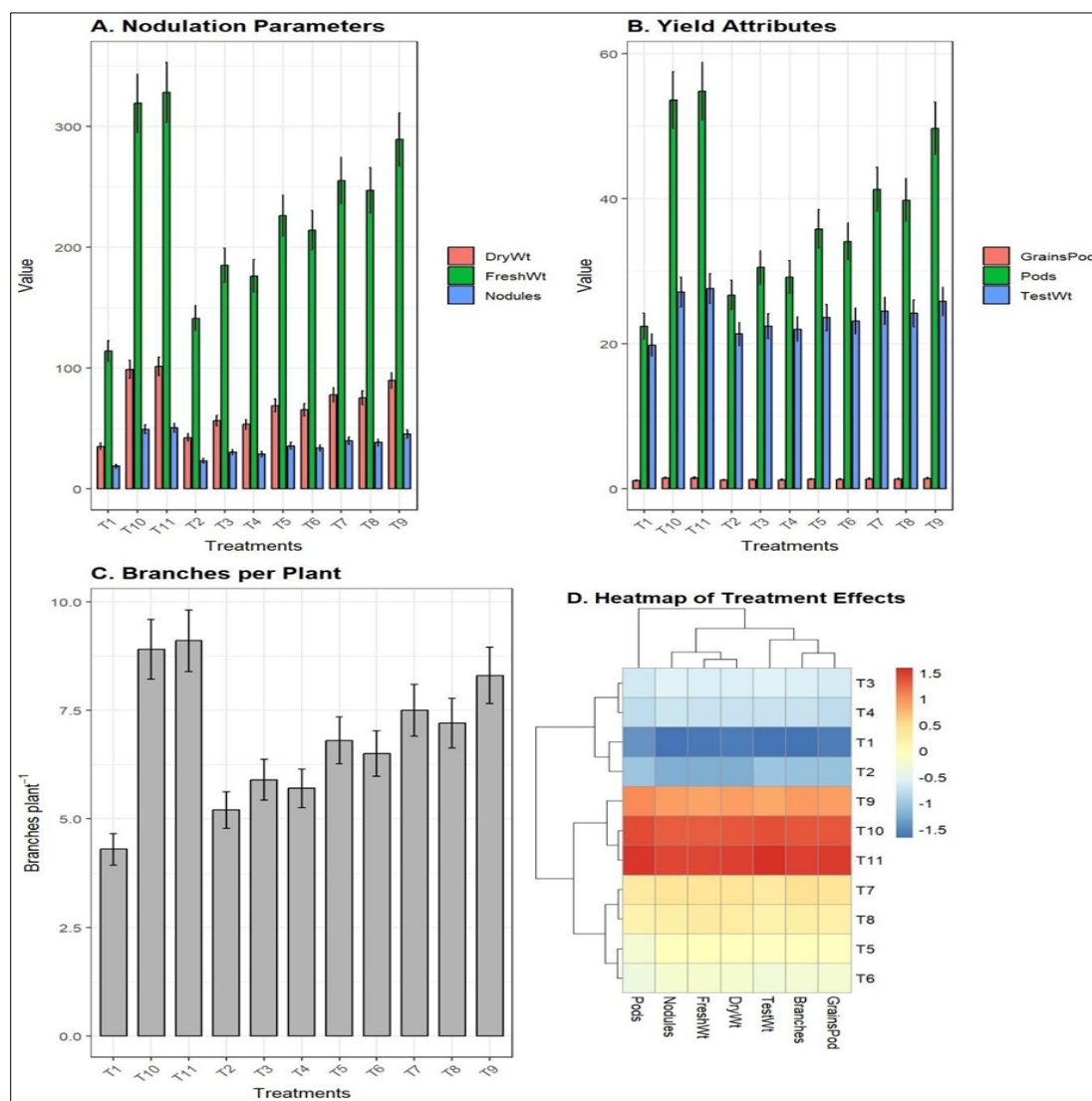


Fig 3: Effect of phosphorus levels, Rhizobium inoculation, vermicompost and bio-stimulant application on nodulation, yield attributes and associated traits of chickpea. Panel A represents nodulation parameters including number of nodules plant⁻¹, fresh weight of nodules and dry weight of nodules. Panel B depicts yield attributes comprising pods plant⁻¹, grains pod⁻¹ and test weight. Panel C shows branches plant⁻¹ under different treatments. Panel D illustrates the heatmap with hierarchical clustering showing treatment-wise variation in nodulation and yield-related traits. Values are presented as mean±SE

3.4 Effect of phosphorus levels, rhizobium inoculation, vermicompost and bio-stimulant application on seed nutrient content, protein content and protein yield of chickpea

The seed nutrient content, protein content and protein yield of chickpea were significantly influenced by different phosphorus levels integrated with Rhizobium inoculation, vermicompost and bio-stimulant application (Table 4; Fig. 4). Integrated nutrient management treatments markedly improved seed quality parameters over the control and sole fertilizer treatments.

Among the treatments, the highest seed nitrogen content was recorded under T₁₁ (60 kg P₂O₅ + Rhizobium + Vermicompost + Bio-stimulant) with 3.64%, which was closely followed by T₁₀ (3.60%) and T₉ (3.56%). The lowest seed nitrogen content was observed in the absolute control (T₁) with 3.05%. A similar increasing trend was observed for seed phosphorus and potassium content. Treatment T₁₁ recorded the maximum seed phosphorus content (0.46%) and seed potassium content (0.98%), whereas the control treatment exhibited the minimum values of 0.34% and 0.78%, respectively.

Protein content in chickpea seeds was also significantly enhanced by integrated nutrient management practices. The highest protein content was recorded in T₁₁ (22.8%), followed by T₁₀ (22.5%) and T₉ (22.3%), while the minimum protein content was observed

under the control treatment (19.1%). The progressive increase in protein content with higher phosphorus levels and combined bio-input application indicated improved nutrient assimilation and nitrogen metabolism in chickpea plants.

Protein yield showed a substantial increase under integrated treatments. The maximum protein yield was recorded in T₁₁ with 634 kg ha⁻¹, followed by T₁₀ (612 kg ha⁻¹) and T₉ (566 kg ha⁻¹), whereas the control treatment recorded the minimum protein yield of 244 kg ha⁻¹. The combined application of phosphorus, Rhizobium, vermicompost and bio-stimulant significantly improved protein productivity compared with sole phosphorus application and individual bio-input treatments.

Among the individual bio-input treatments, Rhizobium inoculation generally resulted in higher seed nutrient concentration and protein yield than vermicompost at corresponding phosphorus levels. Increasing phosphorus application from 30 to 60 kg P₂O₅ ha⁻¹ also significantly enhanced seed nutrient composition and protein-related traits. The clustered column plots and heatmap further highlighted the superior performance of integrated treatments, particularly T₁₀ and T₁₁, which formed a distinct cluster associated with higher nutrient accumulation and protein productivity (Fig. 4).

The improvement in seed nutrient content and protein yield under

integrated nutrient management treatments may be attributed to enhanced phosphorus availability, increased biological nitrogen fixation, improved nutrient uptake and translocation, enhanced metabolic activity and improved overall physiological efficiency resulting from the synergistic interaction of phosphorus, Rhizobium, vermicompost and bio-stimulant application.

Table 4: Effect of phosphorus levels, Rhizobium inoculation, vermicompost and bio-stimulant application on seed nutrient content (N, P, K), protein content and protein yield of chickpea

Treatment	Seed N (%)	Seed P (%)	Seed K (%)	Protein content (%)	Protein yield (kg ha ⁻¹)
T1 - Absolute Control	3.05±0.24	0.34±0.03	0.78±0.06	19.1±1.48	244±19
T2 - RDF (20:40:20)	3.18±0.25	0.36±0.03	0.82±0.07	19.9±1.55	312±24
T3 - 30 kg P ₂ O ₅ + Rhizobium	3.29±0.26	0.38±0.03	0.86±0.07	20.6±1.61	369±29
T4 - 30 kg P ₂ O ₅ + Vermicompost	3.24±0.25	0.37±0.03	0.84±0.07	20.3±1.58	347±27
T5 - 45 kg P ₂ O ₅ + Rhizobium	3.38±0.27	0.40±0.03	0.89±0.07	21.1±1.65	430±33
T6 - 45 kg P ₂ O ₅ + Vermicompost	3.34±0.26	0.39±0.03	0.88±0.07	20.9±1.63	407±31
T7 - 60 kg P ₂ O ₅ + Rhizobium	3.47±0.28	0.42±0.03	0.92±0.08	21.7±1.70	495±38
T8 - 60 kg P ₂ O ₅ + Vermicompost	3.43±0.27	0.41±0.03	0.91±0.07	21.4±1.67	472±36
T9 - 45 kg P ₂ O ₅ + Rhizobium + Vermicompost	3.56±0.28	0.44±0.04	0.95±0.08	22.3±1.75	566±43
T10 - 45 kg P ₂ O ₅ + Rhizobium + Vermicompost + Bio-stimulant	3.60±0.29	0.45±0.04	0.97±0.08	22.5±1.76	612±46
T11 - 60 kg P ₂ O ₅ + Rhizobium + Vermicompost + Bio-stimulant	3.64±0.29	0.46±0.04	0.98±0.08	22.8±1.79	634±48
SEm (±):	0.07	0.01	0.02	0.45	18
CD (P = 0.05):	0.21	0.03	0.06	1.32	52

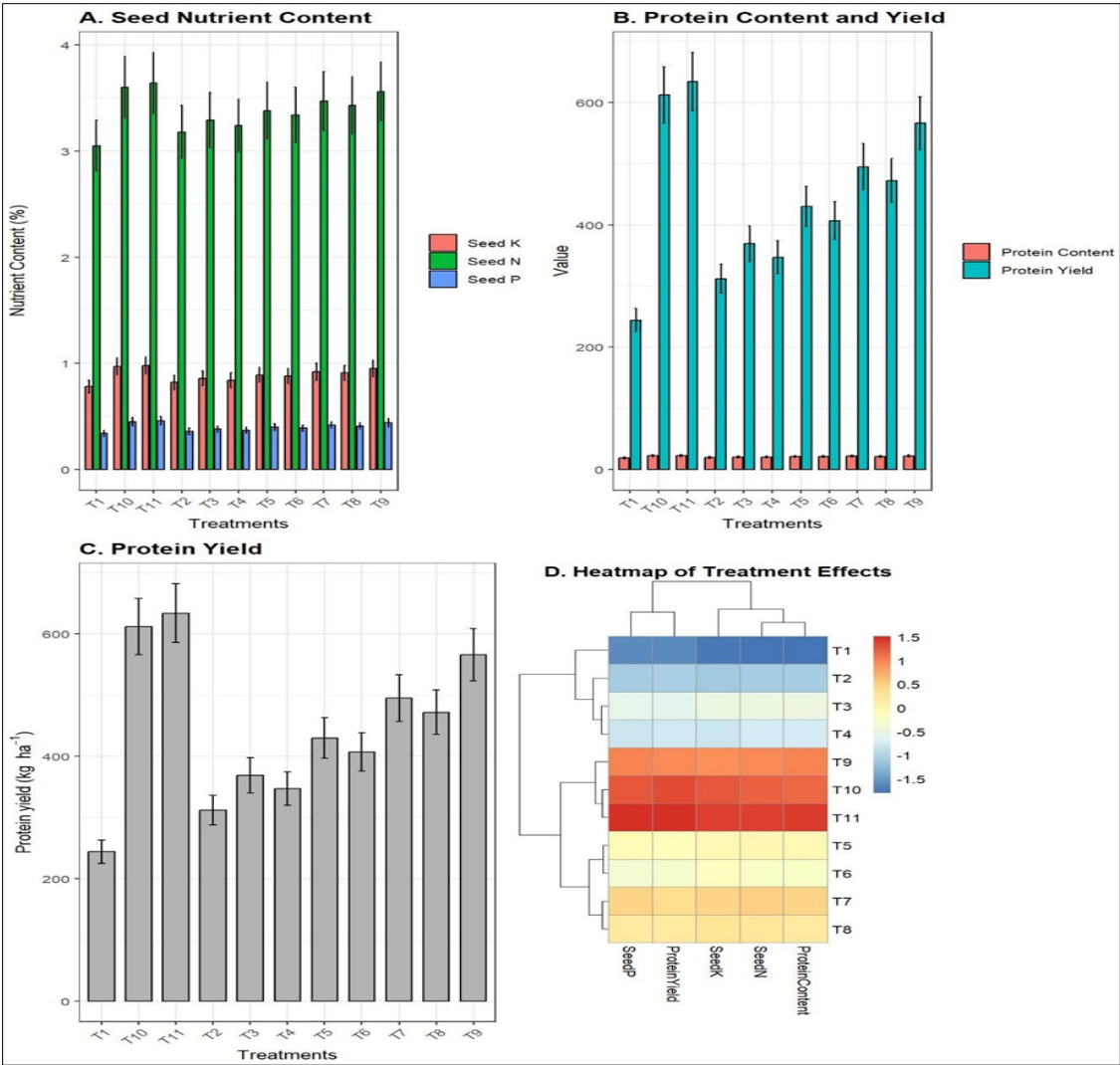


Fig 4: Effect of phosphorus levels, Rhizobium inoculation, vermicompost and bio-stimulant application on seed nutrient content, protein content and protein yield of chickpea. Panel A represents seed nutrient content including seed nitrogen (N), phosphorus (P) and potassium (K) content (%). Panel B depicts protein content (%) and protein yield (kg ha⁻¹) under different treatments. Panel C illustrates protein yield (kg ha⁻¹) of chickpea as influenced by integrated nutrient management treatments. Panel D shows the heatmap with hierarchical clustering indicating treatment-wise variation in seed nutrient composition and protein-related traits. Values are presented as mean±SE

4. Discussion

The present study demonstrated that integrated application of phosphorus, Rhizobium, vermicompost and bio-stimulant significantly improved growth, nodulation, yield attributes and grain quality of chickpea compared with the control and sole nutrient treatments. Among the treatments, T₁₀ and T₁₁ consistently recorded superior performance for most of the observed parameters.

The increased plant height and dry matter accumulation under integrated nutrient management treatments may be attributed to enhanced nutrient availability, improved root growth and greater physiological efficiency. Phosphorus plays an important role in energy transfer, root development and cell division, while Rhizobium inoculation enhances biological nitrogen fixation and nitrogen availability to plants. Vermicompost likely improved soil structure, microbial activity and nutrient mineralization, whereas bio-stimulants may have enhanced metabolic and enzymatic activities, resulting in improved crop growth and biomass accumulation. Similar findings were reported by Minz *et al.* (2023)^[15], Mishra *et al.* (2023) and Kumar *et al.* (2014).

Nodulation parameters, including number of nodules and fresh and dry weight of nodules, were significantly enhanced under integrated treatments. The combined application of phosphorus and bio-inputs possibly created favorable rhizospheric conditions for better root colonization and symbiotic nitrogen fixation. Improved phosphorus availability is known to support nodule formation and nitrogenase activity, thereby enhancing nodulation efficiency. These findings are in accordance with Singh *et al.* (2021)^[21], Parashar *et al.* (2024) and Dinç and Toğay (2026)^[4, 18]. The higher number of branches, pods plant⁻¹, grains pod⁻¹ and test weight observed under integrated nutrient management treatments may be due to improved nutrient uptake and assimilate translocation from source to sink. Enhanced vegetative growth and dry matter production likely contributed to better flowering, pod formation and seed development. Similar results were reported by Yadav *et al.* (2025)^[24].

Integrated nutrient management treatments also significantly improved seed nutrient composition, protein content and protein yield. The higher seed nitrogen content and protein accumulation may be attributed to increased nitrogen fixation and improved nutrient assimilation under Rhizobium inoculation and phosphorus application. Vermicompost and bio-stimulants possibly enhanced nutrient availability and uptake efficiency, resulting in improved nutrient translocation to developing grains. Similar findings were reported by Singh *et al.* (2021)^[21], Subhasmita *et al.* (2023)^[22], Kaur *et al.* (2023) and Yadav *et al.* (2024)^[12].

Overall, the present findings indicate that combined application of phosphorus, Rhizobium, vermicompost and bio-stimulant creates a synergistic effect that enhances nutrient availability, biological nitrogen fixation and physiological activity, ultimately improving growth, yield and grain quality of chickpea.

5. Conclusion

The present investigation clearly demonstrated that integrated nutrient management involving phosphorus, Rhizobium inoculation, vermicompost and bio-stimulant application significantly enhanced growth, nodulation, yield attributes and grain quality of chickpea. The combined application of inorganic phosphorus with biological and organic inputs proved markedly superior to sole fertilizer application and the untreated control throughout the crop growth period.

Among the treatments, T₁₁ (60 kg P₂O₅ + Rhizobium + Vermicompost + Bio-stimulant) consistently recorded the highest

values for plant height, dry matter accumulation, nodulation parameters, yield attributes, seed nutrient content, protein content and protein yield, closely followed by T₁₀. The integrated treatments substantially improved nutrient availability, biological nitrogen fixation, assimilate partitioning and overall physiological efficiency, which collectively contributed to enhanced crop productivity and grain nutritional quality.

The study further established that the synergistic interaction among phosphorus, Rhizobium, vermicompost and bio-stimulant created a favorable rhizospheric environment that promoted better root development, nutrient uptake and metabolic activity. Improved nodulation and enhanced nutrient translocation under integrated nutrient management practices ultimately resulted in superior growth performance and higher quality seed production in chickpea.

Therefore, the combined application of phosphorus along with Rhizobium, vermicompost and bio-stimulant may be considered an efficient and sustainable nutrient management strategy for improving chickpea productivity, grain quality and soil health under integrated farming systems.

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