



RESEARCH ARTICLE

# Enhancing green gram yield and soil nutrient status through organic inputs in dominant soil orders of the NEH region

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## Abstract

The North Eastern Hill (NEH) region of India is renowned for its rich biodiversity and predominance of low-input, chemical-free agricultural practices. In this context, the use of organic inputs is crucial for improving soil fertility and enhancing crop productivity. Keeping these aspects in view, a factorial pot experiment was conducted during the wet season of 2024 to evaluate the effect of different organic manures on green gram (*Vigna radiata* (L.) R. Wilczek var. Pant Moong 6) grown in four dominant soil orders of the NEH region, namely Alfisols, Ultisols, Inceptisols and Entisols. Seven organic manure treatments pig manure, poultry manure, compost, vermicompost, neem cake and farmyard manure (FYM) along with an untreated control were evaluated in a factorial completely randomised design (F-CRD) with three replications. The results revealed that poultry manure significantly enhanced yield attributes of green gram, particularly the number of pods per plant, which translated into a 47.87 % increase in pod yield compared to the control. Irrespective of the compost treatments, green gram performance remained comparable across all soil orders, indicating uniform crop response under organic management. Furthermore, the application of poultry manure and pig manure significantly improved soil available nitrogen, phosphorus and potassium compared to the control, FYM and vermicompost treatments. Overall, the study suggests that poultry manure is a promising organic input for improving green gram yield and soil nutrient status across different soil orders under chemical-free farming systems of the NEH region. However, further validation under field conditions across varied soil types and climatic conditions is recommended.

**Keywords:** Eastern Himalaya; green gram; organic amendments; soil orders

## Introduction

Global pulses production increased at a rate of 1 % per annum during the 21<sup>st</sup> century (1). The demand for pulses has been increasing steadily, causing a gap between production and consumption. This gap might increase because of an increase in population, leading to more consumption. India, the second most populous country in the world, will require around 39 million tonnes of total pulses by 2050 (2). Asia produces the maximum pulse ( $2.9 \times 10^{10}$  kg), whereas the productivity is highest in Europe ( $> 2 \times 10^1$  kg m<sup>-2</sup>). India is the largest producer of pulses, accounting for 25 % of total pulse production, occupying an area of  $3.05 \times 10^{11}$  m<sup>2</sup> with an average productivity of  $0.66 \times 10^1$  kg m<sup>-2</sup> (2). Green gram [*Vigna radiata* (L.) R. Wilczek] provides 14 % of total protein intake and excellent source of high-quality protein (25 %), 1 % fat, 4 % minerals, 4 % fibre and 57 % carbohydrates. The protein content is > 2 times that of cereals (3). Green gram is widely adopted and acclimatised in a wide range of agroclimatic zones (4).

Eastern Himalaya region encompassing northeastern (NE) India, is characterised by a subtropical climate where green gram (mung bean) is cultivated on hill slopes, jhum lands, terraces and plains with minimum nutrient supply during kharif—the monsoon cropping season in South Asia which typically

spans from June to October. The crop is highly responsive to nutrients supply. Locally available nutrient sources such as compost, farmyard manure (FYM), poultry and pig manures and vermicompost or biofertilisers such as *Rhizobium* have been traditionally employed for soil fertility enhancement and sustaining rural livelihoods. Aligning with recent innovations, silica nanoparticles synthesised via an acidic sol-gel method from coir pith have been demonstrated to improve germination economics in legumes. Concurrently, biochar application significantly mitigates soil N<sub>2</sub>O emission by facilitating microbial denitrification pathways and optimising nitrogen use efficiency, thus contributing to economic and environmental sustainability of fertiliser use (5). However, scientific quantification of these organic amendments on green gram productivity and soil fertility remains limited across diverse soil orders. Total geographical area (TGA) of Meghalaya is approximately  $2.24 \times 10^{10}$  m<sup>2</sup>, with about 10 % under cultivation (6); cereals dominate land use with rice occupying 44 %. Pulses cover about  $8.5 \times 10^7$  m<sup>2</sup> along with production of  $1.25 \times 10^7$  kg (7).

Recent studies highlight the importance of organic amendments for improving pulse crop productivity and soil health in mountainous ecosystem. Farmyard manure, compost, vermicompost, poultry manure, pig manure, neem cake and

other organic sources have demonstrated significant positive effects on legume growth and yield through enhanced soil enzymatic activities, nutrient availability and carbon stock in acidic soils of the Eastern Himalaya (8). Micro-structural shocks analysis reveals that technology shocks drive private investment responses, understanding that sustainable agriculture innovations must demonstrate superior risk-adjusted returns to attract capital during economic volatility (9). While, for organic amendments to achieve widespread adoption, they must align with investor preferences for high return, low risk profiles as identified in portfolio optimisation framework, with Sharpe ratios  $> 1$  for agricultural investments (10). Biochar amendments significantly enhanced soil water retention, increasing available water capacity by 28 %, field capacity by 20 % and total porosity by 9 % across soil textures, particularly benefiting coarse soils common in mountainous regions (11).

Biowaste biorefineries, the alternative for biowaste valorisation achieve 74 % profit elevation and 6 years payback through on-site enzyme production coupled with solid-state fermentation of organic municipal waste, reducing policy dependence while remaining energy self-sufficient (12). Whereas insect rearing on biowaste offers fish farmers competitive advantages, with black soldier fly larvae converting organic waste to 75–80 % protein feed and replacing 40–50 % fishmeal, complementing organic amendments for circular bioeconomy integration in pulse production systems (13). In Central Europe, the insect feed market is projected to grow from US\$1537 million by 2025 to over US\$1201.9 million, driven by industrial scale-up of black soldier fly and mealworm production that convert organic waste into sustainable protein, making insect-based feeds increasingly competitive with conventional sources for aquaculture and livestock. The environmental economic nexus demands profitable nutrient management for pulse production under climate stress, where erratic rainfall and temperature extremes reduce yield by 20–40 % (14). Application of organic matter either in the form of crop residue or organic amendment has a significant influence on crop performance (15, 16) and soil fertility (17). Many literature studies are available on the effect of organic amendments on soil properties. However, its effect on crop performance, particularly in these soil orders of Meghalaya, have not been thoroughly investigated. Hence, the present study attempts to identify a suitable organic amendment for their effects on growth and yield of green gram and soil fertility under diverse soil orders (Alfisols, Ultisols, Entisols and Inceptisols) in the Eastern Himalaya, addressing an urgent need to reinforce the environmental-economic nexus for sustainable pulse production.

## Materials and Methods

### Experimental setup

A pot experiment was conducted under controlled greenhouse condition at the College of Post Graduate Studies in Agricultural Sciences (CPGS-AS), Umiam, Meghalaya during kharif 2024. The experiment contains the factors-1 comprised of the four orders: O<sub>1</sub>: Alfisol, O<sub>2</sub>: Entisol, O<sub>3</sub>: Inceptisol and O<sub>4</sub>: Ultisol. Similarly, the factors-2 comprised of the 7 treatments are: T<sub>1</sub>: control, T<sub>2</sub>: FYM, T<sub>3</sub>: compost, T<sub>4</sub>: vermicompost, T<sub>5</sub>: neem cake, T<sub>6</sub>: poultry manure and T<sub>7</sub>: pig manure (Table 1) with 28 treatment combinations laid out in factorial completely randomised design (F-CRD). Uniform sized pots (capacity 10 kg) were filled with 8 kg of processed soil. In each pot, four to five seeds were initially sown; thereafter, two to three plants were maintained to ensure for observation. Green gram was used as a test crop. These organic manures were mixed into the soil at a constant rate of 40 kg ha<sup>-1</sup> phosphorus. These organic amendments were applied into the soil just seven days before sowing. All the organic amendments used in the experiment were well decomposed prior to incorporation and the actual mass of each amendment applied per pot given in Table 1. The moisture at field capacity (29.32 % w/w) throughout the crop growing period and the loss of water due to evaporation was compensated by adding with the appropriate volume of water at every 7 days interval. Temperature and relative humidity during crop growing season varies from 11.7–21.6 °C and 76–87.15 % respectively.

### Agro-climatic zone

The Eastern Himalaya region of agroclimatic zone consists of all the north eastern states such as Meghalaya, Arunachal Pradesh, Hills of Assam, Nagaland, Tripura, Mizoram, Manipur and Sikkim, having rainfall  $> 2000$  mm with average annual temperature varies from 15–32 °C in summer and 0–26 °C in winter (7) and approximately 85 % of the total cultivation area in North East India is covered by shifting cultivation (18).

### Soil type

The physico-chemical properties of soil used for the experiment are presented in Table 2. Major soil order are Ultisol [1.16 mha (51.7 % of TGA of Meghalaya) bulk density (BD): 1.02 g cm<sup>-3</sup>, pH 4.8, organic carbon (OC) : 1.39 %, Available nitrogen (Av. N) : 223.4 kg ha<sup>-1</sup>, Available phosphorus (Av. P) : 6.69 kg ha<sup>-1</sup> and Available potassium (Av. K) : 190 kg ha<sup>-1</sup>]  $>$  Inceptisol [0.83 mha (30.7 % of TGA of Meghalaya) (BD : 1.0 g cm<sup>-3</sup>, pH 5.1, OC : 1.28 %, Av. N : 234.1 kg ha<sup>-1</sup>, Av. P : 12.5 kg ha<sup>-1</sup> and Av. K : 198.6 kg ha<sup>-1</sup>)]  $>$  Entisol [0.25 mha (11.3 % of TGA of Meghalaya) (BD : 1.32 g cm<sup>-3</sup>, pH 4.3, OC 1.1 %, Av. N : 213.0 kg ha<sup>-1</sup>, Av. P : 7.32 kg ha<sup>-1</sup> and Av. K : 189.8 kg ha<sup>-1</sup>)]  $>$  Alfisol [0.14 mha (6.3 % of TGA of Meghalaya)

**Table 1.** Details of experiment

| Details         |                | Symbol                          |
|-----------------|----------------|---------------------------------|
| <b>Factor-1</b> |                |                                 |
| Alfisol         |                | O <sub>1</sub>                  |
| Entisol         |                | O <sub>2</sub>                  |
| Inceptisol      |                | O <sub>3</sub>                  |
| Ultisol         |                | O <sub>4</sub>                  |
| <b>Factor-2</b> |                | <b>Mass applied per pot (g)</b> |
| T <sub>1</sub>  | Control        | 0                               |
| T <sub>2</sub>  | FYM            | 35.0                            |
| T <sub>3</sub>  | Compost        | 27.32                           |
| T <sub>4</sub>  | Vermicompost   | 25.0                            |
| T <sub>5</sub>  | Neem cake      | 13.82                           |
| T <sub>6</sub>  | Poultry manure | 11.57                           |
| T <sub>7</sub>  | Pig manure     | 12.75                           |

**Table 2.** Physico-chemical properties of different soil orders

| Sl. No. | Physico-chemical properties of soil |             |                 |                          |     |        |                              |                              |                              |
|---------|-------------------------------------|-------------|-----------------|--------------------------|-----|--------|------------------------------|------------------------------|------------------------------|
|         | Order                               | Soil colour | Soil texture    | BD (g cm <sup>-3</sup> ) | pH  | OC (%) | Av. N (kg ha <sup>-1</sup> ) | Av. P (kg ha <sup>-1</sup> ) | Av. K (kg ha <sup>-1</sup> ) |
| 1       | Alfisol                             | 7.5YR 4/6   | Sandy loam      | 0.95                     | 5.5 | 1.43   | 293.2                        | 9.27                         | 202.8                        |
| 2       | Entisol                             | 10YR 4/2    | Sandy loam      | 1.32                     | 4.3 | 1.1    | 213.0                        | 7.32                         | 189.8                        |
| 3       | Inceptisol                          | 10YR 3/2    | Sandy clay loam | 1.0                      | 5.1 | 1.28   | 234.1                        | 12.5                         | 198.6                        |
| 4       | Ultisol                             | 7.5 YR 4/6  | Sandy loam      | 1.02                     | 4.8 | 1.39   | 223.4                        | 6.69                         | 190                          |

BD: bulk density; OC: organic carbon; Av. N: available nitrogen; Av. P: available phosphorus; Av. K: available potassium.

(BD : 0.95 g cm<sup>-3</sup>, pH 5.5, OC : 1.43 %, Av. N : 293.2 kg ha<sup>-1</sup>, Av. P : 9.27 kg ha<sup>-1</sup> and Av. K : 202.8 kg ha<sup>-1</sup>) and 2.43 mha (19).

### Soil sampling and processing

A field survey is carried out using soil map (1 : 250000 scale) (NBSSLUP, 2005) and Google image/SENTINEL 2 data, integrate the slope map and soil map in QGIS vs.3.42.4. The sampling sites were located using GPS (accuracy  $\pm$  5 m), a total of 160 composite soil samples at 0–15 cm depth collected from various soil orders (1 : 250000 scale). From each soil order, 40 representative samples were collected, with these 40 samples considered to be representative of the respective soil order. After collecting a composite soil sample, samples were air-dried by spreading on a clean surface and placing them in a shaded area to avoid nutrient loss. After drying, samples were grounded and crushed gently to break clods using a mortar and pestle and passed through 2 mm sieve to remove stone and very coarse particles. After grinding, soil amendments are applied as previously decided. Before application of soil amendments, the soil physical, chemical properties were analysed.

### Organic amendments characterisation

The initial nutrient content of the organic amendments viz., total N, total P and total K were estimated prior to incorporation into the soil as treatments. The nutrient content of organic amendments used for the experiment are presented in Table 3. Total nitrogen was determined by the modified Micro-Kjeldahl digestion, distillation and the titration method as described by Jackson (20), total P was determined by the digestion method with perchloric acid method of Jackson (21). Total K was estimated by tri-acid digestion extract with the help of flame photometer as described by Jackson (21).

### Soil analysis

The colour of the soil was determined by Munsell colour chart (22). The particle size distribution of soil was determined by international pipette method (23). The BD of the soil was derived mathematically from the mean water holding capacity (MWHC) determined by Keen Raczkwaki Box as described by Baruah and Borthakur (24). It was estimated using the following formula.

$$\text{BD (g cm}^{-3}\text{)} = \frac{\text{Oven dry weight of the soil equilibrated with water for MWHC determination}}{\text{Volume of the air dry soil (= volume of keen box)}} \times 100$$

The pH of the soils was measured in soil water suspension (1 : 2.5) using a combined glass electrode (Mettler Toledo, Switzerland) as given by Jackson (21). Organic carbon was determined by the rapid titration method of Walkley and Black (25). Soils (0.5 g) of 0.2 mm sieve was mixed with 10 mL of 1 N K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> and 20 mL of concentrated H<sub>2</sub>SO<sub>4</sub> in a 500 mL conical flask and stood for 30 min. After oxidation, 200 mL of distilled water and 10 mL of H<sub>3</sub>PO<sub>4</sub> was added and then the residual K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> in the flask was titrated with freshly prepared 0.5 N ferrous ammonium sulphate in presence of diphenylamine indicator. Available N in soils was determined by the modified alkaline potassium permanganate method (Subbiah and Asija) (26). A 5 g of soil was taken in Kjeldahl tube and added 25 mL of 0.32 % KMnO<sub>4</sub> and 25 mL of 2.5 % NaOH. Then the mixture was distilled for 6 min in an automated distillation chamber (Classic DX, Pelican Equipment, Chennai). The ammonia gas generated during distillation was collected in 20 mL of 2 % boric acid and the amount of boric acid used for absorption of ammonia was determined by titrating with standardised 0.02 N H<sub>2</sub>SO<sub>4</sub>. Available P was determined by Bray No-1 P (0.03 N NH<sub>4</sub>F + 0.025 N HCl) method of Bray and Kurtz (27). Air dried soil samples were sieved with 2 mm sieve and took 5 g soil with 50 mL Bray No-1 P extractant and shaken for 5 min in a reciprocating shaker. Soil suspension was filtered through Whatman No. 42 and 5 mL of the supernatant filtrate was used for developing blue colour using Dickman Bray's reagent and stannous chloride. The blue colour intensity was measured at 660 nm (Spectrascan UV-2600, Thermo Scientific, USA) and concentration of P was read from the standard curve. Available K was determined by the ammonium acetate method—Hanway and Heidel (28). An air-dried soil (5 g) was extracted with 25 mL of 1 N ammonium acetate (pH 7) by shaking 5 min in a reciprocating shaker. Then, the soil suspension was filtered through Whatman No. 1 and the concentration was measured using a flame photometer.

### Plant parameters

Three to four mung bean seeds are sown in each pot and the crop performance is monitored and studied under different soil orders. Growth and yield components [plant height at 30, 45, 60 days after sowing (DAS) and at harvest], number of leaves per plant, number of branches per plant, days required for first flower initiation, number of nodules per plant (30, 45 and 60 DAS), number of pods per plant, number of seeds per pod, number of seeds per plant and yield (g per pot) were measured.

**Table 3.** Characterisation of organic amendments used for the pot experiment

| Organic amendments | Total N (%) | Total P (%) | Total K (%) |
|--------------------|-------------|-------------|-------------|
| FYM                | 0.713       | 0.401       | 0.610       |
| Compost            | 0.583       | 0.523       | 0.782       |
| Vermicompost       | 0.801       | 0.571       | 1.163       |
| Neem cake          | 1.344       | 1.033       | 1.114       |
| Poultry manure     | 1.661       | 1.234       | 2.132       |
| Pig manure         | 1.520       | 1.120       | 0.645       |

## Statistical analysis

The greenhouse experiment was replicated three times, adopting a F-CRD. The greenhouse experiment data was subjected to statistical analysis by using Microsoft Excel 2019 and R Studio 4.5.1. Analysis of variance (ANOVA) and mean values were compared using Duncan's multiple range test (DMRT) at the 5 % level (Supplementary Table 1–19) (29).

## Results and Discussion

### Plant height

Among soil orders, there was no significant difference in the expression of plant height (Fig. 1); however, a marginally higher plant height was recorded in O<sub>1</sub> (23.0 cm), followed by O<sub>3</sub> (11.27 cm), O<sub>4</sub> (21.4 cm) at 30 DAS. A significantly higher plant height was noted with T<sub>6</sub> (24.68 cm), which was statistically similar to T<sub>7</sub> (24.21 cm), T<sub>5</sub> (23.19 cm) and T<sub>4</sub> (22.45 cm) and significantly superior to the remaining treatments. At 45 DAS, plant height was significantly influenced by soil orders. A significantly higher plant height was observed in O<sub>1</sub> (33.12 cm), which outperformed O<sub>4</sub> (31.57 cm) and O<sub>2</sub> (31.1 cm) and remained statistically at par with O<sub>3</sub> (32.41 cm). In organic amendments, the highest plant height was recorded with T<sub>6</sub> (34.68 cm), which was significantly higher than all the treatments. At 60 DAS, a significant effect on soil order was observed where O<sub>1</sub> (59.57 cm) expressed significantly higher plant height than O<sub>4</sub> (56.82 cm) and O<sub>2</sub> (55.19 cm) and it remained statistically at par with O<sub>3</sub> (58.1 cm). Among organic amendments, the highest plant height was recorded in T<sub>6</sub> (64.0 cm), which was significantly superior to the remaining treatments. At the harvest, soil orders showed a significant effect on plant height where O<sub>1</sub> (60.46 cm) recorded the highest plant height, which was significantly higher than O<sub>4</sub> (57.26 cm) and O<sub>2</sub> (55.68 cm) and it was statistically at par with O<sub>3</sub> (58.67 cm). Organic amendments influenced plant height of green gram at harvest where T<sub>6</sub> (64.54 cm), resulted in significantly higher plant height than all treatments. The application of organic manures showed a significant impact on plant height where; a significant increase was observed in the case of poultry manure over the control. Poultry manure is recognised as a rich source of nutrients as it promotes soil fertility and crop development and it is an enriched source of macronutrients such as N, P and K (30). Therefore, poultry manure can be used as an effective fertiliser to meet all or some of crop plants' nutritional needs. Additionally, poultry manure has a favourable carbon-to-nitrogen ratio, which supports microorganisms and eventually enhances soil characteristics and plant output. The soil's ability to exchange

cations is increased when poultry manure is added (31, 32).

### Nodules per plant

Among soil orders, there was no significant difference was observed at 30 DAS and 45 DAS (Fig. 2). A significantly higher number of nodules per plant was recorded with T<sub>6</sub> (9.06), which was statistically at par with T<sub>7</sub> (8.51), T<sub>5</sub> (8.68), T<sub>4</sub> (8.31), T<sub>3</sub> (8.01), T<sub>2</sub> (7.74) and significantly superior to T<sub>1</sub>. At 45 DAS, the highest number of nodules per plant was found in T<sub>6</sub> (16.95), which was significantly superior to all treatments. At 60 DAS, soil orders resulted in a significant impact on number of nodules per plant. A higher nodules per plant were observed in O<sub>1</sub> (5.92), which was followed by O<sub>3</sub> (5.78), O<sub>4</sub> (5.67) and O<sub>2</sub> (5.48). Among organic amendments, the highest number of nodules per plant was recorded in T<sub>6</sub> (6.24), which was significantly superior to T<sub>2</sub> (5.13) and T<sub>1</sub> (4.52). Poultry manure, alongside supplying major nutrients, NPK also possess calcium (Ca), magnesium (Mg) and sulphur (S) and a huge quantity of micronutrients, which might supplement the supply of nutrients. Macronutrients and micronutrients also contribute indirectly to nodule formation. Phosphorus is necessary for ATP production, which fuels the energy intensive nitrogen fixation process inside the nodules. Iron is vital for both nitrogenase and leghaemoglobin, the oxygen regulating pigment that gives active nodules their characteristic pink colour (33–35).

### Growth characteristics

A significantly higher number of branches per plant was recorded with T<sub>6</sub> (5.19), which is highest over the rest of the treatments (Table 4). Among soil orders, a significant difference was noted where the higher number of leaves per plant was observed in O<sub>1</sub> (30.9), which was statistically at par with O<sub>3</sub> (29.9). A significantly higher number of leaves per plant was observed with the treatment T<sub>6</sub>—recorded the highest number of leaves per plant (32.67), which was higher over the rest of the treatments except T<sub>7</sub> (31.75). In the soil orders O<sub>2</sub> (40.9), O<sub>4</sub> (42.19) and O<sub>3</sub> (40.9) were statistically at par to take time for flowering, while the minimum time taken by O<sub>1</sub> (30.9). A significantly higher number of days is taken by T<sub>1</sub> (46.33) which was significantly superior to the rest of the treatments except T<sub>2</sub>: FYM, T<sub>3</sub> and minimum days taken for the first flowering by T<sub>6</sub> (37.25). However, there was no significant interaction between soil orders and organic amendments for number of pods per plant of green gram. Poultry manure sharply supplies phosphorus, which improve plant cell structure, thus increasing the number of branches per plant. The result were similar to the findings of previous studies (36–38).

**Table 4.** Effect of organic amendments on branches per plant, leaves per plant, days taken for first flowering and number of pods per plant under different soil orders

|              | Treatments                      | Branches per plant        | Leaves per plant           | First Flowering            |
|--------------|---------------------------------|---------------------------|----------------------------|----------------------------|
| Factor 1 (O) | O <sub>1</sub> : Alfisol        | 4.43 ± 0.15 <sup>a</sup>  | 30.9 ± 0.76 <sup>a</sup>   | 39.86 ± 1.03 <sup>b</sup>  |
|              | O <sub>2</sub> : Entisol        | 3.92 ± 0.17 <sup>a</sup>  | 27.38 ± 0.56 <sup>c</sup>  | 42.71 ± 0.85 <sup>a</sup>  |
|              | O <sub>3</sub> : Inceptisol     | 4.26 ± 0.15 <sup>a</sup>  | 29.9 ± 0.81 <sup>ab</sup>  | 40.9 ± 0.94 <sup>ab</sup>  |
|              | O <sub>4</sub> : Ultisol        | 4.05 ± 0.2 <sup>a</sup>   | 28.71 ± 0.7 <sup>bc</sup>  | 42.19 ± 0.88 <sup>ab</sup> |
|              | T <sub>1</sub> : Control        | 3.03 ± 0.11 <sup>f</sup>  | 25.08 ± 0.54 <sup>e</sup>  | 46.33 ± 0.92 <sup>a</sup>  |
|              | T <sub>2</sub> : FYM            | 3.64 ± 0.12 <sup>e</sup>  | 27.08 ± 0.53 <sup>de</sup> | 45.25 ± 0.41 <sup>a</sup>  |
|              | T <sub>3</sub> : Compost        | 4 ± 0.11 <sup>d</sup>     | 28.33 ± 0.59 <sup>cd</sup> | 44.5 ± 0.6 <sup>a</sup>    |
| Factor 2 (T) | T <sub>4</sub> : Vermicompost   | 4.14 ± 0.19 <sup>cd</sup> | 29.5 ± 0.99 <sup>c</sup>   | 39.42 ± 0.66 <sup>b</sup>  |
|              | T <sub>5</sub> : Neemcake       | 4.38 ± 0.08 <sup>c</sup>  | 30.17 ± 0.75 <sup>bc</sup> | 39 ± 0.88 <sup>b</sup>     |
|              | T <sub>6</sub> : Poultry manure | 5.19 ± 0.11 <sup>a</sup>  | 32.67 ± 0.9 <sup>a</sup>   | 37.25 ± 0.84 <sup>b</sup>  |
|              | T <sub>7</sub> : Pig manure     | 4.78 ± 0.1 <sup>b</sup>   | 31.75 ± 0.74 <sup>ab</sup> | 38.17 ± 0.78 <sup>b</sup>  |
| O × T        | NS                              | NS                        | NS                         | NS                         |

Values are mean ± SE. Means followed by the same letter within a row do not differ significantly (DMRT,  $p < 0.001$ ).

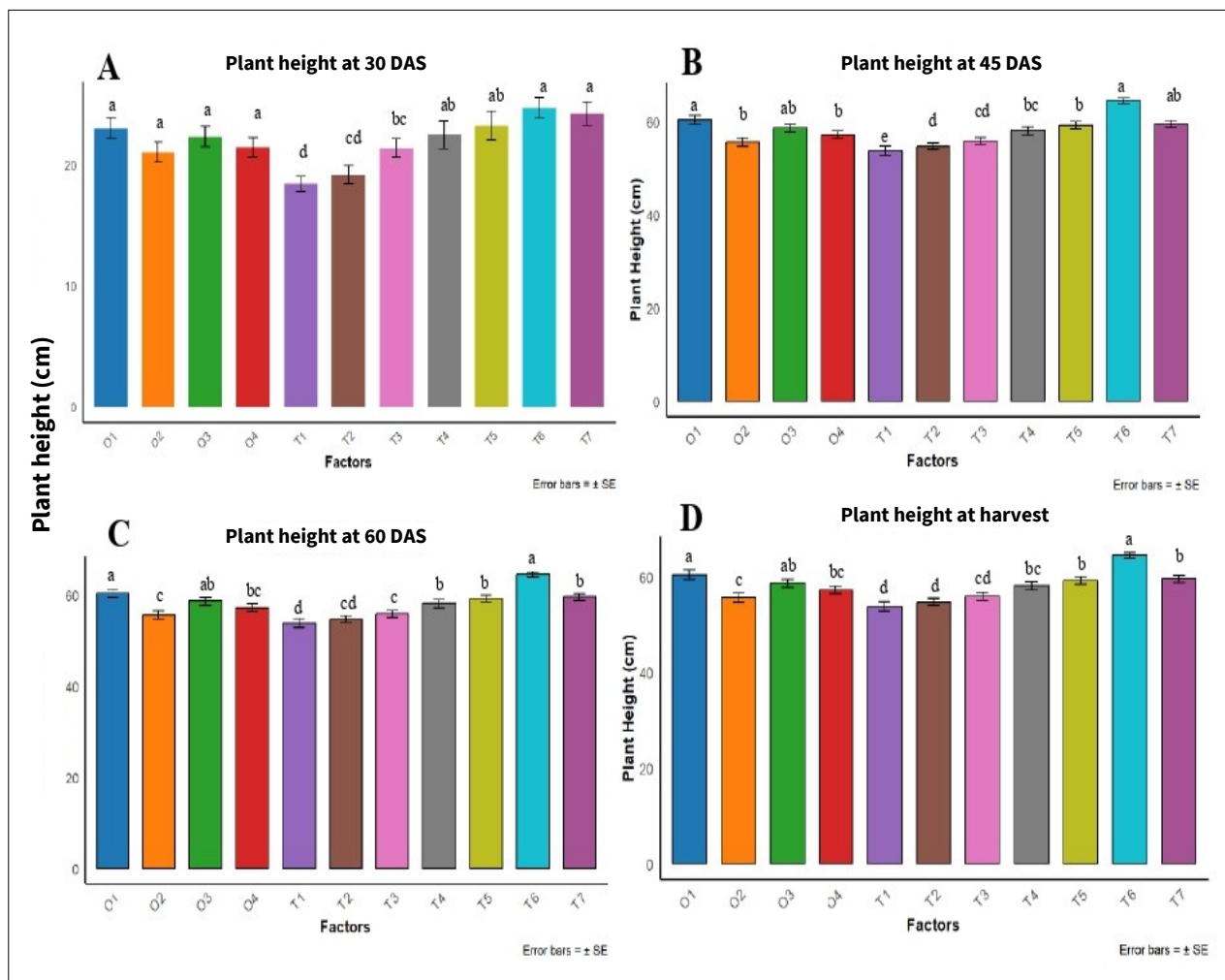


**Fig. 1.** Effect of organic amendments on plant height under different soil orders. A: Plant height at 30 DAS; B: Plant height at 45 DAS; C: Plant height at 60 DAS; D: Plant height at harvest stage. Bars with the same letters are not significantly different according to DMRT ( $p < 0.001$ ).

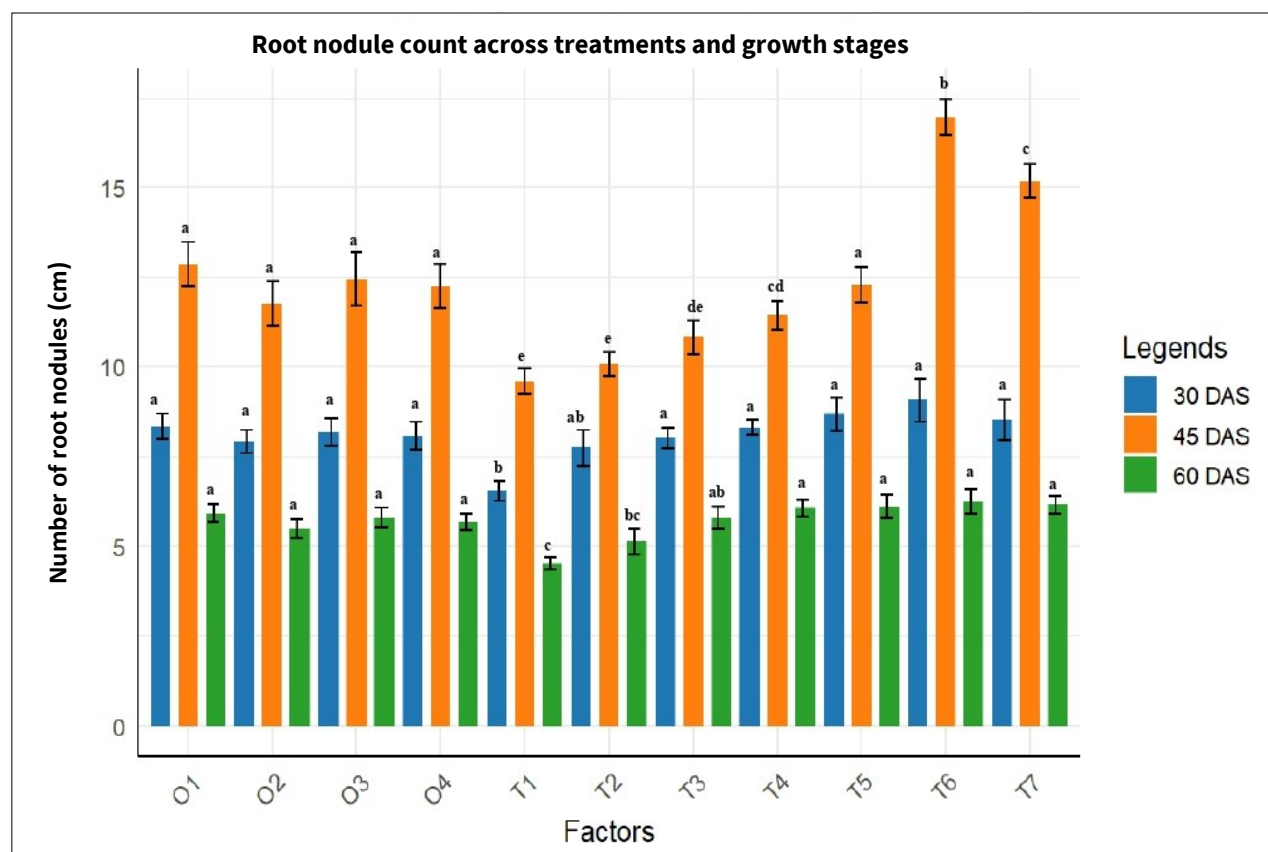


**Fig. 2.** Effect of organic amendments on the number of nodules per plant under different soil orders. Means represented by bars with the same letter do not differ significantly according to DMRT ( $p < 0.001$ ).

## Yield parameters

Among soil orders, there was no significant difference was observed; the highest number of pods per plant was observed in O<sub>1</sub> (17.14), followed by O<sub>3</sub> (16.33), O<sub>4</sub> (16.0) and the minimum was recorded in O<sub>2</sub> (15.43) (Table 5). A significantly higher number of pods per plant was noted with T<sub>6</sub> : poultry manure (20.75) which is highest over the rest of the treatments except T<sub>7</sub> : pig manure (19.58). There was non-significant impact of soil orders for increasing the number of branches per plant; however, there was significant difference in producing seeds per pod where, the highest number of seeds per pod was recorded with O<sub>1</sub> (10.62) which is at par with O<sub>3</sub> (10.19) and O<sub>4</sub> (9.95) and significantly superior to O<sub>2</sub> (8.90). A significantly higher seed per pod was observed. The treatment T<sub>6</sub> (12.25) recorded significantly higher seed per pod than the rest of the treatments. Among soil orders, a significant difference was observed in the seeds per plant. The highest number of seeds per plant was noted in O<sub>1</sub> (188.62), which was statistically at par with O<sub>3</sub> (172.57), O<sub>4</sub> (164.14) and the lowest was recorded in O<sub>2</sub> (142.24). A significantly higher seed per plant was observed with T<sub>6</sub> (256.83), which was significantly higher than the rest of the treatments. Among soil orders, there was no significant difference was observed in terms of the seed yield. A significantly higher yield was registered with T<sub>6</sub> (75.65 g plant<sup>-1</sup>), which was significantly higher over the rest of the treatments. The interaction between factors (soil order × organic amendments) was also non-significant ( $p < 0.001$ ), suggesting that the combined influence of the two factors did not differ significantly from their individual effects. The rapid release of nitrogen from poultry manure, in contrast to other organic manures, can be ascribed to its enhanced efficacy relative to the latter. Nitrogen affected grain output via a source-sink connection, leading to enhanced photosynthate production and greater translocation to reproductive structures. Nitrogen, a crucial nutrient for plant growth and development, is recognised for its ability to enhance crop output (39). The reason for higher grain yield in poultry manure is that it increases the root nodulation by better root development and high nutrient availability, resulting in vigorous plant growth and dry matter accumulation, which resulted in improved flowering, fruiting and pod formation and ultimately there was a beneficial effect on seed yield. The trend of increase in yield in this study is in close conformity with the result of previous studies (40). Similar findings due to the application of organic manures alone were also observed by previous researchers (41–43). The variation observed in plant parameters can be attributed to the fertility gradient of the soils, since both Alfisols and Inceptisols are characterised by comparatively levels of available nutrients and organic carbon.

The interaction between soil order and organic amendments was not statistically significant ( $p < 0.001$ ). Post-hoc power ( $< 0.80$ ), suggesting limited sensitivity to detect small interaction effects. Likewise, the priori power analysis showed that the sample size ( $n = 3$  replications) was insufficient for detecting moderate to small effects within the  $4 \times 7$  factorial design. Thus, the non-significant interaction should be interpreted with caution : it may reflect a negligible effect, or alternatively, inadequate experimental power. Increasing replication or reducing factors levels would enhance the ability to detect interaction effect in future studies.

## Soil properties

The application of organic amendments significantly affected nutrient availability across soil orders and treatments, with all main effects and their interactions being highly significant (0.001). Among soil orders, Alfisols recorded the highest available N (309.58 kg ha<sup>-1</sup>) and K (215.31 kg ha<sup>-1</sup>), while Inceptisol exhibited the greatest phosphorus (32.15 kg ha<sup>-1</sup>). In contrast, Entisol consistently showed the lowest nutrient values, particularly for N (241.59 kg ha<sup>-1</sup>) and P (12.76 kg ha<sup>-1</sup>). Across treatments, poultry manure proved most effective, resulting in significantly higher N (291.70 kg ha<sup>-1</sup>) and P (31.26 kg ha<sup>-1</sup>) compared to the control (248.06 kg ha<sup>-1</sup> and 12.52 kg ha<sup>-1</sup>, respectively). T<sub>7</sub> also enhanced N (288.88 kg ha<sup>-1</sup>) and P (24.73 kg ha<sup>-1</sup>), while T<sub>5</sub> contributed to increase K (205 kg ha<sup>-1</sup>) (Table 6). Vermicompost and compost showed moderate improvement over the control, through their effects were less pronounced than those of poultry manure and pig manure. Overall, poultry manure consistently outperformed other amendments in enhancing soil fertility, particularly N and P availability, while Alfisol and Inceptisol were more responsive to organic amendments compared to Entisol and Ultisol. When manures break down, acid is released, which reacts chemically with salts that are only weakly soluble to make them more soluble. The results showed that using organic manure and fertilisers significantly increased the NPK level. The nutrients contributed to the soil through the breakdown of organic matter and the release of CO<sub>2</sub> are likely responsible for the increased primary nutrient levels in the manure-added plots. Due to increased microbial activity and delayed P fixation in soil, the organic acid generated during the breakdown of organic manures speeds up P solubilisation. The increased cation exchange capacity of soil, which enhances the soil's ability to hold more exchangeable K and lowers K leaching losses, may be linked to the higher K content of soil (44).

**Table 5.** Effect of organic amendments on seeds per pod, seeds per plant and yield (g plant<sup>-1</sup>) under different soil orders

|              | Treatments                      | No. of pods per plant     | Seeds per pod             | Seeds per plant              | Yield                      |
|--------------|---------------------------------|---------------------------|---------------------------|------------------------------|----------------------------|
| Factor 1 (O) | O <sub>1</sub> : Alfisol        | 17.14 ± 0.8 <sup>a</sup>  | 10.62 ± 0.46 <sup>a</sup> | 188.62 ± 16.23 <sup>a</sup>  | 63.61 ± 2.6 <sup>a</sup>   |
|              | O <sub>2</sub> : Entisol        | 15.43 ± 0.8 <sup>a</sup>  | 8.9 ± 0.34 <sup>b</sup>   | 142.24 ± 12.52 <sup>b</sup>  | 58.42 ± 1.7 <sup>a</sup>   |
|              | O <sub>3</sub> : Inceptisol     | 16.33 ± 0.81 <sup>a</sup> | 10.19 ± 0.45 <sup>a</sup> | 172.57 ± 15.4 <sup>ab</sup>  | 61.14 ± 2 <sup>a</sup>     |
|              | O <sub>4</sub> : Ultisol        | 16 ± 0.76 <sup>a</sup>    | 9.95 ± 0.34 <sup>ab</sup> | 164.14 ± 13.07 <sup>ab</sup> | 60.18 ± 2.44 <sup>a</sup>  |
|              | T <sub>1</sub> : Control        | 11.5 ± 0.29 <sup>d</sup>  | 7.75 ± 0.28 <sup>f</sup>  | 89.75 ± 5.02 <sup>e</sup>    | 51.16 ± 1.49 <sup>d</sup>  |
|              | T <sub>2</sub> : FYM            | 13.33 ± 0.45 <sup>c</sup> | 8.58 ± 0.31 <sup>ef</sup> | 115.58 ± 7.35 <sup>de</sup>  | 52.75 ± 1.32 <sup>d</sup>  |
|              | T <sub>3</sub> : Compost        | 14.17 ± 0.32 <sup>c</sup> | 9.08 ± 0.47 <sup>de</sup> | 129.67 ± 8.8 <sup>d</sup>    | 55.06 ± 1.38 <sup>cd</sup> |
| Factor 2 (T) | T <sub>4</sub> : Vermicompost   | 16.42 ± 0.42 <sup>b</sup> | 10 ± 0.35 <sup>cd</sup>   | 165.5 ± 9.65 <sup>c</sup>    | 58.35 ± 2.15 <sup>c</sup>  |
|              | T <sub>5</sub> : Neemcake       | 17.83 ± 0.52 <sup>b</sup> | 10.58 ± 0.4 <sup>bc</sup> | 190.42 ± 2.23 <sup>bc</sup>  | 65.2 ± 1.48 <sup>b</sup>   |
|              | T <sub>6</sub> : Poultry manure | 20.75 ± 0.93 <sup>a</sup> | 12.25 ± 0.35 <sup>a</sup> | 256.83 ± 17.05 <sup>a</sup>  | 75.65 ± 1.74 <sup>a</sup>  |
|              | T <sub>7</sub> : Pig manure     | 19.58 ± 0.45 <sup>a</sup> | 11.17 ± 0.41 <sup>b</sup> | 220.5 ± 13.01 <sup>b</sup>   | 67.7 ± 2.2 <sup>b</sup>    |
| (O × T)      |                                 | NS                        | NS                        | NS                           | NS                         |

Values are mean ± SE. Means followed by the same letter within a row do not differ significantly (DMRT,  $p < 0.001$ ).

**Table 6.** Effect of organic amendments on soil properties after experiment

|                | Treatments                      | Available N                 | Available P                 | Available K                 |
|----------------|---------------------------------|-----------------------------|-----------------------------|-----------------------------|
| Factor 1 (O)   | O <sub>1</sub> : Alfisol        | 309.58 ± 3.31 <sup>a</sup>  | 22.47 ± 1.52 <sup>b</sup>   | 215.31 ± 1.23 <sup>a</sup>  |
|                | O <sub>2</sub> : Entisol        | 241.59 ± 2.13 <sup>d</sup>  | 12.76 ± 0.85 <sup>c</sup>   | 194.94 ± 0.78 <sup>c</sup>  |
|                | O <sub>3</sub> : Inceptisol     | 269.39 ± 5.53 <sup>b</sup>  | 32.15 ± 1.97 <sup>a</sup>   | 200.83 ± 0.66 <sup>b</sup>  |
|                | O <sub>4</sub> : Ultisol        | 253.6 ± 3.75 <sup>c</sup>   | 14.41 ± 1.02 <sup>c</sup>   | 199.76 ± 1.38 <sup>b</sup>  |
|                | T <sub>1</sub> : Control        | 248.06 ± 7.44 <sup>c</sup>  | 12.52 ± 1.43 <sup>d</sup>   | 197.28 ± 2.18 <sup>c</sup>  |
|                | T <sub>2</sub> : FYM            | 253.84 ± 7.48 <sup>bc</sup> | 16.32 ± 1.88 <sup>cd</sup>  | 199.33 ± 2.39 <sup>bc</sup> |
|                | T <sub>3</sub> : Compost        | 256.56 ± 7.85 <sup>bc</sup> | 15.95 ± 1.95 <sup>cd</sup>  | 201.35 ± 2.2 <sup>bc</sup>  |
| Factor 2 (T)   | T <sub>4</sub> : Vermicompost   | 264.03 ± 7.62 <sup>bc</sup> | 19.64 ± 2.25 <sup>bcd</sup> | 205 ± 2.88 <sup>ab</sup>    |
|                | T <sub>5</sub> : Neemcake       | 276.7 ± 8.13 <sup>ab</sup>  | 22.73 ± 2.63 <sup>bc</sup>  | 205.99 ± 2.33 <sup>ab</sup> |
|                | T <sub>6</sub> : Poultry manure | 291.7 ± 8.59 <sup>a</sup>   | 31.26 ± 3.22 <sup>a</sup>   | 210.14 ± 2.68 <sup>a</sup>  |
|                | T <sub>7</sub> : Pig manure     | 288.88 ± 8.63 <sup>a</sup>  | 24.73 ± 3.03 <sup>ab</sup>  | 199.89 ± 1.91 <sup>bc</sup> |
| Soil order (O) |                                 | 0.001                       | 0.001                       | 0.001                       |
| Treatment (T)  |                                 | 0.001                       | 0.001                       | 0.001                       |
| O×T            |                                 | 0.001                       | 0.001                       | 0.001                       |

Values are mean ± SE. Means followed by the same letter within a row do not differ significantly (DMRT,  $p < 0.001$ ).

## Conclusion

The addition of poultry manure in mungbean improved plant growth parameters, crop yield and soil properties. The presence of higher nutrient content in poultry manure favoured the vegetative growth as well as improved the nutrient status of the crop and soil. The release of nutrients from decomposition of organic manures particularly poultry manure acted as a major factor for these results. Thus, present study inferred that the application of organic amendments (poultry manure) may prove beneficial for sustainability of mungbean and to retain the soil fertility. Apart from the strengths of the present study, a major limitation is the variation in nutrient levels present in organic amendments which have different effect on plant growth, yield and soil properties. Thus, before the application of organic amendments, different levels of nutrients should be evaluated properly.

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## Authors' contributions

DKD, NJS, SS and BT contributed to the conception and design of the study, data collection, analysis and interpretation of the results and preparation of the manuscript. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

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