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EFFECT OF INTEGRATED NUTRIENT MANAGEMENT ON GROWTH, YIELD AND SOIL FERTILITY OF PIGEON PEA (*Cajanus cajan* L.) IN ASSAM, INDIA

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ABSTRACT

The present study assesses the impact of integrated nutrient management on the growth, yield, soil fertility, and economics of pigeon pea (*Cajanus cajan* L.). Eight nutrient regimes comprising different combinations of recommended dose of fertilizers (RDF), farmyard manure (FYM), vermicompost (VC), and microbial consortium were evaluated in a Randomized Block Design with three replications. The treatment receiving VC @1 t ha^{-1} + 75% RDF (T_6) recorded the highest plant height (239 cm), branches plant^{-1} (34.03), no. of seeds per pod (3.46) pods plant^{-1} (318.22) and seed yield (13.29 q ha^{-1}), resulting in maximum net returns (Rs 90,072.73 ha^{-1}) and benefit–cost ratio (3.10). Post-harvest soil analysis indicated significant improvement in pH, organic carbon, and available N, P and K over control and sole RDF. The results demonstrate that INM, particularly VC @1 t ha^{-1} + 75% RDF, can simultaneously enhance productivity, profitability, and soil health of pigeon pea under humid subtropical conditions of Assam.

Key words : Integrated nutrient management, Pigeon pea, Soil fertility, Seed yield.

Introduction

Pigeon pea (*Cajanus cajan* L.), an important legume crop in tropical and subtropical regions, serves as a critical source of dietary protein, especially in vegetarian diets, and plays a vital role in improving soil fertility through biological nitrogen fixation. In India, pigeon pea occupies approximately 4.6 million hectares with an average productivity of around 850 kg ha^{-1}, which remains considerably lower than the crop's potential yield (Choudhary *et al.*, 2022). In Assam, pigeon pea is predominantly grown under rainfed conditions with minimal nutrient input, often resulting in suboptimal productivity and progressive soil degradation.

Maintaining soil fertility and sustaining crop productivity in such systems necessitate a shift from conventional fertilizer-dependent practices to more integrated approaches. Integrated Nutrient Management (INM), which encompasses the judicious combination of organic amendments, inorganic fertilizers, and beneficial microorganisms, has been recognized as a viable strategy to improve nutrient use efficiency, enhance soil biological activity, and sustain long-term productivity (Singh *et al.*, 2023). Organic sources such as farmyard manure (FYM) and vermicompost not only supply essential macro- and micronutrients, but also improve soil structure, moisture retention, and microbial diversity (Kumar *et al.*, 2021). The inclusion of microbial consortia—comprising nitrogen-fixing, phosphate-solubilizing and plant growth-promoting rhizobacteria—further augments nutrient availability and enhances plant vigor (Patel *et al.*, 2024).

Recent studies have demonstrated that integrated nutrient application significantly improves the growth, yield, and nutrient uptake in pigeon pea, while simultaneously restoring soil organic carbon and macro-nutrient status (Jat *et al.*, 2022 and Barik *et al.*, 2023). Moreover, INM practices contribute to climate-resilient agriculture by reducing dependence on synthetic fertilizers and improving agroecosystem stability. Despite the proven

advantages, region-specific research on INM in pigeon pea under the agro-climatic conditions of Assam remains scant.

Given this context, the present investigation was undertaken to evaluate the effect of integrated nutrient management on growth, yield, quality, and soil fertility in pigeon pea under the humid subtropical conditions of Assam. The study aims to provide evidence-based recommendations for sustainable pigeon pea cultivation that can enhance both productivity and soil health in the north eastern region of India.

Materials and Methods

The field experiment was conducted over two years during the *kharif* season of 2023-2024, 2024-2025 and 2025-2026 at the Assam Agricultural University, Zonal Research Station, Shillongani, Nagaon, Assam (26.32° N latitude, 92.69° E longitude, 64 m MSL) under a humid subtropical climate (Agro-climatic Zone III), characterized by high rainfall and moderate temperatures. The soil was sandy clay loam, acidic (pH 5.6), and medium in fertility, with organic carbon of 0.62%, available N (232.5 kg ha^{-1}), P_2O_5 (18.4 kg ha^{-1}) and K_2O (145.6 kg ha^{-1}). During the crop season, total rainfall was 1125.4 mm, with mean maximum and minimum temperatures of 33.5°C and 24.3°C, respectively and relative humidity ranging from 78% to 88%. The experiment followed a Randomized Block Design with eight treatments and three replications using pigeon pea variety (ICPL87091), sown in mid-June with row to row spacing of 75cm and plant to plant 30 cm in 4.0 × 3.0 m plots. Treatments included varying combinations of FYM, vermicompost, RDF, and microbial consortia, with RDF applied at 15:40:0 kg N:P_2O_5: K_2O ha^{-1}. Organic amendments were incorporated 15 days prior to sowing, and microbial consortia were applied as per treatment. Eight treatments comprise T_1 (Control), T_2 (100% RDF), T_3 (FYM 5t + 50% RDF), T_4 (FYM 5t + 75% RDF), T_5 (VC 1t + 50% RDF), T_6 (VC 1t + 75% RDF), T_7 (50% RDF + Microbial consortia), T_8 (75% RDF + Microbial consortia). Standard agronomic practices were uniformly adopted. Data were collected on growth and yield attributes (plant height, branches, pods plant^{-1}, seeds pod^{-1}, 100-seed weight, seed and stover yield), post-harvest soil fertility parameters (pH, organic carbon, available N, P and K) over the years were determined as per the method outlined by Jackson 1979. Economic indicators (cost of cultivation, gross and net returns, B:C ratio) were also calculated. All data were statistically analysed and analysis of variance was performed using online statistically programme OPSTAT with treatment effects tested at 5% significance level, and SEm and CD values reported for interpretation.

A field experiment was conducted during two consecutive *kharif* seasons of 2023–2024 and 2024–2025 at the Assam Agricultural University, Zonal Research Station, Shillongani, Nagaon, Assam, India (26.32° N latitude, 92.69° E longitude, 64 m above mean sea level). The experimental site falls under the humid subtropical climatic conditions of Agro-Climatic Zone III (Central Brahmaputra Valley Zone) of Assam, characterized by high rainfall and moderate temperature. The soil of the experimental field was sandy clay loam in texture, acidic in reaction (pH 5.6), and medium in fertility, containing 0.62% organic carbon, 232.5 kg ha^{-1} available N, 18.4 kg ha^{-1} available P_2O_5 and 145.6 kg ha^{-1} available K_2O.

During the crop-growing period, the total rainfall received was 1125.4 mm, with mean maximum and minimum temperatures of 33.5°C and 24.3°C, respectively. The relative humidity ranged from 78% to 88%. The experiment was laid out in a Randomized Block Design (RBD) with eight treatments replicated three times. Pigeon pea (*Cajanus cajan* L.) variety ICPL 87091 was sown in mid-June with a spacing of 75 cm × 30 cm in plots measuring 4.0 m × 3.0 m.

The treatments consisted of different combinations of farmyard manure (FYM), vermicompost (VC), recommended dose of fertilizers (RDF), and microbial consortia as follows: T_1 – Control, T_2 – 100% RDF, T_3 – FYM 5 t ha^{-1} + 50% RDF, T_4 – FYM 5 t ha^{-1} + 75% RDF, T_5 – VC 1 t ha^{-1} + 50% RDF, T_6 – VC 1 t ha^{-1} + 75% RDF, T_7 – 50% RDF + Microbial consortia and T_8 – 75% RDF + Microbial consortia.

The RDF was applied at 15:40:0 kg N:P_2O_5 :K_2O ha^{-1}. Organic manures (FYM and VC) were incorporated into the soil 15 days prior to sowing, while microbial consortia containing nitrogen-fixing, phosphate-solubilizing and plant growth-promoting rhizobacteria (PGPR) were applied as per treatment. Standard agronomic practices were uniformly adopted for all treatments.

Observations were recorded on growth and yield attributes including plant height, number of branches plant^{-1}, number of pods plant^{-1}, number of seeds pod^{-1}, 100-seed weight, seed yield and stover yield. Post-harvest soil samples were analyzed for pH, organic carbon, and available N, P and K using standard procedures described by Jackson (1973). Economic parameters, namely cost of cultivation, gross return, net return, and benefit–cost (B:C) ratio, were computed using prevailing market prices.

The experimental data were statistically analyzed following the analysis of variance (ANOVA) procedure

appropriate for RBD, and treatment means were compared at a 5% level of significance. Statistical analysis was carried out using the online statistical software OPSTAT (Sheoran *et al*., 1998). The standard error of mean (SEm±) and critical difference (CD) values were reported for interpretation.

Results and Discussion

Growth attributes

Integrated nutrient management (INM) treatments significantly influenced the growth parameters of pigeon pea over the pooled data of two years (Table 1). The treatment receiving vermicompost @ 1 t ha^{-1} + 75% RDF (T_6) recorded the maximum plant height (239 cm) and number of branches per plant (34.03), which were significantly superior to other treatments. The improvement in plant growth may be attributed to the synergistic effect of organic and inorganic nutrient sources that ensured a balanced and continuous nutrient supply, enhanced microbial activity, and improved soil physical properties, thereby facilitating better root proliferation and nutrient uptake (Kumar *et al*., 2023). The higher branching in T6 indicates enhanced vegetative growth due to improved hormonal balance and sustained nutrient availability, corroborating the findings of Patel *et al.* (2022).

The number of pods per plant was highest in T_3 (FYM 5 t ha^{-1} + 50% RDF), while T_7 (50% RDF + microbial consortium) recorded the maximum number of seeds per pod. The higher pod numbers under T_3 can be ascribed to the slow-release nature of farmyard manure that prolonged nutrient availability during the reproductive stage, whereas microbial inoculants in T_7 may have enhanced flower retention and pod set through the production of plant growth-promoting substances (Jat *et al*., 2022 and Barik *et al*., 2023). However, despite higher pod numbers in T_3, the treatment did not translate into the highest yield due to smaller seed size and weight, highlighting the importance of nutrient balance during seed filling.

Seed weight per plot and 100-seed weight were significantly higher in T_6, indicating better seed development and grain filling. Vermicompost provides not only macro- and micronutrients but also humic substances that improve photosynthesis and assimilate translocation to the reproductive sinks (Singh *et al*., 2023). Consequently, T_6 also resulted in the highest seed yield (13.29 q ha^{-1}), demonstrating the superiority of combined

Table 1 : Effect of INM on growth parameters of Pigeon Pea (Pooled data for last three years).

Treatments	Plant height (cm)	No. of Branches per plant	No. of seeds per pod	No. of pods per plant	No. seed weight (kg) per plot	Seed weight (g) per 100 seed	Seed yield (q/ha)
T_1	234.3	27.25	3.32	268.43	1.01	9.74	8.45
T_2	237.0	32.13	3.59	245.38	1.22	10.98	10.19
T_3	235.3	29.96	3.56	377.42	1.05	10.05	8.79
T_4	236.1	29.8	3.36	263.57	1.25	10.93	10.37
T_5	235.8	28.63	3.33	331.17	1.13	10.64	9.43
T_6	239.0	34.03	3.46	318.22	1.58	11.74	13.29
T_7	234.8	26.16	4.03	212.98	1.05	9.77	8.80
T_8	236.2	30.13	3.69	223.97	1.34	11.07	11.25
C.D.	0.05	2.85	0.06	0.82	0.02	0.07	0.95
SE(m)	0.02	0.93	0.02	0.27	0.01	0.02	0.31
SE(d)	0.02	1.31	0.03	0.38	0.01	0.03	0.44
C.V.	0.01	5.41	0.94	0.17	0.77	0.38	5.32

Table 2 : Effect of INM on yield parameters of Pigeon pea.

Treatments	2023-24	2024-25	Avg. Straw yield (q/ha)
	Seed yield (q/ha)	Seed yield (q/ha)	
T_1	8.3	8.51	32.21
T_2	9.37	11.08	31.69
T_3	8.43	9.08	29.4
T_4	9.97	10.72	25.48
T_5	9.35	9.69	24.1
T_6	12.76	13.58	27.62
T_7	8.59	9.00	28.04
T_8	10.88	11.53	21.78
C.D.	0.499	0.916	1.416
SE(m)	0.163	0.299	0.462
SE(d)	0.231	0.423	0.654
C.V.	2.909	4.979	2.908

application of vermicompost and reduced fertilizer dose. Similar observations were reported by Meena *et al.* (2022) in pigeon pea under integrated nutrient regimes.

Yield attributes and productivity

The effect of INM was also evident on yield attributes and productivity (Table 2). The treatment T_6 consistently produced the highest seed yield during both years (12.76 and 13.58 q ha^{-1}), followed by T_8 (75% RDF + microbial consortium). The higher yield in T_6 may be ascribed to enhanced vegetative growth, improved reproductive efficiency and greater nutrient uptake, which collectively ensured superior assimilate partitioning towards grains. The findings corroborate earlier reports where vermicompost in combination with chemical fertilizers enhanced seed yield in pulses (Singh *et al*., 2023 and Meena *et al*., 2022).

Interestingly, the control treatment (T_1) recorded the highest straw yield (32.21 q ha^{-1}) despite the lowest seed yield. This indicates that in nutrient-deficient conditions, pigeon pea tends to allocate assimilates towards vegetative biomass rather than reproductive parts, thereby lowering the harvest index. On the other hand, treatments like T_6 and T_2 maintained a balance between seed and straw yield, suggesting improved partitioning efficiency under integrated regimes, as also observed by Sharma *et al.* (2021).

Soil fertility status

Post-harvest soil fertility parameters were markedly improved under INM treatments (Table 3). The treatment T_6 resulted in the highest organic carbon content (1.05%), available nitrogen (367.72 kg ha^{-1}), phosphorus (21.50 kg ha^{-1}) and potassium (286.1 kg ha^{-1}), along with a marginal increase in soil pH (5.98) compared to the initial acidic condition (5.6).

Soil pH

The soil pH increased slightly across all INM treatments compared to the control (5.85), with the highest value observed under T_6 (5.98). The marginal rise in pH may be attributed to the liming effect of vermicompost and farmyard manure, which contain exchangeable bases such as Ca^{2+}, Mg^{2+} and K^+ that neutralize soil acidity. This effect is particularly important in the acidic soils of Assam. Organic amendments also improve buffering capacity, thereby maintaining a favorable pH for nutrient availability and microbial activity. The improvement in soil properties can be attributed to the addition of organic matter from vermicompost, which enhanced soil buffering capacity, cation exchange, and microbial mineralization of nutrients (Kumar *et al*., 2023) reported that vermicompost addition in pulses ameliorates soil acidity and enhances nutrient uptake.

Soil Organic Carbon (OC %)

Organic carbon content was significantly higher under INM treatments, ranging from 0.93 to 1.05%, compared to 0.86% in the control. The maximum OC was recorded in T_6 (1.05%), closely followed by T_8 (1.04%). The improvement in OC is a direct consequence of the addition of organic matter through vermicompost and FYM, which contribute humic substances and microbial biomass carbon (Patel *et al*., 2022). Higher

Table 3 : Effect of INM on fertility status of Soil (Pooled data for last two years).

Treatments	Soil Properties					Bacteria	Fungi
	pH	OC %	Av. N	Av. P_2O_5	Av. K_2O	(CFU×10^6 per gram of oven dry soil)	(CFU×10^3 per gram of oven dry soil)
			kg ha^{-1}				
T_1	5.85	0.86	347.37	19.87	273.9	19.7	18.6
T_2	5.89	0.97	358.47	20.17	278.7	24.2	22.4
T_3	5.89	0.93	350.37	20.88	275.5	20.6	19.6
T_4	5.92	0.98	360.25	21.27	280.5	25.7	23.4
T_5	5.87	0.96	354.35	21.33	277.7	22.2	21.2
T_6	5.98	1.05	367.72	21.50	286.1	27.8	24.9
T_7	5.86	0.93	351.77	21.30	274.9	20.7	19.8
T_8	5.97	1.04	361.87	21.35	281.3	27.5	24.3
C.D.	0.047	0.029	0.835	0.140	0.784	0.92	0.78
SE(m)	0.015	0.010	1.180	0.046	0.256	0.30	0.25
SE(d)	0.022	0.013	0.406	0.065	0.362	0.43	0.36
C.V.	0.446	1.707	2.556	0.377	0.159	3.2	3.8

OC improves soil structure, moisture retention and cation exchange capacity, thereby sustaining soil fertility. Barik *et al.* (2023) also found that combined use of organics and inorganics increased OC in pigeon pea soils.

Available Nitrogen (N)

Available N improved substantially under INM treatments, with values ranging from 350.37 to 367.72 kg ha^{-1}, compared to 347.37 kg ha^{-1} in the control. T_6 recorded the maximum available N (367.72 kg ha^{-1}). This could be due to supply of nitrogen in mineralizable forms through Vermicompost and FYM, while microbial consortia enhance biological nitrogen fixation, thereby enriching the soil N pool (Singh *et al*., 2023; Jat *et al*., 2022). Furthermore, organics reduce N losses through leaching and volatilization by improving soil aggregation.

Available Phosphorus (P_2O_5)

Available phosphorus ranged from 19.87 to 21.50 kg ha^{-1}, with the highest value under T_6 (21.50 kg ha^{-1}). The increase in available P can be attributed to the solubilization of native phosphates by organic acids released during decomposition of vermicompost and FYM. It could be the role of microbial consortia in solubilizing phosphorus and mobilizing potassium further contributed to higher nutrient availability (Patel *et al*., 2024). In treatments with microbial consortia, phosphate-solubilizing bacteria further enhanced P availability by secreting organic acids and phosphatases (Meena *et al*., 2022).

Available Potassium (K_2O)

Available K was also enhanced under INM treatments, with maximum values under T_6 (286.1 kg ha^{-1}) followed by T_8 (281.3 kg ha^{-1}), compared to 273.9 kg ha^{-1} in the control. The improvement in K availability could be due to the release of K from organic manures through mineralization and the action of K-mobilizing microorganisms present in the microbial consortia. Additionally, organic acids from vermicompost may help in the weathering of soil minerals, thereby releasing exchangeable K (Sharma *et al*., 2021). Jat *et al.* (2022) also reported higher K availability under integrated use of manures and fertilizers in pigeon pea.

Soil microbial population

The soil microbial population was markedly influenced by the different nutrient management practices (Table 3). The bacterial population ranged from 19.7×10^6 CFU g^{-1} of oven-dry soil in the control (T_1) to 27.8×10^6 CFU g^{-1} in T_6 (75% RDF + vermicompost + biofertilizer consortium), while the fungal population varied from 18.6 $\times 10^3$ CFU g^{-1} in T_1 to 24.9 $\times 10^3$ CFU g^{-1} in T_6. The differences among treatments were found to be significant at $P \leq 0.05$. The maximum bacterial and fungal counts observed under T_6 were closely followed by T_8 (100% RDF + vermicompost + biofertilizer) and T_4 (50% RDF + vermicompost + biofertilizer), whereas the minimum was recorded under control (T_1).

The pronounced microbial activity under T_6 can be attributed to the synergistic effect of organic and inorganic nutrient sources, which enhanced soil organic carbon, improved nutrient availability, and created a favorable microhabitat for microbial proliferation. The addition of vermicompost supplied easily decomposable organic matter that served as an energy source for soil microbes, while the biofertilizer consortium enriched the rhizosphere with beneficial microorganisms such as *Rhizobium*, *Azotobacter* and *Trichoderma*, thereby improving biological nitrogen fixation and nutrient mineralization. In contrast, treatments with only chemical fertilizers (T_2) supported relatively lower microbial populations due to limited organic carbon input and possible adverse effects of high salt concentration on microbial survival.

These findings corroborate the results of Naeem *et al.* (2015), Sharma *et al.* (2020) and Bandyopadhyay *et al.* (2021), who reported that the integration of organic manures and microbial inoculants enhances microbial biomass and enzymatic activities by improving soil physicochemical conditions. Hence, the present study clearly indicates that integrated nutrient management (T_6) significantly improved the bacterial and fungal populations, thereby promoting soil biological health and nutrient cycling, which are crucial for maintaining soil fertility and sustainable productivity of pigeon pea under the humid subtropical conditions of Assam.

The overall improvement in soil fertility parameters under INM, particularly in T_6 (VC @ 1 t ha^{-1} + 75% RDF), underscores the long-term benefits of integrating organic manures with chemical fertilizers. The increase in soil organic carbon and available macronutrients not only sustains higher productivity of pigeon pea but also enhances soil biological activity and nutrient cycling efficiency. Improved pH buffering further ensures nutrient stability in the acidic soils of Assam. These findings corroborate the view that INM practices play a pivotal role in building soil organic reserves and improving nutrient-use efficiency, which are crucial for sustaining crop yields over time (Kumar *et al*., 2023; Singh *et al*., 2023). Moreover, by reducing dependence on sole chemical fertilizers and enhancing soil resilience against degradation, INM contributes significantly to the development of climate-resilient production systems in

Table 4 : Economics.

Treatment	Yield (q/ha)	Gross Return	Total Cost	Net Return	B:C
T_1 (Control)	8.45	84,500	29,770.20	54,729.80	2.84
T_2 (100% RDF)	10.19	101,900	33,846.29	68,053.71	3.01
T_3 (FYM 5t + 50% RDF)	8.79	87,900	41,808.24	46,091.76	2.10
T_4 (FYM 5t + 75% RDF)	10.37	103,700	42,827.27	60,872.73	2.42
T_5 (VC 1t + 50% RDF)	9.43	94,300	41,808.24	52,491.76	2.26
T_6 (VC 1t + 75% RDF)	13.29	132,900	42,827.27	90,072.73	3.10
T_7 (50% RDF + Microbial consortia)	8.80	88,000	33,008.24	55,991.76	2.66
T_8 (75% RDF + Microbial consortia)	11.25	112,500	37,027.27	79,472.73	3.03

rainfed pigeon pea-based agroecosystems. Thus, integrated nutrient strategies represent a viable pathway to achieving both productivity enhancement and ecological sustainability in the humid subtropical regions of Northeast India

Economics

Economic evaluation of different nutrient management practices revealed distinct variations in gross returns, net returns, and benefit–cost (B:C) ratio (Table 4). The integration of vermicompost with inorganic fertilizers (T_6: VC @ 1 t ha^{-1} + 75% RDF) consistently outperformed other treatments in terms of profitability. T_6 achieved the highest gross return (` 132,900 ha$^{-1}$), net return (` 90,072.73 ha^{-1}) and B:C ratio (3.10), followed by T_8 (75% RDF + microbial consortium) with a B:C ratio of 3.03. The higher profitability of T_6 was primarily due to its superior seed yield (13.29 q ha^{-1}) coupled with moderate cost of cultivation.

The results clearly indicate that the combined use of vermicompost and fertilizers improves nutrient-use efficiency, thereby reducing the need for higher chemical fertilizer inputs and ensuring better returns per unit investment. Similar findings were reported by Yadav *et al.* (2024), who demonstrated that INM practices in pulses substantially improved economic efficiency under rainfed conditions.

The sole application of inorganic fertilizers (T_2: 100% RDF) also recorded a high B:C ratio (3.01) owing to reasonably good yields (10.19 q ha^{-1}), but it was inferior to integrated treatments in terms of soil fertility improvement. On the other hand, treatments involving only organics, such as T_3 (FYM 5 t ha^{-1} + 50% RDF) and T_5 (VC 1 t ha^{-1} + 50% RDF), recorded lower profitability due to higher cost of manures and comparatively modest yield gains. This aligns with the observations of Meena *et al.* (2022), who noted that sole reliance on bulky organics increases production cost and reduces economic efficiency in pulse-based systems.

Interestingly, T_7 (50% RDF + microbial consortium) recorded a moderate B:C ratio (2.66), higher than organics alone, which suggests that biofertilizers can serve as low-cost inputs to partially substitute chemical fertilizers. However, their yield potential remained limited compared to vermicompost-based INM, emphasizing the need for synergistic use of biofertilizers along with organics and inorganics (Patel *et al.*, 2024).

Overall, the economic analysis demonstrates that vermicompost-based INM practices not only enhance productivity but also provide maximum monetary benefits, making them both agronomically and economically sustainable. These results reinforce earlier studies highlighting INM as a cost-effective and eco-friendly alternative to sole fertilizer use in legumes (Kumar *et al.*, 2023 and Yadav *et al.*, 2024).

Conclusion

The present study demonstrates that the integration of vermicompost with a reduced dose of chemical fertilizers (T_6: VC @ 1 t ha^{-1} + 75% RDF) is most effective in enhancing growth, yield, soil fertility, and economic returns of pigeon pea under the humid subtropical conditions of Assam. While sole RDF improved yield over the control, it was inferior to INM treatments in terms of soil health and profitability. Treatments with microbial inoculants (T_7 and T_8) also showed potential, particularly when combined with RDF. Thus, INM offers a balanced approach that not only maximizes productivity but also ensures sustainability of pigeon pea cultivation in the region. Overall, T_6 (VC 1 t ha^{-1} + 75% RDF) consistently improved soil pH, organic carbon, and available macronutrients (N, P and K), indicating the superiority of INM over sole fertilizer or control treatments. These results confirm that integrated approaches not only sustain productivity but also restore soil fertility, thereby ensuring long-term soil health and resilience of pigeon pea-based systems under humid subtropical conditions.

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