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Short-term Effects of Organic Manure and Microbial Biofertilizer Doses on Soil Properties under Cluster Bean Cultivation in Southern Odisha, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To evaluate the impact of different doses of organic amendments (FYM and vermicompost), with or without Rhizobium inoculation, on soil physical and chemical properties during clusterbean (*Cyamopsis tetragonoloba*) cultivation.

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Design of Study: A field-based factorial randomized block design (RBD) with nine treatments and three replications.

Place and Duration of Study: The experiment was conducted during the summer of 2025 at the Postgraduate Research Farm, Ranadevi, M.S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha, India.

Methodology: Nine treatments involved combinations of FYM and vermicompost at 100% and 150% recommended levels, with and without Rhizobium inoculation. Soil samples were collected at 30, 60, and 90 days after sowing (DAS) from the 0–15 cm depth. Physical (bulk density, texture) and chemical (pH, SOC, and available N, P, K) properties were analyzed using standard procedures.

Results: All organic treatments reduced soil bulk density, with 150% vermicompost + Rhizobium showing the lowest values (1.22 g/cm³ at 90 DAS). The texture remained sandy loam, with minor improvements in silt and clay fractions. pH was moderated most effectively by combined organic + Rhizobium treatments, maintaining near-neutral values. SOC increased across all treatments, with 100% FYM showing the highest (0.88% at 90 DAS). Available N, P, and K also improved significantly, with 150% vermicompost + Rhizobium consistently showing superior nutrient levels, especially for phosphorus (25.44 mg/kg) and potassium (206.08 mg/kg) at 90 DAS.

Keywords: Soil health; organic amendments; rhizobium inoculation; cluster bean (Cyamopsis tetragonoloba); soil fertility management.

1. INTRODUCTION

Soil health is determined by the balance and interaction of its physical, chemical, and biological properties, all of which are essential for sustainable crop production. A disturbance in one property often influences others, leading to a decline in overall soil quality. In recent decades, the rapid growth of the global population and the corresponding increase in food demand have intensified agricultural activities. This has led to excessive use of synthetic fertilizers, frequent tillage, and reliance on heavy machinery practices that have significantly degraded soil structure and fertility (Tsyliuryk *et al.,* 2025). In India, the Green Revolution successfully boosted food grain production and addressed immediate food insecurity. However, it also contributed to a long-term issue of nutrient imbalance and soil degradation, resulting in what is now termed as "hidden hunger" or nutrient deficiency in soils and crops (Singh & Verma, 2025).

India, with only 2.4% of the world's geographical area, supports over 17% of the global population, making it crucial to preserve and enhance soil health for sustained agricultural productivity. The indiscriminate use of chemical fertilizers without adequate organic inputs has led to declining organic carbon levels, poor soil structure, reduced microbial diversity, and diminishing fertilizer-use efficiency (Altynbay *et al.,* 2024). To reverse this trend and restore soil fertility, an integrated approach involving balanced fertilization—combining organic and inorganic nutrient sources is necessary. The application of organic amendments such as farmyard manure (FYM), vermicompost, and biofertilizers not only replenishes soil organic matter but also improves physical structure, enhances microbial activity, and increases the efficiency of nutrient uptake (Singh *et al.,* 2024). Therefore, promoting the combined use of organic and microbial inputs is critical for sustaining soil health and achieving long-term food security.

Organic manure plays a crucial role in enhancing crop productivity and promoting sustainable agricultural practices by improving the physical, chemical, and biological properties of soil. Studies have demonstrated that the application of organic amendments significantly improves soil structure, increases the proportion of water-stable macroaggregates, and reduces bulk density, which enhances water infiltration and decreases erosion risks (Verma *et al.,* 2024) Compared to inorganic fertilizers, organic manure increases soil organic carbon (SOC) by approximately 27% and total nitrogen by 33%, supporting long-term nutrient availability (Wang *et al.,* 2025). These improvements are particularly important for addressing soil degradation caused by conventional farming systems, which are linked to compaction, nitrogen leaching, salinity, and groundwater contamination (Rehman *et al.,* 2023).

Additionally, organic amendments enrich soil microbial biomass and enzymatic activities, promoting nutrient cycling and suppressing soilborne pathogens such as *Fusarium spp.* (Wei *et al.,* 2025). Improved microbial diversity and function are closely associated with soil quality, which refers to the soil's capacity to support plant growth and maintain environmental quality (Xing *et al.,* 2025). Though not directly measurable, soil quality is assessed through physical and biological indicators influenced by land use and management. High soil quality is correlated with improved water and air regulation, reduced greenhouse gas emissions, and increased agronomic efficiency. Therefore, integrating organic manure into soil management strategies is essential for achieving long-term agricultural sustainability and environmental health.

Organic fertilization is inherently more complex than mineral fertilization due to the variable and often less predictable nutrient composition of organic amendments. Unlike mineral fertilizers, which supply nutrients in immediately plant-available forms, organic fertilizers require microbial decomposition for nutrient release, making their effects more gradual and long-term (Panday *et al.,* 2024). However, their fertilization value can be significantly enhanced through careful management of composition, application rates, timing, and placement. Long-term field experiments are essential for assessing the cumulative impact of organic inputs on soil, particularly changes in soil organic matter (SOM), which is best characterized by sustained increases or decreases in total soil organic carbon (SOC) content in the upper layers of soil (Bonfanti *et al.,* 2025). To mitigate these adverse effects while maintaining crop productivity, researchers recommend integrated nutrient management (INM), which combines organic and inorganic amendments. This holistic approach improves nutrient cycling, strengthens soil aggregation, enhances microbial activity, and reduces environmental degradation, thereby fostering long-term soil health and sustainable agricultural productivity (Rai & Sarkar 2025).

2. MATERIALS AND METHODS

The experiment was conducted during the summer season of 2025 at the Postgraduate Research Farm, Ranadevi, M.S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha, India. The site is geographically situated at 11°0'7.65"N latitude and 76°55'33.16"E longitude, at an altitude of 145 m above mean sea level, falling under the North-Eastern Ghat agro-climatic zone characterized by sub-humid and sub-tropical conditions. The region receives an average annual rainfall of 1400 mm, with the monsoon typically active from June to September. During the experiment, maximum and minimum temperatures ranged between 26.5 °C–38.9 °C and 12.3 °C–27.4 °C, respectively. Relative humidity varied from 75.71% to 95.9% morning and 33.86% to 64.9% afternoon. Sunshine hours ranged from 3.0 to 10.3 hours/day, and evaporation rates from 1.5 mm to 7.06 mm/day. Weather data were recorded from the university meteorological observatory.

The field experiment was conducted using a factorial Randomized Block Design (RBD) with nine treatments and three replications. The test crop was cluster bean (*Cyamopsis tetragonoloba*), variety HG-365, with a crop duration of three months. The nine treatments consisted of different combinations of organic manures and biofertilizer as follows: T0 (Control), T1 (100% FYM), T2 (150% FYM), T3 (100% Vermicompost), T4 (150% Vermicompost), T5 (100% FYM + Rhizobium), T6 (150% FYM + Rhizobium), T7 (100% Vermicompost + Rhizobium), and T8 (150% Vermicompost + Rhizobium).

Prior to sowing, green manure was incorporated into the field. The land was prepared by ploughing 2–3 times, followed by a resting period of two days before marking rows. Organic fertilization was carried out by applying a nutrient dose equivalent to 20:40:20 kg NPK ha^{-1}, tailored to each treatment. Farmyard manure (FYM), vermicompost, and Rhizobium were applied based on the treatment requirements to support optimal crop growth and soil health.

To investigate the short-term effects of different doses of farmyard manure (FYM), vermicompost, and biofertilizer on soil properties, soil samples were collected at three time 30, 60, and 90 days after sowing (DAS). Samples were taken from the surface layer at a depth of 0–15 cm. for the assessment of physical properties, bulk density was measured under field conditions using the core sampling method. for chemical analysis, the collected 0-15 cm surface soil samples were air-dried, and passed through a 2 mm sieve. the sieved samples were then used to determine soil texture, pH, soil organic carbon (soc) and available macronutrients nitrogen (n), phosphorus (p), and potassium (k) following standard analytical procedures (Table 1).

Table 1. Methods used for analysis of soil physical and chemical properties

Soil Property	Unit	Method of Analysis	Reference/Standard
Bulk Density (BD)	g/cm³	Core sampler method	Blake & Hartge (1986)
Soil Texture	% sand, silt, clay	Hydrometer method	Bouyoucos (1927)
Soil pH	–	1:2.5 soil-to-water suspension using digital pH meter	Jackson (1973)
Electrical Conductivity (EC)	dS/m	1:2.5 soil-to-water extract using digital EC meter	Jackson (1973)
Soil Organic Carbon (SOC)	%	Walkley and Black wet oxidation method	Walkley & Black (1934)
Available Nitrogen (N)	kg/ha	Alkaline potassium permanganate method	Subbiah & Asija (1956)
Available Phosphorus (P)	kg/ha	Olsen’s method (for neutral to alkaline soils)	Olsen et al. (1954)

3. RESULTS AND DISCUSSION

The study evaluated the effects of various organic treatment regimes on soil physical and chemical properties at different crop growth stages (30, 60, and 90 days after sowing). The physical properties assessed included soil texture and bulk density, while the chemical properties comprised pH, electrical conductivity (EC), and available nitrogen (N), phosphorus (P), and potassium (K) levels in soil.

Across all sampling intervals, a consistent decline in bulk density was observed in organically treated plots compared to the control. At 30 days, the control exhibited the highest bulk density (1.41 g/cm³), while the lowest was recorded under 150% vermicompost + *Rhizobium* 1.27 g/cm³. A similar trend persisted at 60 and 90 days, where the control remained highest (1.43 and 1.44 g/cm³, respectively), and 150% vermicompost + *Rhizobium* showed the lowest values 1.24 and 1.22 g/cm³, respectively (Table 2).

The progressive decrease in bulk density with increasing organic input, particularly at higher application rates and in combination with *Rhizobium*, may be attributed to improved soil aggregation, increased organic matter content, and enhanced microbial activity. This is consistent with previous findings that organic amendments improve soil structure and porosity, thereby reducing compaction (Topa *et al.,* 2021; Tian *et al.,* 2022). Treatments with FYM and vermicompost alone or combined with *Rhizobium* consistently performed better than the control in lowering bulk density, with the most notable improvement under 150% vermicompost + *Rhizobium.*

The textural class of the soil across all treatments remained sandy loam, with minor variations in sand, silt, and clay percentages. The sand content ranged from 64.5% to 68.2%, silt from 20.5% to 22.8%, and clay from 11.3% to 12.8%. While the organic treatments did not significantly alter the soil texture class, slight increases in silt and clay fractions in organically treated plots may indicate better soil aggregation and organic matter binding over time.

Soil pH measurements at 30, 60, and 90 days after sowing revealed marked variability across treatments. At 30 DAS, the 150% FYM + Rhizobium and 100% Vermicompost + Rhizobium treatments recorded the highest pH values (7.900), followed by the 100% Vermicompost treatment (7.80). The lowest pH (7.38) appeared in the 100% FYM treatment. By 60 DAS, the highest pH shifted to the 100% FYM treatment (7.900), while the control plots showed the lowest pH (7.46). Treatments with Rhizobium—specifically 100% FYM + Rhizobium and 150% Vermicompost + Rhizobium—maintained moderately high pH values (7.83 and 7.74, respectively). At 90 DAS, most treatments showed a slight decline in pH. The 100% Vermicompost treatment displayed the lowest pH (6.93), suggesting potential acidifying effects over time, whereas 100% FYM + Rhizobium and 150% FYM + Rhizobium stabilized at pH values of 7.813 and 7.267, respectively (Table 3.). Treatments combining organic amendments with Rhizobium inoculation generally sustained more stable and moderate pH values. Standard error of the mean (SEm) ranged from 0.125 to 0.229 and the coefficient of variation (CV) ranged from 2.802% to 5.136%, indicating acceptable variability among treatments (Fig. 1).

Table 2. Effect of different organic treatments on soil bulk density and texture at 30, 60, and 90 days after sowing

Treatment	30 Days	60 Days	90 Days	Sand (%)	Silt (%)	Clay (%)	Texture Class
Control	1.41 ± 0.02	1.43 ± 0.02	1.44 ± 0.01	68.2	20.5	11.3	Sandy Loam
100% FYM	1.34 ± 0.03	1.33 ± 0.02	1.31 ± 0.02	66.0	21.5	12.5	Sandy Loam
150% FYM	1.30 ± 0.02	1.28 ± 0.02	1.27 ± 0.01	65.3	22.0	12.7	Sandy Loam
100% Vermicompost	1.32 ± 0.02	1.30 ± 0.02	1.29 ± 0.01	66.4	21.1	12.5	Sandy Loam
150% Vermicompost	1.29 ± 0.02	1.27 ± 0.01	1.25 ± 0.01	65.7	21.8	12.5	Sandy Loam
100% FYM + Rhizobium	1.31 ± 0.02	1.29 ± 0.01	1.28 ± 0.01	65.1	22.3	12.6	Sandy Loam
150% FYM + Rhizobium	1.28 ± 0.02	1.26 ± 0.01	1.24 ± 0.01	64.7	22.6	12.7	Sandy Loam
100% Vermicompost + Rhizobium	1.30 ± 0.01	1.28 ± 0.01	1.26 ± 0.01	65.2	22.0	12.8	Sandy Loam
150% Vermicompost + Rhizobium	1.27 ± 0.02	1.24 ± 0.01	1.22 ± 0.01	64.5	22.8	12.7	Sandy Loam

Table 3. Effect of organic treatments on soil pH and soil organic carbon (SOC) at 30, 60, and 90 days after sowing

Treatment details		Soil pH			Soil Organic Carbon		
Sl. No	**Treatments**	**30 days**	**60days**	**90days**	**30 days (%)**	**60days (%)**	**90days (%)**
1	Control	7.74	7.46	7.3	0.4	0.537	0.857
2	100% FYM	7.38	7.9	7.62	0.61	0.55	0.887
3	150% FYM	7.69	7.73	7.66	0.507	0.72	0.71
4	100% Vermicompst	7.8	7.83	6.93	0.567	0.7	0.8
5	150% Vermicompost	7.74	7.86	7.71	0.487	0.52	0.68
6	100% FYM + Rhizobium	7.69	7.83	7.81	0.64	0.477	0.817
7	150% FYM + Rhizobium	7.9	7.44	7.26	0.367	0.577	0.657
8	100% Vermicompost +Rhizobium	7.9	7.69	7.62	0.31	0.527	0.607
9	150% Vermicompost + Rhizobium	7.73	7.74	7.42	0.48	0.7	0.6
C.D.		N/A	N/A	N/A	0.137	N/A	0.19
SE(m)		0.125	0.229	0.184	0.045	0.075	0.063
SE(d)		0.177	0.324	0.26	0.064	0.106	0.089
C.V.		2.802	5.136	4.247	16.199	22.033	14.789

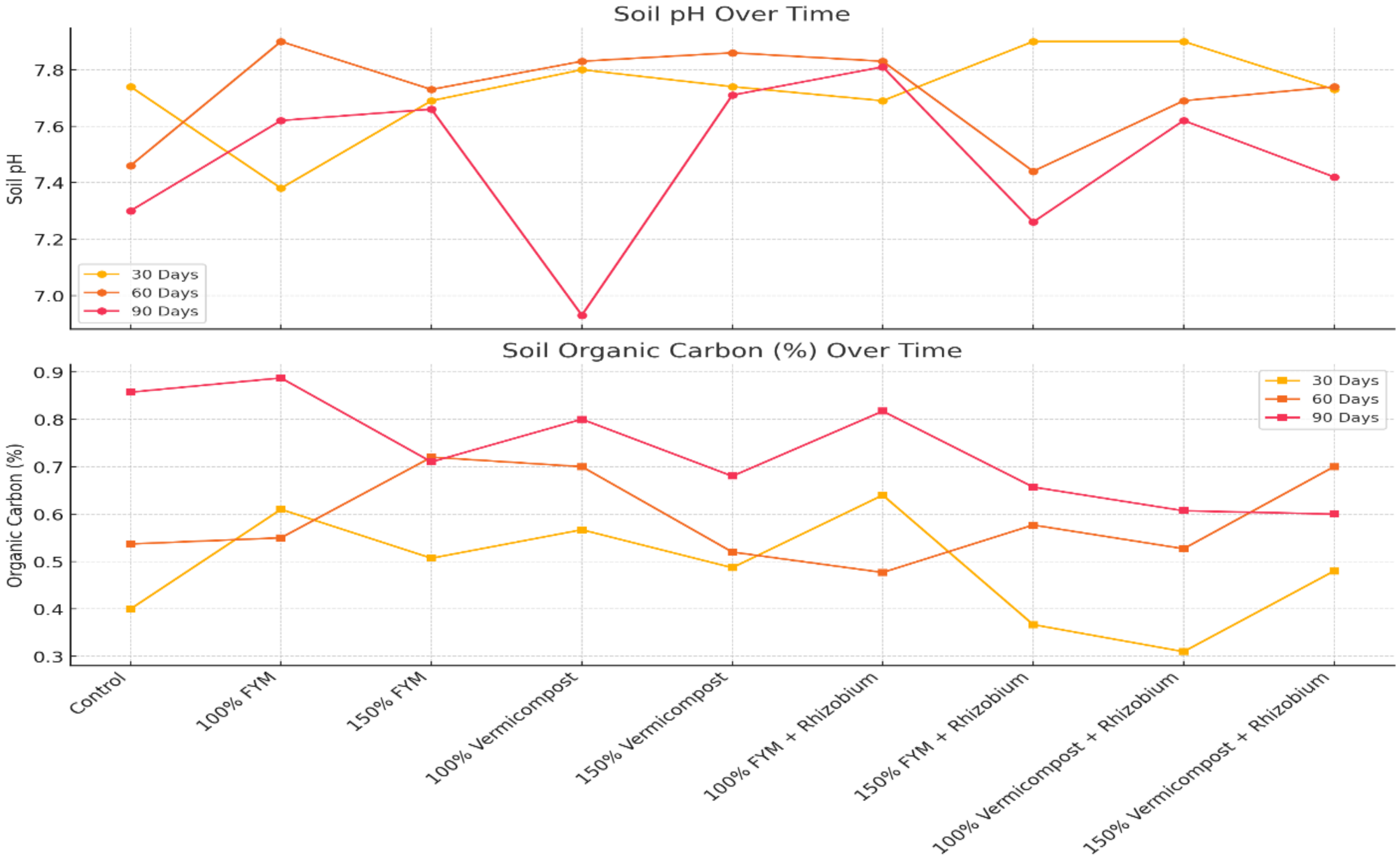

Fig. 1. Effect of different organic amendments on soil bulk density over time (30, 60, and 90 days)

These findings align with observations that vermicompost acts as a buffering agent, helping moderate soil pH fluctuations due to its ability to release microbial metabolites and humic substances (Makkar *et al.,* 2023; Rehman *et al.,* 2023) .Initial pH elevation in Rhizobium-inoculated treatments may be attributed to microbial nitrogen fixation and associated organic acid dynamics, while long-term declines in pH for standalone vermicompost treatments may result from progressive mineralization of organic acids during decomposition (Arthanari *et al.,* 2025)

Combined treatments of FYM or vermicompost with Rhizobium inoculation dampened extreme pH shifts and maintained near-neutral pH levels throughout the observation period. This suggests that the synergistic effects of organic manure and microbial inoculants can stabilize soil pH more effectively than single-input treatments. Similar observations have been reported in legume cropping systems, where Rhizobium inoculation improved soil chemical balance and nutrient availability when applied alongside organic amendments.

Overall, these results highlight the importance of integrating organic amendments with biofertilizers to maintain soil chemical equilibrium. Standalone organic amendments may yield short-term pH variation, whereas combined treatments offer more stable conditions, thereby promoting better nutrient availability and soil health over the early crop growth stages.

The temporal dynamics of soil organic carbon (SOC) revealed significant variations across treatments and time intervals, indicating that both the type and dose of organic amendment, as well as the presence of Rhizobium, substantially influenced SOC trends during the early crop growth stages. At 30 days, SOC was highest in the 100% FYM + Rhizobium treatment (0.64%), reflecting a synergistic effect likely due to enhanced microbial activity and nitrogen fixation, consistent with findings by Gupta et al. (2022) who reported similar carbon enrichment through organic and biofertilizer combinations. By 60 days, the highest SOC was recorded in the 150% FYM (0.72%), suggesting that higher rates of FYM provide sustained carbon input due to slower decomposition of complex organic matter (Sheoran *et al.,* 2024). Interestingly, the SOC under 100% FYM + Rhizobium decreased at this stage, potentially due to early-stage microbial mineralization—a trend aligned with microbial succession patterns . At 90 days, SOC increased across most treatments, with 100% FYM maintaining the highest level (0.88%), indicating its long-term benefit on carbon buildup, as also supported by field results. However, the lowest SOC in the 150% vermicompost + Rhizobium treatment at this stage (0.60%) may reflect rapid decomposition and carbon loss in high-dose vermicompost systems Adhikari *et al.* (2019). These outcomes emphasize the importance of integrated nutrient management strategies that balance organic input types and doses to enhance carbon retention and soil quality sustainably Adhikari et al. (2016).

Table 4. Effect of organic treatments on soil available nitrogen (kg/ha) at 30, 60, and 90 days after sowing

		Soil Available Nitrogen		
Sl. No	**Treatments**	**30 days**	**60days**	**90days**
1	Control	56.447	81.53	108.385
2	100% FYM	65.227	67.77	120.437
3	150% FYM	44.55	70.835	129.92
4	100% Vermicompst	68.667	92.117	130.27
5	150% Vermicompost	57.64	72.167	131.635
6	100% FYM + Rhizobium	40.047	56.497	121.39
7	150% FYM + Rhizobium	62.75	81.76	122.79
8	100% Vermicompost +Rhizobium	39.5	64.48	129.59
9	150% Vermicompost + Rhizobium	39.867	57.987	124.785
C.D.		14.83	8.196	8.029
SE(m)		4.904	2.71	2.655
SE(d)		6.936	3.833	3.755
C.V.		16.106	6.549	3.698

Table 5. Effect of organic treatments on soil available phosphorus (kg/ha) at 30, 60, and 90 days after sowing

Soil Available Phosphorus				
Sl. No	**Treatments**	**30days**	**60days**	**90days**
1	Control	13.31	15.117	15.9
2	100% FYM	15.417	15.007	16.57
3	150% FYM	17.917	13.66	18.527
4	100% Vermicompost	13.137	15.117	16.64
5	150% Vermicompost	14.107	18.14	15.32
6	100% FYM + Rhizobium	16.687	18.477	21.3
7	150% FYM + Rhizobium	16.46	19.147	15.59
8	100% Vermicompost +Rhizobium	15.225	16.127	23.2
9	150% Vermicompost + Rhizobium	18.25	16.907	25.437
C.D.		N/A	N/A	5.42
SE(m)		1.779	1.181	1.792
SE(d)		2.516	1.67	2.535
C.V.		19.741	12.467	16.583

Table 6. Effect of organic treatments on soil available potassium (kg/ha) at 30, 60, and 90 days after sowing

Soil Available Potassium				
Sl. No	**Treatments**	**30days**	**60days**	**90days**
1	Control	173.6	190.4	207.2
2	100% FYM	185.92	190.4	201.04
3	150% FYM	184.24	188.72	197.68
4	100% Vermicompost	190.4	194.32	198.8
5	150% Vermicompost	187.6	192.08	199.36
6	100% FYM + Rhizobium	180.32	187.6	202.16
7	150% FYM + Rhizobium	186.95	193.2	212.8
8	100% Vermicompost +Rhizobium	190.4	193.2	200.48
9	150% Vermicompost + Rhizobium	189.573	194.32	206.08
C.D.		9.167	N/A	8.497
SE(m)		3.032	3.237	2.81
SE(d)		4.287	4.578	3.974
C.V.		2.832	2.926	2.4

Soil available nitrogen varied significantly over time and among organic treatments. At 30 DAS, higher nitrogen levels in 100% vermicompost and FYM indicated rapid mineralization, while lower levels in *Rhizobium*-inoculated treatments suggested microbial immobilization. By 60 DAS, nitrogen content increased across most treatments, with 100% vermicompost and 150% FYM + *Rhizobium* performing best. Lower nitrogen in *Rhizobium*-based treatments may reflect delayed biological nitrogen fixation. At 90 DAS, all treatments showed a marked increase, especially with 150% vermicompost, 100% vermicompost, and 150% FYM, due to cumulative mineralization. *Rhizobium* treatments also improved, indicating effective nitrogen fixation at later stages. The decreasing coefficient of variation over time and significant C.D. values confirm consistent and effective nitrogen release, especially from vermicompost and FYM (Table 4.) Reddy *et al.* (2022). These results support integrated use of organics and bio-inoculants for sustained nitrogen availability (Folina *et al.,* 2025) (Fig. 2).

Soil available Phosphorus (P) levels showed significant variation across treatments and time intervals (30, 60, and 90 days), highlighting the effectiveness of organic amendments and biofertilizers in enhancing nutrient availability. At 30 days, the highest P content was recorded in the 150% vermicompost + Rhizobium treatment (18.25 mg kg^{-1}), while the control had the lowest (13.31 mg kg^{-1}). By 60 days, phosphorus levels increased in most treatments, peaking in 150% FYM + Rhizobium (19.15 mg kg^{-1}). At 90 days, P content was highest in 150% vermicompost +

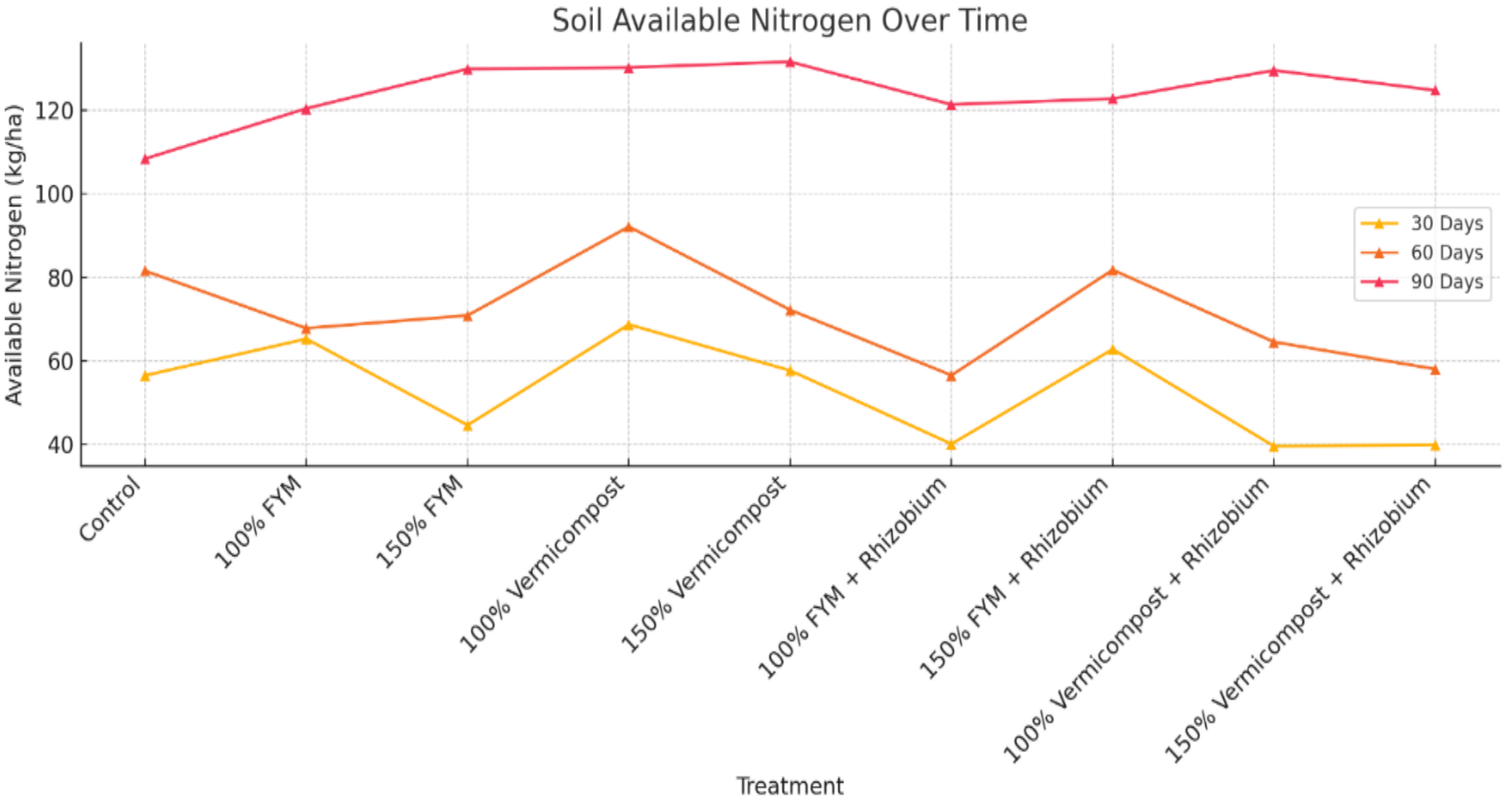

Fig. 2. Changes in soil available nitrogen (kg/ha) over time under different organic and inorganic fertilization treatments

Rhizobium (25.44 mg kg⁻¹), followed by 100% vermicompost + Rhizobium (23.20 mg kg⁻¹) and 100% FYM + Rhizobium (21.30 mg kg⁻¹), again with the control showing the lowest value (15.90 mg kg⁻¹). These patterns suggest that Rhizobium inoculation, especially when combined with higher doses of organic inputs, plays a crucial role in phosphorus mobilization. The observed improvements are consistent with previous findings indicating that vermicompost and FYM enhance P availability by stimulating microbial activity and organic matter decomposition Pal et al. (2020). Rhizobium contributes to this effect by promoting enzymatic processes and solubilizing bound phosphorus, increasing its uptake by plants. These synergistic interactions were also observed by Shome et al. (2022), who reported increased P availability through microbial mineralization pathways, who highlighted the role of organic inputs in improving soil nutrient dynamics Pal et al. (2020) (Table 5.).

Soil available Potassium (K) exhibited significant treatment- and time-dependent variations over the 30, 60, and 90-day intervals, highlighting the influence of organic amendments and *Rhizobium* inoculation. Control plots showed a steady increase in K from 173.6 mg kg⁻¹ at 30 days to 207.2 mg kg⁻¹ at 90 days. Treatments with 100% and 150% FYM saw moderate increases, with values rising from approximately 185 to 201 mg kg⁻¹. Vermicompost treatments—both 100% and 150%—recorded higher initial K (190.4 and 187.6 mg kg⁻¹ respectively), reaching 198–199 mg kg⁻¹ by 90 days. When combined with *Rhizobium*, the increases were more pronounced: 150% FYM + *Rhizobium* rose from 186.95 to 212.8 mg kg⁻¹, and 150% vermicompost + *Rhizobium* increased from 189.57 to 206.08 mg kg⁻¹. Critical differences at 30 and 90 days (9.17 and 8.50) confirmed that treatment effects were statistically significant. Standard errors ranged from 2.8 to 3.2 and CV remained between 2.4% and 2.93%, indicating good data reliability. This pattern aligns with earlier findings that vermicompost significantly enhances available potassium in soil by supplying soluble K and stimulating microbial activity (Al-Maamori *et al.,* 2023; Wu *et al.,* 2023). Organic amendments such as FYM and vermicompost have been shown to increase soil K through mineralization and microbial-mediated mobilization of both exchangeable and fixed potassium pools. The synergistic effects observed between organic inputs and *Rhizobium* inoculation may be attributed to enhanced microbial solubilization and nutrient retention (Pain *et al.,* 2013), supporting the view that integrating biofertilizers with composted organics is a more efficient strategy for improving soil potassium availability than either input used alone Maitra et al. (2020) (Table 6).

4. CONCLUSION

The study clearly demonstrated that the application of organic amendments—particularly at higher doses—and their integration with *Rhizobium* inoculation significantly improved soil physical and chemical properties under clusterbean cultivation. Organic treatments consistently reduced bulk density and enhanced soil organic carbon, while maintaining a stable sandy loam texture. Combined applications of FYM or vermicompost with *Rhizobium* effectively moderated soil pH, increased nutrient availability (N, P, and K), and improved microbial activity. Among all treatments, 150% vermicompost + *Rhizobium* was most effective in enhancing overall soil health. These findings support the adoption of integrated organic and microbial management strategies for sustainable soil fertility enhancement and improved crop productivity in legume-based systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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