

## **INTEGRATING COMPOST, CHEMICAL FERTILIZERS, AND PLANT GROWTH-PROMOTING RHIZOBACTERIA FOR IMPROVING PRODUCTIVITY OF PEA (*Pisum sativum* L.)**

M. Jamil<sup>1</sup>, S. Masood<sup>2\*</sup>, M. A. Qazi<sup>3</sup>, S. Jehan<sup>4</sup>, M. Liaquat<sup>5</sup>, A. Rasool<sup>6</sup>, M. Aon<sup>2</sup>, M. U. H. Khan<sup>1</sup> and M. K. Rasheed<sup>7</sup>

<sup>1</sup>Soil and Water Testing Laboratory, Pakpattan Road, 81-Sahiwal, Pakistan.

<sup>2</sup>Department of Soil Science, Faculty of Agricultural Sciences & Technology, Bahauddin Zakariya University, 60800-Multan, Pakistan.

<sup>3</sup>Soil Fertility Research Institute, 53710-Lahore, Punjab, Pakistan.

<sup>4</sup>Institute of Soil and Environmental Sciences, Pir Mehr Ali Shah Arid Agriculture University, 46300-Rawalpindi, Pakistan.

<sup>5</sup>Department of Horticulture, Pir Mehr Ali Shah Arid Agriculture University, 46300-Rawalpindi, Pakistan.

<sup>6</sup>Department of Environmental Engineering, Faculty of Mining and Geology, VSB-Technical University of Ostrava, 17 Listopadu 2172/15, 70800-Ostrava-Poruba, Czechia.

<sup>7</sup>Soil and Water Testing Laboratory, Old Shujjabad Road, 60750-Multan, Pakistan.

\*Corresponding author's email: [sajidmasood@bzu.edu.pk](mailto:sajidmasood@bzu.edu.pk)

### **ABSTRACT**

Although chemical fertilizers provide essential nutrients, prolonged use of inorganic fertilizers not only deteriorates soil health but also damages crop yield. However, application of organic amendments like compost and plant growth-promoting rhizobacteria (PGPR) along with chemical fertilizers is considered as a sustainable approach for improving nutrient availability in soil-plant systems. A pot experiment was carried out according to completely randomized design (CRD) to assess their impact on pea (*Pisum sativum* L.) growth and yield. Following treatments: control, 100% NPK, 100% compost, 50% NPK + 50% compost both with and without PGPR (*Bacillus subtilis* RP-01) inoculation were established with four replications of each. The results revealed that plant growth and yield were highest in treatment T4 when PGPR-inoculated plants were subjected to 50% NPK + 50% compost. Organic amendment like 100% compost in conjunction with PGPR inoculation resulted in the maximum root nodulation (54.50 root nodules pot<sup>-1</sup>) and bacterial population (8x10<sup>5</sup> CFU g<sup>-1</sup> fresh soil). By contrast, 100% compost and PGPR did not result in the maximum nutrient availability in soil-plant system as compared to inoculated 50% compost + 50% NPK. In conclusion, integration of 50% compost, 50% NPK and PGPR inoculation enhanced pea yield by 22.56% when compared with 100% NPK alone. Moreover, integrated approach like PGPR + 50% compost + 50% NPK enhanced pea yield by reducing NPK inputs up to 50%.

**Keywords:** Chemical fertilizers; Nodulation; Nutrient uptake; PGPR inoculation; Pea yield; Sustainable agriculture.

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### **INTRODUCTION**

Whilst chemical fertilizers are crucial for replenishing plant growth, excessive application of fertilizers damages soil health and plant productivity (Cui *et al.*, 2022). Moreover, continuous and imbalanced use of chemical fertilizers results in soil pH fluctuations, insect and pest diseases in plants, inhibited plant growth, soil organic matter depletion, and greenhouse gas emissions (Bisht and Chauhan, 2021). In general, overuse of chemical fertilizers not only affects soil and plant health, but also results in the pollution of waterways, thereby affecting natural biodiversity and ecosystem stability (Tripathi *et al.*, 2020). Therefore, studies

investigating the advantages of integrated use of chemical fertilizers, organic amendments such as compost, and the growth-promoting potential of PGPR have gained much attention (Hussain *et al.*, 2016; Muhammad *et al.*, 2025).

Given above, compost is considered as one of the rich sources of organic matter, which not only improves soil physico-chemical properties but also promotes soil microbial population (Tumuhairwe and Tenywa, 2018). There is increasing evidence that compost may remain friendly to the environment when applied in high amounts (Aziz *et al.*, 2024). According to Ghanim *et al.* (2023), organic manures, including compost are slowly decomposed by the microbes, thereby provide nutrient-rich compounds in soil-plant system. In

this regard, the use of PGPR has been considered as an effective strategy for sustainable crop production and maintaining plant health and productivity (Yang *et al.*, 2024). PGPR normally colonize plant roots and enhance crop yield through different mechanisms such as higher nutrient use efficiency, plant growth hormone synthesis, and disease control (de Andrade *et al.*, 2023). According to Ayuso-Calles *et al.* (2021) and Ullah *et al.* (2020), PGPR also improve plant growth through the increased nutrient mobilization. Therefore, the use of PGPR in crop production in recent times is important for paradigm shift towards eco-friendly and sustainable strategies from conventional methods of using chemical inputs (Mishra and Barolia, 2020).

Despite the importance of PGPR in sustainable crop production, their performance may vary under field conditions because of diverse nature of the soil, abrupt changes in climate, imbalanced preparations, and use of unsuitable carrier materials (Wang *et al.*, 2023). Therefore, co-provision of PGPR with a nutrient-rich source like compost may combat the chemical fertilizers demand through enhanced microbial population and nutrient mineralization (Ahmed *et al.*, 2023).

Pea (*Pisum sativum* L.) belongs to Fabacea family, is often characterized by root nodule formation, especially under the application of biofertilizers, including PGPR (Abou-El-Hassan and Elbatran, 2020). *Bacillus megaterium* (PGPR) in combination with rhizobium has also been resulted in the growth enhancement of common bean in comparison to rhizobium alone (Korir *et al.*, 2017). In addition, qualitative and quantitative effects of either 100% or 50% chemical fertilizers both with and without PGPR on wheat have been studied (Sedri *et al.*, 2022). In our earlier study, we investigated the effects of various organic and inorganic amendments on pea yield (Aziz *et al.*, 2024). However, root nodulation and soil bacterial population in closed association with pea roots, especially when subjected to PGPR and the application of suitable carrier material like compost has not been studied yet. We thus hypothesized that integration of PGPR, compost, and chemical fertilizers improves root nodulation and soil bacterial population, thereby enhancing nutrient availability in soil-plant system. Hence, the present study was carried out to assess: 1) the effect of chemical fertilizers, compost, and PGPR on root nodulation and soil bacterial population, 2) optimization of compost and chemical fertilizers requirement for improved pea growth and yield, especially when interacted with PGPR inoculation, and 3) nutrient availability in soil-plant system with reference to the integrated approach of using chemical fertilizers, compost and PGPR for enhanced pea yield on sustainable basis.

## MATERIALS AND METHODS

**Experimental site description and plant material:** A pot experiment was carried out in the wirehouse of Soil and Water Testing Laboratory, Sahiwal, Punjab, Pakistan (30.639818 °N, 73.11856 °E) on 21 October, 2023 to assess the effects of compost as a soil amendment coupled with PGPR inoculation and chemical fertilizers on soil and plant nutrient status as well as growth and yield of pea. Ten pea seeds (variety Meteor) were cultivated in pots (25 × 22.5 cm<sup>2</sup>) having 10 kg sterilized soil, which were later thinned to six plants. The soil used in the experiment was collected from the surrounding at a depth of 0-30 cm, which was thus air-dried, ground and passed through 2 mm sieve. The experimental soil was clay loam and analyzed for following soil physico-chemical properties: pH; 8.19, EC; 1.03 mS cm<sup>-1</sup>, soil organic matter (SOM); 0.97%, total N; 0.06 mg kg<sup>-1</sup> dry soil; available P; 7.44 mg kg<sup>-1</sup> dry soil, extractable K; 178 mg kg<sup>-1</sup> dry soil, and available B; 0.54 mg kg<sup>-1</sup> dry soil. Pea plants received natural sunlight with average light duration of 10-11 h, day/night temperatures of 20 °C/15 °C, and relative humidity of 36%.

**PGPR culture preparation and establishment of treatments:** *Bacillus subtilis* strain (RP-01) was obtained from Institute of Soil and Environmental Sciences, Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, Pakistan. Bacterial culture was prepared in liquid broth and kept overnight in shaker-incubator (ECELLA E23, California, USA), followed by centrifugation at a speed of 3000 rpm for 20 min. Eluent was discarded, whereas obtained pellet of bacterial culture was spun in sterile water to ensure optical density of one using a spectrophotometer (C-7200, Peaks Instruments, Shanghai, China) at a wavelength of 535 nm. Afterwards, seeds were soaked in 10<sup>7-8</sup> CFU ml<sup>-1</sup> bacterial culture for 4-5 h after following the procedure as reported by Israr *et al.* (2016). Likewise, remaining seeds were put in sterile water without PGPR and then used for sowing.

Following treatments were established: control (no compost and no NPK), 100% NPK, 100% compost, and 50% compost + 50% NPK both with and without PGPR. After establishing various combinations of compost and NPK, half of the pots received PGPR inoculated seeds, whereas other half received non-inoculated seeds. In general, 32 pots having eight treatments with four replications of each were randomly arranged to reduce variations. Before initiation of treatments, compost was analyzed for following properties: OM; 23%, CEC; 65 meq 100 g<sup>-1</sup>, and C:N; 1:22. NPK fertilizers were applied at the rate of 45:90:90 kg N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O ha<sup>-1</sup> viz. urea (0.10 g pot<sup>-1</sup>), di-ammonium phosphate (0.98 g pot<sup>-1</sup>), and sulphate of potash (0.90 g pot<sup>-1</sup>), respectively. All the amounts of phosphorus (P) and potassium (K) fertilizers were applied

at the time of pot filling, whereas N was applied in three splits: 1/3<sup>rd</sup> at sowing, 1/3<sup>rd</sup> at vegetative stage, and last 1/3<sup>rd</sup> at pod filling.

Plants were grown for 85 days and harvested to collect yield data and related attributes. Soil samples were collected from the pots at the time of harvesting for the determination of soil nutrients and bacterial population. Likewise, plant roots were collected for the determination of root fresh and dry weights and nodulation efficiency. These roots were washed with sterile water and blotted dry. Afterwards, root nodules per plant were counted, which were thus multiplied with number of plants to get nodulation per pot.

**Determination of nitrogen, phosphorus, potassium and boron in soil after plant harvest:** The collected soil samples from each pot were air-dried, and analyzed for soil nutrients. Total N in soil samples was measured using Kjeldahl distillation apparatus after extracting them in 2 M KCl solution. Likewise, available soil P was determined on spectrophotometer (C-7200 Peaks Instruments, Shanghai, China) at a wavelength of 880 nm using 0.5 M NaHCO<sub>3</sub> as an extracting material according the procedure described by Olsen *et al.* (1954). Extractable K was measured with the help of flame photometer (PFP 7, Jenway, London, UK) at wavelength of 767 nm using ammonium acetate as an extracting solution. Finally, available soil B was analyzed according to hot water extraction method. Azomethine-H solution was used a color developing reagent and then B concentrations were determined on spectrophotometer (C-7200, Peaks Instruments, Shanghai, China) at a wavelength of 410 nm (Berger and Truog, 1939).

**Determination of nitrogen, phosphorus, potassium and boron pea leaves:** For determination of P, K, and B in pea, leaf tissues (0.1 g of each sample) were dried, ground, and digested in an acid mixture (HNO<sub>3</sub>:HClO<sub>4</sub>; 4:1 v/v) until the clear solutions were obtained. Afterwards, collected digests were filtered, diluted with distilled water and subsequently used for analysis of B, P, and K at a spectrophotometer and flame photometer, respectively.

For total N analysis, plant material (0.1 g) was digested in H<sub>2</sub>SO<sub>4</sub> solution at a temperature of 200-250 °C for 4-5 h along with the addition of 10 drops of H<sub>2</sub>O<sub>2</sub> till the clear the solution was not achieved. Afterwards, acid-digests were diluted with distilled water to make final volume of 50 ml and used for plant N analysis with the help of Kjeldahl distillation apparatus.

**Determination of soil bacterial population after plant harvest:** The total bacterial population after plant harvest was measured according to the modified procedure as described by Masood *et al.* (2019). For this purpose, one gram fresh soil was shaken with 10 ml sterile water at a speed of 200 rpm for 4-5 h. Afterwards, 1 ml of soil

suspension containing bacterial population was put in 1.5 ml *Eppendorf* tubes and heat-shocked at 80 °C to discard non-sporulated microbes. Finally, 100 µl of serial dilutions of soil suspensions were spread on LB medium containing various antibiotics: purine, streptomycin, and putrecine di-hydrochloride (25 µg ml<sup>-1</sup>) and bacterial colonies were counted for total bacterial population in CFU g<sup>-1</sup> fresh soil.

**Experimental design and statistics:** Completely randomized design (CRD) was followed in our experiment. The means and analysis of variance (ANOVA) were computed in Statistix 8.1 software to compare the differences among means using Tukey's post-hoc test at  $p \leq 0.05$  level. Pearson's correlation coefficients were also obtained to exhibit association among the measured attributes at  $p < 0.001$ , 0.01, and 0.05 levels, respectively.

## RESULTS

**Plant growth:** In the absence of PGPR, compost application either alone or in combination with NPK fertilizers resulted in the improved plant growth when compared with the control (Table 1). Moreover, 100% compost supply although enhanced majority of the plant growth attributes but remained insignificant when compared with the 100% NPK. Combined application of compost and NPK fertilizers enhanced the plant height by 43%, 11%, and 16% as compared to control, 100% NPK, and 100% compost, respectively (Table 1). In general, plant height was maximum under co-application of compost and NPK followed by 100% NPK.

PGPR inoculation in any of the treatment combinations resulted in the improvement of plant growth traits when compared with the non-inoculated treatments (Table 1). PGPR-induced increase in root and shoot biomass of pea followed the same fashion as compost and NPK application improved the plant growth. PGPR inoculation under combined application of compost and NPK enhanced the plant height, root fresh and dry weights, shoot fresh and dry weights by 15%, 16%, 24%, 22%, and 21% when compared with their uninoculated 50% compost + 50% NPK (Table 1).

**Pea yield and related traits:** Without PGPR inoculation, either compost or NPK fertilization increased the pod length, number of pods and grain yield of pea when compared with the control (Table 2). NPK fertilization treatment resulted in the highest grain yield and related attributes after co-application of compost and NPK.

In the presence of PGPR, all the combinations produced higher pea yield as compared to their non-inoculated treatments (Table 2). Highest grain yield was obtained when pea plants were inoculated with PGPR under combined application of compost and NPK. Furthermore, PGPR-inoculation in conjunction with

compost and NPK improved the pea grain yield by 7% as compared to non-inoculated 50% compost + 50% NPK (Table 2).

**Nodulation:** Under non-inoculated conditions, compost application remained superior in producing maximum number of nodules  $\text{pot}^{-1}$  (Fig. 1). Nodules formation in pea plants was same when compost treatment was compared with 100% NPK and therefore, co-provision of compost and NPK enhanced the number of nodules by 233%, 131%, and 98% as compared to control, NPK, and compost, respectively (Fig. 1).

PGPR-inoculation in any treatment combinations resulted in the increased number of nodules in pea plants (Fig. 1). A linear relationship in the nodules formation was observed with the compost application when inoculated compost treatments were compared with inoculated control and NPK treatments. Similarly, PGPR supply under co-provision of compost and NPK improved the nodulation by 114%, 81%, 96%, and 27% when compared with their non-inoculated 50% compost + 50% NPK.

**Soil bacterial population:** Without PGPR, only compost supply influenced the soil bacterial population either when compared with the control or NPK (Fig. 2). Bacterial population ( $\text{CFU g}^{-1}$  fresh soil) increased by PGPR inoculation when compared with their un-

inoculated treatments and maximum no. of colony forming units were observed in T8 followed by T6.

**Soil organic matter and nutrients concentrations:** Regardless of PGPR inoculation or not, compost application improved the SOM, macronutrients (N, P, and K) and micronutrient (B) when compared with control (Table 3). There was only a slight increase in soil N, P, and K concentrations by the application of 100% NPK both with and without PGPR when compared with 100% compost, but combined application of 50% compost and 50% NPK both with and without PGPR resulted in the maximum SOM and nutrients (N, P, and K) concentrations as compared to either control or 100% compost (Table 3). In general, inoculated treatment combinations improved the SOM and soil nutrients (N, P, K, and B) concentrations as compared to their non-inoculated treatments.

Leaf nutrients (N, P, K, and B) concentrations were influenced in similar fashion as of soil nutrients concentrations (Table 4). Chemical fertilization i.e. 100% NPK though resulted in a bit higher uptake of nutrients by pea, compost application, especially at the rate 50% along with 50% NPK both with and without PGPR inoculation enhanced N, P, K, and B uptake by pea as compared to either control or 100% compost (Table 4).

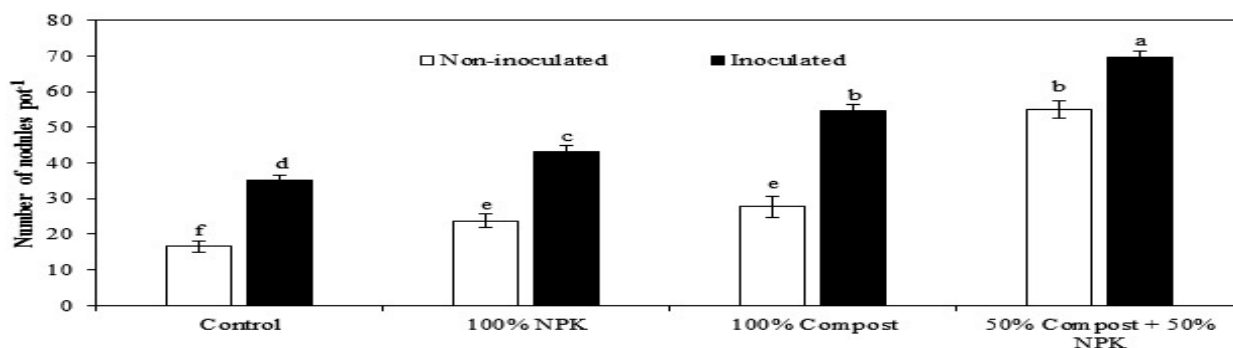


Fig. 1. The effect of integrated supply of compost, chemical fertilizers, and PGPR on root nodulation potential in pea. All the values are means, whereas letters indicate significant differences among the treatments  $\pm$  standard error of four replicates at  $p \leq 0.05$  level.

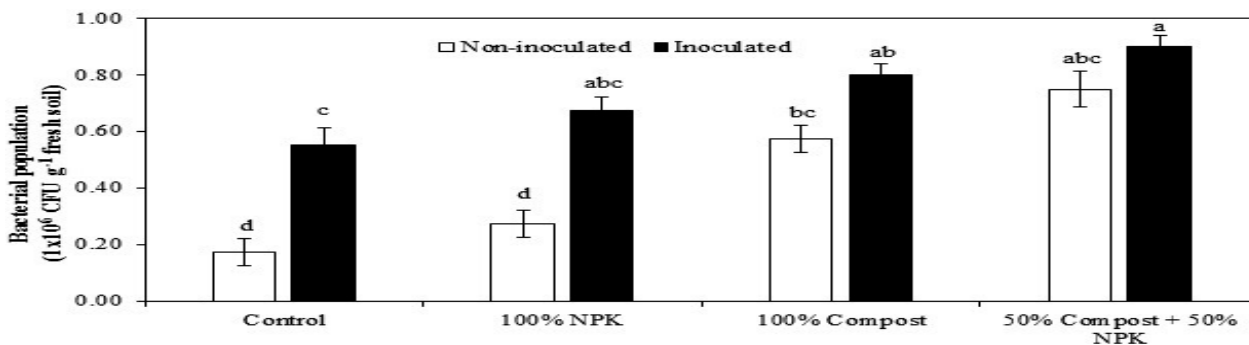


Fig. 2. The effect of integrated supply of compost, chemical fertilizers, and PGPR on soil bacterial population after plant harvest ( $1 \times 10^6 \text{ CFU g}^{-1}$  fresh soil). All the values are means, whereas letters indicate significant differences among the treatments  $\pm$  standard error of four replicates at  $p \leq 0.05$  level.

**Table 1. Plant growth attributes as influenced by integrated supply of compost, PGPR, and NPK fertilization**

	Non-inoculated					Inoculated				
	Plant height (cm)	Root fresh weight (g pot <sup>-1</sup> )	Shoot fresh weight (g pot <sup>-1</sup> )	Root dry weight (g pot <sup>-1</sup> )	Shoot dry weight (g pot <sup>-1</sup> )	Plant height (cm)	Root fresh weight (g pot <sup>-1</sup> )	Shoot fresh weight (g pot <sup>-1</sup> )	Root dry weight (g pot <sup>-1</sup> )	Shoot dry weight (g pot <sup>-1</sup> )
Control	79.37±1.12 <sup>g</sup>	6.21±0.29 <sup>e</sup>	11.46±0.45 <sup>f</sup>	2.51±0.20 <sup>g</sup>	4.51±0.08 <sup>f</sup>	89.86±1.51 <sup>f</sup>	8.05±0.12 <sup>e</sup>	17.24±0.32 <sup>e</sup>	3.12±0.06 <sup>f</sup>	6.18±0.09 <sup>e</sup>
100% NPK	102.24±1.26 <sup>de</sup>	11.02±0.43 <sup>d</sup>	21.53±0.37 <sup>d</sup>	4.04±0.04 <sup>e</sup>	8.07±0.07 <sup>d</sup>	117.19±1.63 <sup>b</sup>	14.71±0.74 <sup>c</sup>	29.35±0.73 <sup>c</sup>	5.58±0.12 <sup>c</sup>	11.55±0.33 <sup>c</sup>
100% Compost	98.04±1.19 <sup>e</sup>	11.44±0.41 <sup>d</sup>	23.94±0.54 <sup>d</sup>	4.56±0.13 <sup>d</sup>	8.99±0.14 <sup>d</sup>	108.55±2.27 <sup>cd</sup>	15.04±0.55 <sup>c</sup>	29.08±0.48 <sup>c</sup>	5.47±0.07 <sup>c</sup>	10.94±0.24 <sup>c</sup>
50% Compost + 50% NPK	113.70±2.17 <sup>bc</sup>	17.90±0.52 <sup>b</sup>	33.56±0.87 <sup>b</sup>	6.41±0.05 <sup>b</sup>	12.88±0.33 <sup>b</sup>	130.91±1.29 <sup>a</sup>	20.71±0.36 <sup>a</sup>	41.07±0.68 <sup>a</sup>	7.97±0.08 <sup>a</sup>	15.67±0.29 <sup>a</sup>

Lowercase letters exhibit significant differences among the treatment means, whereas all the values are means ± standard error of four replicates at p≤0.05 level

**Table 2. Yield-related attributes and grain yield of pea as influenced by integrated supply of compost, PGPR, and NPK fertilization**

	Non-inoculated					Inoculated				
	Pod length (cm)	No. of pods pot <sup>-1</sup>	100-grain weight (g)	Grain yield (g pot <sup>-1</sup> )	Pod length (cm)	No. of pods pot <sup>-1</sup>	100-grain weight (g)	Grain yield (g pot <sup>-1</sup> )		
Control	3.88±0.07 <sup>g</sup>	22.50±0.65 <sup>e</sup>	42.94±0.50 <sup>e</sup>	131.98±5.03 <sup>f</sup>	4.47±0.09 <sup>f</sup>	26.50±0.71 <sup>d</sup>	54.92±1.16 <sup>d</sup>	148.28±1.73 <sup>e</sup>		
100% NPK	6.12±0.06 <sup>c</sup>	32.50±0.61 <sup>c</sup>	64.79±1.52 <sup>c</sup>	180.64±3.74 <sup>c</sup>	8.36±0.10 <sup>c</sup>	36.75±0.89 <sup>ab</sup>	74.24±1.08 <sup>b</sup>	198.68±2.87 <sup>b</sup>		
100% Compost	5.60±0.13 <sup>e</sup>	28.75±0.85 <sup>d</sup>	56.21±1.00 <sup>d</sup>	174.62±3.10 <sup>d</sup>	7.58±0.13 <sup>d</sup>	32.25±0.68 <sup>c</sup>	62.16±0.88 <sup>c</sup>	197.12±3.98 <sup>b</sup>		
50% Compost + 50% NPK	9.51±0.17 <sup>b</sup>	36.00±0.91 <sup>b</sup>	71.23±1.27 <sup>b</sup>	206.53±6.52 <sup>b</sup>	11.00±0.16 <sup>a</sup>	39.50±0.63 <sup>a</sup>	80.58±0.82 <sup>a</sup>	221.40±4.12 <sup>a</sup>		

Lowercase letters exhibit significant differences among the treatment means, whereas all the values are means ± standard error of four replicates at p≤0.05 level

**Table 3. Soil fertility and mineral concentrations after plant harvest as influenced by integrated supply of compost, PGPR, and NPK fertilization**

	Non-inoculated					Inoculated				
	% SOM					% SOM				
	N	P	K	B	N	P	K	B		
Control	0.85±0.03 <sup>e</sup>	362±3.50 <sup>e</sup>	7.58±0.20 <sup>e</sup>	166±2.10 <sup>f</sup>	0.49±0.01 <sup>e</sup>	9.25±0.11 <sup>d</sup>	172±1.49 <sup>ef</sup>	0.62±0.02 <sup>cd</sup>		
100% NPK	0.93±0.02 <sup>de</sup>	421±5.21 <sup>bc</sup>	10.57±0.21 <sup>abc</sup>	187±3.20 <sup>bcd</sup>	0.57±0.02 <sup>d</sup>	11.00±0.08 <sup>a</sup>	196±2.14 <sup>ab</sup>	0.64±0.02 <sup>cd</sup>		
100% Compost	1.03±0.02 <sup>cd</sup>	399±3.22 <sup>d</sup>	10.02±0.04 <sup>c</sup>	180±1.65 <sup>de</sup>	0.71±0.01 <sup>bc</sup>	10.62±0.09 <sup>ab</sup>	192±2.53 <sup>abc</sup>	0.77±0.01 <sup>ab</sup>		
50% Compost + 50% NPK	1.10±0.03 <sup>bc</sup>	410±1.51 <sup>cd</sup>	10.24±0.06 <sup>bc</sup>	184±2.58 <sup>cd</sup>	0.73±0.01 <sup>b</sup>	11.04±0.05 <sup>a</sup>	201±1.55 <sup>a</sup>	0.82±0.01 <sup>a</sup>		

Lowercase letters exhibit significant differences among the treatment means, whereas all the values are means ± standard error of four replicates at p≤0.05 level

Here SOM= Soil organic matter; N= Nitrogen; P= Phosphorus; K= Potassium; B= Boron

Table 4. Nutrient uptake by pea as influenced by integrated supply of compost, PGPR, and NPK fertilization

	Non-inoculated				Inoculated			
	mg g <sup>-1</sup> dry weight		µg g <sup>-1</sup> dry weight		mg g <sup>-1</sup> dry weight		µg g <sup>-1</sup> dry weight	
	N	P	K	B	N	P	K	B
Control	19.82±0.21 <sup>f</sup>	1.09±0.03 <sup>f</sup>	13.59±0.31 <sup>f</sup>	12.19±0.22 <sup>f</sup>	22.51±0.21 <sup>e</sup>	1.39±0.01 <sup>e</sup>	17.47±0.20 <sup>d</sup>	16.19±0.12 <sup>c</sup>
100% NPK	23.79±0.18 <sup>cd</sup>	1.38±0.03 <sup>e</sup>	18.66±0.14 <sup>cd</sup>	18.26±0.12 <sup>bc</sup>	26.60±0.28 <sup>ab</sup>	1.42±0.02 <sup>de</sup>	19.46±0.14 <sup>c</sup>	18.57±0.20 <sup>ab</sup>
100% Compost	23.24±0.20 <sup>d</sup>	1.53±0.02 <sup>cd</sup>	17.62±0.20 <sup>d</sup>	17.24±0.07 <sup>d</sup>	24.26±0.20 <sup>b</sup>	1.68±0.04 <sup>b</sup>	23.99±0.65 <sup>b</sup>	18.53±0.15 <sup>ab</sup>
50% Compost + 50% NPK	23.58±0.28 <sup>d</sup>	1.60±0.02 <sup>bc</sup>	16.19±0.24 <sup>e</sup>	17.62±0.20 <sup>cd</sup>	29.67±0.25 <sup>a</sup>	1.82±0.02 <sup>a</sup>	25.12±0.43 <sup>a</sup>	19.16±0.11 <sup>a</sup>

Lowercase letters exhibit significant differences among the treatment means, whereas all the values are means ± standard error of four replicates at p≤0.05 level

Here N= Nitrogen; P= Phosphorus; K= Potassium; B= Boron

Table 5. Pearson's correlation matrix exhibiting significant interaction among the studied attributes at p<0.05, 0.011, and 0.001 levels.

	Plant height	No. of nodules	Root FW	Shoot FW	Shoot DW	Root DW	Shoot DW	Pod length	No. of Pods	100 g grain weight	Grain yield	SOM	Total N	Soil P	Soil K	Soil B	CFU	Leaf N	Leaf P	Leaf K	Leaf B		
Plant height	1.000	****	****	****	****	****	****	****	****	****	*	****	****	****	****	****	****	****	****	****	****	****	
No. of nodules	0.920	1.000	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	
Root FW	0.936	0.990	1.000	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	
Shoot FW	0.925	0.988	0.993	1.000	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	
Root DW	0.946	0.990	0.996	0.995	1.000	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	
Shoot DW	0.941	0.978	0.959	0.967	0.972	1.000	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	
Pod length	0.981	0.878	0.886	0.860	0.913	0.972	1.000	****	****	****	****	****	****	****	****	****	****	****	****	****	****	****	
No. of pods	0.958	0.821	0.841	0.812	0.849	0.872	0.986	1.000	****	****	****	****	****	****	****	****	****	****	****	****	****	****	
100 g grain weight	0.953	0.947	0.949	0.922	0.948	0.941	0.941	0.882	1.000	****	****	****	****	****	****	****	****	****	****	****	****	****	
Grain yield	0.465	0.715	0.712	0.717	0.672	0.579	0.579	0.271	0.601	0.601	1.000	ns	Ns	ns	***	ns	ns	ns	ns	ns	ns	ns	
SOM	0.868	0.694	0.712	0.681	0.720	0.700	0.700	0.833	0.869	0.869	0.285	1.000	****	****	ns	****	****	****	****	****	****	****	****
Total N	0.767	0.595	0.642	0.569	0.629	0.559	0.559	0.792	0.812	0.812	0.247	0.911	1.000	****	*	****	****	****	****	****	****	****	****
Soil P	0.869	0.682	0.702	0.683	0.715	0.697	0.697	0.821	0.844	0.844	0.274	0.993	0.869	1.000	ns	****	****	****	****	****	****	****	****
Soil K	0.527	0.703	0.736	0.699	0.685	0.544	0.544	0.387	0.686	0.686	0.917	0.420	0.518	0.381	1.000	ns	ns	ns	ns	ns	ns	ns	ns
Soil B	0.866	0.769	0.733	0.746	0.757	0.834	0.834	0.815	0.819	0.819	0.321	0.861	0.618	0.878	0.265	1.000	****	****	****	****	****	****	****
CFU	0.653	0.513	0.473	0.430	0.480	0.610	0.610	0.793	0.612	0.612	0.041	0.649	0.611	0.611	0.037	0.739	1.000	ns	****	****	****	****	****
Leaf N	0.608	0.599	0.663	0.583	0.637	0.528	0.528	0.656	0.672	0.672	0.353	0.473	0.724	0.405	0.644	0.192	0.356	1.000	*	****	****	****	****
Leaf P	0.573	0.263	0.351	0.294	0.340	0.311	0.311	0.717	0.433	0.433	0.151	0.624	0.739	0.623	0.107	0.389	0.561	0.546	1.000	****	****	****	****
Leaf K	0.440	0.152	0.245	0.182	0.250	0.205	0.205	0.608	0.311	0.311	0.339	0.443	0.631	0.426	0.024	0.152	0.416	0.658	0.886	1.000	****	****	****
Leaf B	0.558	0.524	0.604	0.521	0.574	0.440	0.440	0.604	0.620	0.620	0.329	0.465	0.736	0.402	0.646	0.127	0.274	0.988	0.588	0.691	1.000	****	****

\*\*\*\*= significant at p<0.001

\*\*= significant at p<0.01

\*= significant at p<0.05

ns= not-significant

## DISCUSSION

In the present study, synergism was observed between compost and NPK both with and without PGPR inoculation for improving plant growth. This synergistic interaction among the aforesaid amendments provides a suitable soil-plant-microbial environment for integrated nutrient management, contributing to an increase in plant yield and other plant growth traits (Muhammad *et al.*, 2025). Previously, Tahiri *et al.* (2022) reported that PGPR inoculation in compost-amended soil improved the tomato growth and yield. Similarly, tomato plants showed an improvement in plant growth traits when inoculated with *Bacillus pumilus* under NPK fertilization (Masood *et al.*, 2020).

As compost and PGPR improved the root proliferation in the current study, the enhancement in root biomass possibly attributed to more space for nutrient absorption, thereby promoting growth of pea plants (Aziz *et al.*, 2024). Moreover, the effects of co-application of organic and inorganic amendments are often appeared in the form of improved grain yield. Organic amendments like compost improves soil fertility by promoting soil organic matter decomposition and soil aggregation (Ma *et al.*, 2020). The increased plant yield under combined application of chemical fertilizers and organic amendments is thus related to higher root proliferation that resulted in higher nutrient uptake by the plants (Table 5) and water absorption from deep soil layers (Sowmya and Ganapthy, 2021; Muhammad *et al.*, 2023).

It is well known that compost is a rich source of carbon for microbes, which possibly enhances soil organic carbon and plant nutrients, thereby contributing to an improvement in soil enzymes activities and crop productivity (Hafez *et al.*, 2021; Tortosa *et al.*, 2018). It has also been reported that compost is used as a carrier material for bacterial inoculation in cereals to improve microbial activities (Singh *et al.*, 2019). Studies have revealed that compost application improved the root nodulation in soybean plants when inoculated with *Bradyrhizobium diazoefficiens* and *Bacillus subtilis* (Tortosa *et al.*, 2023; Moraes *et al.*, 2025). Similarly, Ulzen *et al.* (2020) and Ben-Laouane *et al.* (2021) reported that soybean and *Medicago sativa* plants when inoculated with *Bradyrhizobium* and *Rhizobium* in a soil amended with fertisol and quack grass compost had a higher root nodulation as compared to un-inoculated plants. In the present study, bacterial population after plant harvest was enhanced when inoculated with PGPR under compost and NPK-amended soil as compared to non-inoculated plants (Fig. 2). The higher soil bacterial population under combined application of PGPR and compost occurred due to more root nodulation ( $r=0.513$  at  $p<0.05$ , Table 5). The enhanced soil bacterial population under chemical fertilizers application and PGPR inoculation has been reported in rapeseed and

tomato (Masood *et al.*, 2019, 2020). Therefore, the results of the present investigation support our hypothesis that integrated use of compost, PGPR, and NPK fertilizers enhances root nodulation that occurred due to improved soil microbial activity.

The combined application of organic amendments and chemical fertilizers usually minimizes the need of chemical fertilizers without compromising the need of plants. In the present study, combined application of compost and NPK fertilizers reduced 50% of the demand of chemical fertilizers either with or without PGPR inoculation. This decreased demand of NPK fertilizers occurred due to higher organic matter, soil aggregation, moisture content, and nutrient mineralization (Majeed *et al.*, 2024, 2025). Since organic matter serves as a food for microorganisms (Tortosa *et al.*, 2023), increased microbial activity as a result of organic matter decomposition further plays a crucial role soil key processes like N mineralization, and P-solubilization (Wei *et al.*, 2024).

The increased nutrients (N, P, K, and B) uptake by pea plants under combined application of compost and PGPR in NPK-fertilized soil occurred due to enhanced carbon availability (SOM) fostering rhizobacterial proliferation (Hye *et al.*, 2020). The enhancement in nutrient use efficiency and nutrient accumulation in plants shoots by the application of humic acid and compost in NPK-fertilized soil has been reported (Muhammad *et al.*, 2023). Similarly, combined application of organic and inorganic amendments resulted in the increased nutrient uptake by rapeseed (Liu *et al.*, 2022). Because of pot experiment, we were able to monitor rhizobial proliferation and its relationship with pea yield. However, certain limitations may occur under diverse field conditions such soil type, compost quality, and differences in PGPR strains (Wang *et al.*, 2023). Therefore, application and optimization of PGPR, compost, and NPK rates under different field conditions is required to support root microbial-ecology-related effects on plant growth and yield.

**Conclusions and recommendations:** Individually, both compost and PGPR improved the pea growth and yield, whereas synergistic interaction was observed between compost and PGPR under NPK-fertilized soil for enhancing pea growth and yield. Furthermore, 50% compost in conjunction with PGPR inoculation minimized the chemical fertilizers demand by 50% and resulted in the maximum pea yield. The enhancement in pea growth and yield occurred due to improved nodulation by the co-provision of compost and NPK fertilizers both with and without PGPR. This integrated approach of using organic and inorganic fertilizers together further improved the soil organic matter that contributed to higher bacterial population, which thus enhanced the nutrient availability and soil-plant system.

Our results suggest that potential of PGPR and compost must be evaluated in field conditions for sustainable crop production.

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