LR-5548
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RESEARCH ARTICLE
Legume Research- An International Journal

A Sustainable Approach Towards Pigeonpea Production: Effects of Planting Pattern and Nutrients Supply on Yield, Uptake and Nutritional Quality

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10.18805/LR-5548

ABSTRACT

Background: Pigeonpea (*Cajanus cajan* L.) is a significant pulse crop identified for its capacity to fix atmospheric nitrogen and its adaptability to semi-arid environments. However, productivity can be affected by inadequate agronomic practices, specifically inappropriate planting patterns and imbalanced nutrient management. Integrated nutrient management (INM) provides a sustainable strategy which combines organic and inorganic nutrient sources to improve soil fertility, crop yield and quality.

Methods: A field experiment was conducted during the kharif seasons of 2023 and 2024 at Lovely Professional University ,Phagwara, Punjab, in a split-plot design with four planting patterns (P_1: 50×25 cm, P_2: 30×25 cm, P_3: Raised bed, P_4: 60×20 cm) as main plots and four nutrient sources (N_1: Control, N_2: RDF, N_3: FYM, N_4: Integrated nutrient management) as sub-plots, replicated thrice.

Result: Raised bed planting (P_3) with INM (N_4) significantly enhanced yield attributes, seed yield (1188.23 and 1051.04 kg ha^{-1}) and total nutrient uptake (N, P, K) compared to other treatments. The same combination also recorded the highest protein content (20.17% and 20.43%) and protein yield (268.42 and 273.75 kg ha^{-1}). Microbial populations were also significantly higher under INM with raised bed planting, indicating improved soil biological health. The study highlights that integrating raised bed planting with INM is a practical strategy for improving Pigeonpea productivity, nutrient use efficiency and soil health under Punjab's agro-climatic conditions.

Key words: Integrated nutrient management, Nutrient uptake, Pigeonpea, Planting pattern, Protein yield, Soil microbes.

INTRODUCTION

Pigeonpea (*Cajanus cajan* L.) is a significant legume crop widely cultivated in semi-arid tropical regions, valued for its drought resistance, capacity to enhance soil fertility via biological nitrogen fixation and provision of high-protein food and fodder (Dash *et al.,* 2024). Pigeonpea is vital for nutritional security and the maintenance of soil health in India, especially within rainfed agricultural systems. Notwithstanding its agronomic and ecological importance, Pigeonpea productivity is unsatisfactory due to ineffective crop management strategies, particularly with planting geometry and nutrient inputs (Bhardwaj *et al.,* 2023). The planting pattern is a crucial agronomic element that affects crop development, resource utilisation efficiency and ultimately output. Optimal spacing allows better light interception, efficient canopy structure and less intra-specific competition. Conventional sowing techniques can result in inadequate plant density and insufficient aeration, hence limiting production potential (Venkatesh *et al.,* 2023). Nutrient management is crucial for achieving higher productivity. Depending only on synthetic fertilisers may result in nutritional imbalances and declining soil health over time. Integrated nutrient management (INM), which combines organic manures, biofertilizers and chemical fertilizers, is gaining interest for increasing nutrient availability, improving soil microbial activity and maintaining long-term soil fertility (Math *et al.,* 2020). Although many studies evaluate the impacts of planting geometry and fertilizer management on pulse crops, the synergistic influence of these variables on yield, nutrient uptake and grain quality in Pigeonpea has yet to be thoroughly investigated (De *et al.,* 2025). Comprehending these connections is essential for developing effective and sustainable agricultural techniques. This study was conducted to assess the combined effect of different planting patterns and nutrient management strategies on the growth, yield characteristics, uptake of nutrients and quality of pigeonpea in the agro-climatic conditions of Punjab. The study aims to identify an agronomic strategy

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How to cite this article: Pallavi, Singh, A., Sarkar, S. and Thakur, S. (2025). A Sustainable Approach Towards Pigeonpea Production: Effects of Planting Pattern and Nutrients Supply on Yield, Uptake and Nutritional Quality. *Legume Research*. 1-11. doi: 10.18805/LR-5548.

Submitted: 07-08-2025 **Accepted:** 08-12-2025 **Online:** 02-01-2026

that improves productivity while enhancing soil health and sustainability.

MATERIALS AND METHODS

Experimental site and weather

The entitled study was conducted at agricultural research farm of Lovely Professional University, Phagwara (Punjab) and agricultural farm is situated at a latitude of 31°24′N and a longitude of 75°69′E, with an altitude of 245 m above mean sea level (Fig 1). The region falls within the Trans-Gangetic Plains agroclimatic zone and experiences a semi-arid subtropical climate with hot summers and cold winters. The Meteorological Observatory, Department of Agronomy, Lovely Professional University, provided data on weather parameters, such as temperature (maximum and minimum), relative humidity, wind speed, dew point and rainfallfor two experimentation years (*Kharif* 2023 to *Kharif* 2024) as per data shown in Fig 2a and 2b.

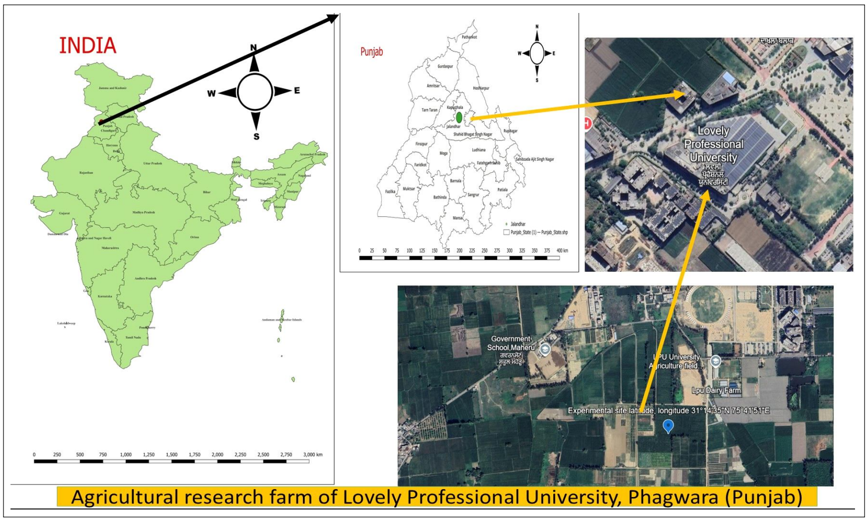

Fig 1: Geographical location of experimental site.

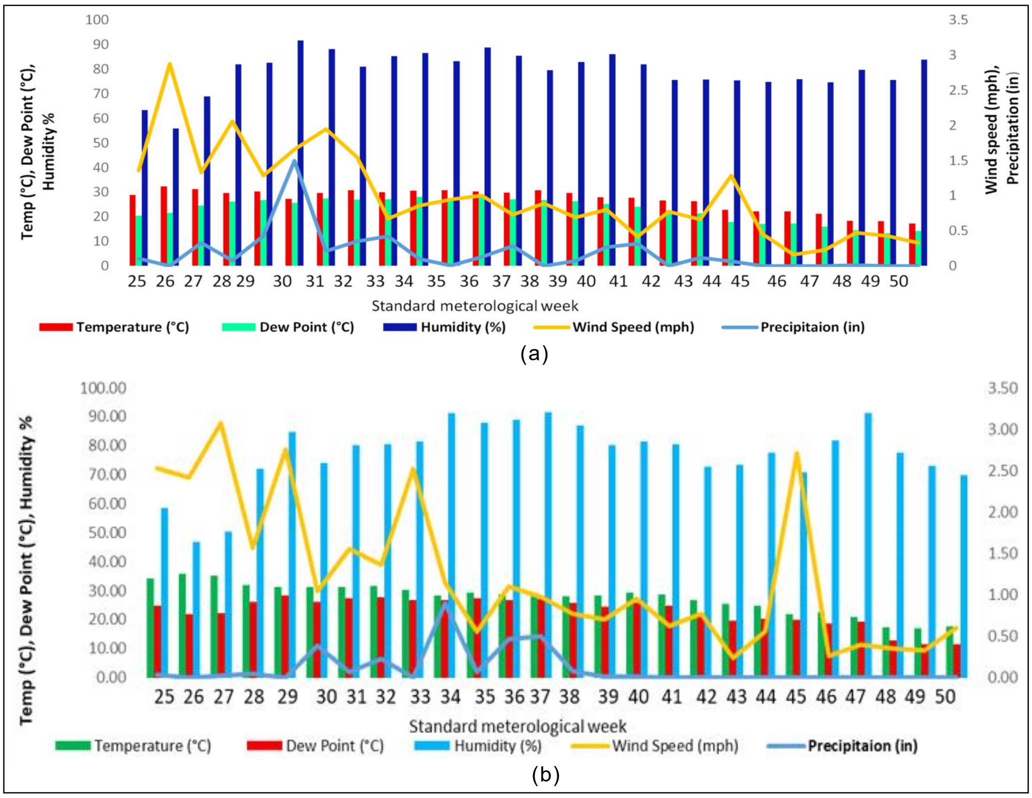

Fig 2a and 2b: Standard week wise meteorological data during the crop growth period June 2023-2024 to November 2023-2024.

Experimental details

A field experiment was conducted during the kharif seasons of 2023 and 2024 at Lovely Professional University, Phagwara, Punjab, in a split-plot design with four planting patterns (P_1: 50×25 cm, P_2: 30×25 cm, P_3: Raised bed 67.5 cm apart, P_4: 60×20 cm) as main plots and four nutrient sources (N1: Control, N_2: RDF, N_3: FYM, N_4: Integrated nutrient management (INM)) as sub-plots which replicated three times. Plot size for the current study was determined to be 6×5 m, or 30 m^2. Before seed was sown, it was treated with Rhizobium culture. In control plot no fertilizer applied, in case of RDF 15 kg N and 40 kg P_2O_5 supplied through urea and SSP as a basal dose, FYM was applied on the dry weight basis @ 3 t ha^{-1} at the time of land preparation and in INM 50% N supplied from RDF and 50% N from FYM.

Crop management

AL882 variety of Pigeonpea was used for the experiment which is short stature and early maturing variety. The seeds were sownduring 15th June and 18th June by dibbling method @ 15 kg ha^{-1} after treatment with Rhizobium culture during 2023 and 2024. All the intercultural operations were done as per the package and practices of PAU, Ludhiana for the normal growth of crops. Harvesting of Pigeonpea was done during 5th November and 8th November with sickle when the pods fully dried and brownish in colourindicated by a rattling sound when shaken. Harvesting was done manually by cutting the plants with a sickle. After cutting, the plants were left to dry in the field for several days before threshing. Threshing was done by separating the seeds from the pods by beating them with a stick.

Data recording

Data related to yield attributes were collected following established protocols (Rana and Kumar, 2014; Rana *et al.,* 2014). Following the final harvest, the Pigeonpea crops underwent sun-drying for a few days, after which their weights were recorded to determine the biological yield. Subsequently, the seed yield was documented. The stover yield was calculated by deducting the seed yield from the total biological yield. All recorded yields, including seed, straw and biological yield, were converted into kilograms per hectare (kg ha^{-1}). Harvest index typically expresses the ratio of economic yield to the above ground biomass and estimated by formula (Donald, 1962). Samples of seeds and stover were collected at harvest from various treatment plots. These samples, pertaining to both seed and stover of pigeonpea, were then subjected to oven drying at 65°C until a consistent dry weight was achieved. Following this, the samples were grounded and utilized for the quantification of nitrogen, phospho-rus and potassium content in both the stover and straw. The processed plant samples should be checked by micro-Kjeldahl's method to find nitrogen uptake (Jackson, 1973). Wet digestion (di-acid) method was used for the preparation of aliquot to analyze P and K uptake in plant samples. Vando-molybdate yellow colour method was used for the analysis of phosphorous by using spectrophotometer (Jackson, 1973) and flame photometer for the potassium as discussed by Richards (1954). Total nitrogen was taken into consideration for the estimation of crude protein using the standard nitrogen-to-protein conversion factor.Protein yield was then estimated from protein content multiplied by seed yield.Soil microbial population-bacteria, fungi and actinomycetes were estimated by serial dilution and pour plate method suggested by (Waksman, 1922; Alexander, 1977).

Statistical analysis

To assess the statistical significance of each param-eter, the data were analyzed using analysis of variance (ANOVA). The F-test was used to analyze all the sample data obtained from the two-year experiment, following the approach outlined by (Gomez and Gomez*,* 1984). The significance of the difference between treatment means was determined using Least Significant Difference (LSD) val-ues at a significance level of $p<0.05$.

RESULTS AND DISCUSSION

Effect of different planting pattern and nutrient management on seed yield and yield attributes of pigeonpea

The yield attributes of Pigeonpea were significantly affected by planting patterns and nutrient management strategies in both years of the study (Table 1). Raised bed planting (P_3) consistently showed the highest pod count $plant^{-1}$ (98.85 and 86.47), followed by conventional sowing (P_1) with 97.27 and 84.67 pods $plant^{-1}$, however the lowest counts were observed under narrow spacing (P_2) with 82.76 and 70.85 pods $plant^{-1}$ in 2023 and 2024, respectively. Likewise, the quantity of seeds pod^{-1}, pod length and seed index were significantly enhanced in P_3, recording values of 3.81 and 2.72 seeds pod^{-1}, 5.24 and 4.09 cm in pod length and 10.77 and 8.55 g for seed index during the two years. The enhanced performance of P_3 may be attributed to superior aeration, increased root proliferation and improved resource utilization efficiency linked to raised bed systems. Among the nutrient treatments, Integrated Nutrient Management (N_4) shows a notable enhancement in yield components. N_4 exhibited the highest pod count $plant^{-1}$ (106.65 and 93.77), maximum seed count pod^{-1} (3.98 and 3.04), greatest pod length (5showsd 4.41 cm) and highest seed index (11.0 and 8.93 g). On the other hand, the control (N_1) demonstrated the lowest values for these characteristics. The enhanced performance under N_4 may result from the synergistic interaction of organic and inorganic nutrition sources, which increases nutrient availability and facilitates improved physiological processes, as noted by Garud *et al.,* 2018. Seed yield was markedly affected by planting patterns and nutrient management (Table 2). P_3 performed better among all other planting configurations, yielding the highest seed output (1188.23 and 1051.04 kg ha^{-1}), closely followed by P_1. The minimum seed production was recorded in P_2 (968.18 and 825.51 kg ha^{-1}). N_4 demonstrated superiority among

Table 1: Effect of nutrient management and planting patterns on yield attributes of pigeonpea.

Treatments	Number of pods plant^{-1}		Number of seeds pod^{-1}		Pod length (cm)		Seed index (g)	
	At harvest		At harvest		At harvest		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
Main plot factor: Planting pattern								
P_1	97.27	84.675	3.61	2.415	4.68	3.744	10.42	8.266
P_2	82.76	70.852	2.82	1.775	4.04	3.092	9.92	7.999
P_3	98.85	86.476	3.81	2.72	5.24	4.097	10.77	8.55
P_4	93.73	78.351	3.38	2.524	4.27	3.598	10.18	8.319
SE(m)±	0.21	0.736	0.11	0.018	0.05	0.008	0.09	0.072
CD (p<0.05)	0.74	2.598	0.41	0.065	0.20	0.027	0.32	0.253
Sub plot factor: Nutrient source								
N_1	72.42	59.651	2.87	1.369	3.99	2.463	9.43	7.479
N_2	100.78	88.077	3.52	2.567	4.59	3.937	10.57	8.488
N_3	92.76	78.852	3.25	2.456	4.42	3.722	10.29	8.238
N_4	106.65	93.774	3.98	3.043	5.24	4.41	11.00	8.93
SE(m)±	0.48	0.599	0.07	0.014	0.08	0.025	0.12	0.074
CD(p<0.05)	1.40	1.759	0.22	0.04	0.24	0.072	0.37	0.218
P × N								
Factor (B) at same level of A	2.85	3.756	NS	0.086	NS	0.145	NS	0.457
Factor (A) at same level of B	2.54	3.988	NS	0.094	NS	0.128	NS	0.453

*P_1: 50×25 cm, P_2: 30×25 cm, P_3: Raised bed 67.5cm apart, P_4: 60×20 cm, N_1: Control, N_2: RDF, N_3: FYM, N_4: INM.

Table 2: Effect of planting pattern and nutrient management on seed, stover and biological yields and HI of pigeonpea.

Treatments	Seed yield (kgha^{-1})		Stover yield (kg ha^{-1})		Biological yield (kg ha^{-1})		HI (%)	
	2023	2024	2023	2024	2023	2024	2023	2024
Main plot factor: Planting pattern								
P_1	1147.75	968.97	4827.67	3918.08	5975.42	4887.05	19.16	19.91
P_2	968.18	825.53	4254.17	3244.75	5222.35	4070.28	18.54	20.18
P_3	1188.23	1051.05	4961.75	4133.35	6149.98	5184.40	19.32	20.21
P_4	1082.10	969.98	4621.83	3906.22	5703.93	4876.20	18.91	19.86
SE(m)±	7.32	6.82	30.26	33.90	32.08	38.98	0.14	0.09
CD ($p<0.05$)	25.85	24.07	106.75	119.60	113.18	137.52	0.49	NS
Sub plot factor: Nutrient source								
N_1	860.4	754.78	3812.17	3126.35	4672.57	3881.13	18.41	19.44
N_2	1168.57	1021.72	5069.33	4115.20	6237.90	5136.93	18.79	19.95
N_3	1025.55	913.48	4236.50	3627.75	5262.05	4541.23	19.34	20.09
N_4	1331.75	1125.55	5547.42	4333.10	6879.17	5458.65	19.47	20.68
SE(m)±	7.10	7.25	32.17	26.89	30.09	27.35	0.18	0.17
CD($p<0.05$)	20.84	21.29	94.48	78.94	88.35	80.31	0.53	0.51
P × N								
Factor (B) at same level of A	43.89	44.53	197.62	168.90	186.48	173.68	NS	NS
Factor (A) at same level of B	44.25	43.89	194.75	180.93	189.64	194.79	NS	NS

*P_1: 50×25 cm, P_2: 30×25 cm, P_3: Raised bed 67.5cm apart, P_4: 60×20 cm, N_1: Control, N_2: RDF, N_3: FYM, N_4: INM.

nutritional sources, yielding 1331.75 kg ha^{-1} in 2023 and 1125.55 kg ha^{-1} in 2024. The control treatment showed the lowest yields (860.4 and 754.77 kg ha^{-1}). A same trend was noted for stover and biological yields. P_3 produced the maximum stover yield (4961.75 and 4133.35 kg ha^{-1}), while P_2 provided the minimum (4254.17 and 3244.76 kg ha^{-1}). The combination of INM (N_4) significantly improved stover yield (5547.42 and 4333.12 kg ha^{-1}), while the control exhibited the lowest stover production. The biological yield exhibited a similar trend, with highest levels recorded under P_3 (6149.98 and 5184.40 kg ha^{-1}) and N_4 (6879.17 and 5458.60 kg ha^{-1}), indicating enhanced biomass accumulation through integrated methodologies. The harvest index (HI), indicative of the efficiency of assimilate allocation to economic yield, was influenced by planting patterns and nutrient treatments. The highest HI was recorded in P_3 (19.32% and 20.21%) and in N_4 (19.47% and 20.68%) in 2023 and 2024, respectively. The lowest values were recorded in P_2 and the control group (N_1). The interaction effect of planting pattern and nutrient management was non-significant for harvest index; however, the overall improvement under P_3 and integrated nutrient management treatments may be due to improved nutrient absorption, superior root development and increased microbial activity in the rhizosphere, promoted by the incorporation of farmyard manure and optimal plant arrangement (Rao *et al.,* 2022; Garud *et al.,* 2018).These findings highlight the necessity of optimizing spatial configuration and nutrient integration to improve yield characteristics and productivity in pigeonpea.

Effect of different planting pattern and nutrient management on nutrient uptake, nutrient content and quality of pigeonpea

The concentrations of nitrogen, phosphorus and potassium in the seed and stover of Pigeonpea were considerably influenced by planting pattern and nutrient management during both years, as indicated in Table 3. The highest concentrations of nitrogen (3.15, 3.16%), phosphorus (0.394, 0.491%) and potassium (0.815, 0.824%) in seeds were observed in P3 throughout planting patterns for 2023 and 2024. The minimum concentrations of nitrogen (2.588, 2.398%), phosphorus (0.309%, 0.409%) and potassium (0.731, 0.748%) were recorded in P_2 for both years. N_4 demonstrated the maximum concentrations of nitrogen (3.228, 3.270%), phosphorus (0.408, 0.508%) and potassium (0.815, 0.841%) in the years 2023 and 2024. The control, without any external nutrition, had the lowest concentrations of nitrogen (2.469, 2.142%), phosphorus (0.310, 0.412%) and potassium (0.719, 0.707%) in seeds for the years 2023 and 2024.

A comparable pattern was noted regarding stover content in both years, with P_3 showing the highest levels of nitrogen (1.66, 1.328%), P (0.133, 0.145%) and K (1.362, 1.165%) in stalk. nitrogen, phosphorus and potassium concentrations in Pigeonpea stover are enhanced by N_4, indicating highest levels of nitrogen (1.206, 1.523%), phosphorus (0.133, 0.156%) and potassium (1.376, 1.165%), as presented in Table 4. The interaction effect of planting pattern and nutrient sources was determined to be non-significant for the nitrogen, phosphorus and potassium content in the seeds and stalks of Pigeonpea.

Table 3: Effect of planting pattern and nutrient sources on nutrient content % in seed.

Treatments	Nitrogen content (%) in seed		Phosphorus content (%) in seed		Potassium content (%) in seed	
	2023	2024	2023	2024	2023	2024
Main plot factor: Planting pattern						
P_1	2.951	2.973	0.393	0.493	0.774	0.798
P_2	2.588	2.398	0.309	0.409	0.731	0.748
P_3	3.159	3.168	0.394	0.494	0.815	0.825
P_4	2.686	2.768	0.329	0.429	0.758	0.778
SE(m)±	0.025	0.076	0.004	0.004	0.004	0.009
CD(p<0.05)	0.087	0.267	0.012	0.012	0.015	0.031
Sub plot factor: Nutrient source						
N_1	2.469	2.142	0.312	0.412	0.719	0.707
N_2	2.994	3.098	0.373	0.473	0.79	0.823
N_3	2.692	2.798	0.333	0.433	0.754	0.778
N_4	3.228	3.27	0.408	0.508	0.815	0.841
SE(m)±	0.028	0.067	0.007	0.007	0.007	0.006
CD(p<0.05)	0.083	0.198	0.022	0.022	0.021	0.018
P × N						
Factor (B) at same level of A	0.172	NS	NS	NS	NS	NS
Factor (A) at same level of B	0.167	NS	NS	NS	NS	NS

*P_1: 50×25 cm, P_2: 30×25 cm, P_3: Raised bed 67.5cm apart, P_4: 60×20 cm, N_1: Control, N_2: RDF, N_3: FYM, N_4: INM.

The uptake of nitrogen, phosphorus and potassium in both seeds and stalks was significantly influenced by planting patterns and fertiliser management over both years of the study. Table 5 presents data regarding the overall uptake, including both seed and stover uptake. P_3 had the highest nitrogen uptake (96.15 and 108.93 kg ha^{-1}) for the years 2023 and 2024, respectively. In the same way, regarding phosphorus and potassium uptake (Table 6), the highest phosphorus uptake (11.42, 13.34 kg ha^{-1}) and potassium uptake (77.54, 68.08 kg ha^{-1}) was recorded in P_3, while the lowest uptake of nitrogen (72.63, 77.35 kg ha^{-1}), phosphorus (7.48, 9.02 kg ha^{-1}) and potassium (63.63, 53.45 kg ha^{-1}) was observed for both years. The N_4 treatment of the subplot demonstrated the highest absorption of

Table 4: Effect of planting pattern and nutrient sources on Nutrient content % in stover.

Treatments	Nitrogen content % in stover		Phosphorus content (%) in stover		Potassium content (%) in stover	
	2023	2024	2023	2024	2023	2024
Main plot factor: Planting pattern						
P_1	1.146	1.332	0.117	0.135	1.353	1.124
P_2	1.091	1.216	0.103	0.115	1.325	1.081
P_3	1.166	1.382	0.133	0.145	1.362	1.165
P_4	1.125	1.27	0.109	0.118	1.323	1.108
SE(m)±	0.018	0.017	0.004	0.009	0.006	0.004
CD(p<0.05)	NS	0.061	0.015	NS	0.02	0.015
Sub plot factor: Nutrient source						
N_1	1.032	0.716	0.1	0.08	1.308	1.069
N_2	1.175	1.465	0.116	0.134	1.345	1.14
N_3	1.115	1.495	0.113	0.143	1.333	1.104
N_4	1.206	1.523	0.133	0.156	1.376	1.165
SE(m)±	0.016	0.017	0.006	0.01	0.006	0.007
CD (p<0.05)	0.046	0.051	0.018	0.029	0.018	0.021
P × N						
Factor (B) at same level of A	NS	NS	NS	NS	NS	NS
Factor (A) at same level of B	NS	NS	NS	NS	NS	NS

*P_1: 50×25 cm, P_2: 30×25 cm, P_3: Raised bed 67.5cm apart, P_4: 60×20 cm, N_1: Control, N_2: RDF, N_3: FYM, N_4: INM.

Table 5: Effect of planting pattern and nutrient sources on nitrogen uptake (kg ha^{-1}) by seed and stalk and Total nitrogen uptake kg ha^{-1}.

Treatments	Nitrogen uptake by seed kg ha^{-1}		Nitrogen uptake by stalk (kg ha^{-1})		Total nitrogen uptake (kg ha^{-1})	
	2023	2024	2023	2024	2023	2024
Main factor: Planting pattern						
P_1	34.205	34.684	55.767	65.965	89.972	100.648
P_2	25.723	23.959	46.914	53.397	72.637	77.356
P_3	37.939	38.386	58.218	70.547	96.157	108.936
P_4	29.542	30.718	52.373	60.147	81.915	90.863
SE(m)±	0.282	0.632	0.778	0.619	0.646	1.14
CD(p<0.05)	0.995	2.231	2.744	2.183	2.279	4.02
Sub factor: Nutrient source						
N_1	21.445	18.65	39.429	27.502	60.874	46.151
N_2	35.202	36.382	59.584	74.45	94.785	110.835
N_3	27.815	28.915	47.279	63.378	75.094	92.293
N_4	42.948	43.801	66.98	84.725	109.928	128.524
SE(m)±	0.4	0.789	0.637	0.878	0.761	0.971
CD(p<0.05)	1.176	2.317	1.871	2.577	2.234	2.851
P × N						
Factor(B) at same level of A	2.419	NS	3.992	5.302	NS	2.851
Factor(A) at same level of B	2.262	NS	4.23	4.958	NS	6.063

50×25 cm, P_2: 30×25 cm, P_3: Raised bed 67.5cm apart, P_4: 60×20 cm, N_1: Control, N_2: RDF, N_3: FYM, N_4: INM.

nitrogen (109.92, 128.52 kg ha^{-1}), phosphorus (12.94, 15.51 kg ha^{-1}) and potassium (87.25, 75.98 kg ha^{-1}), whereas the control exhibited the lowest uptake of nitrogen (60.87, 46.15 kg ha^{-1}), phosphorus (6.52, 6.65 kg ha^{-1}) and K (56.06, 46.88 kg ha^{-1}) in the years 2023 and 2024, respectively. The interaction effect of planting pattern and nutrient management sources was significant for total nitrogen and potassium uptake, however the interaction for phosphorus uptake was non-significant in both years. The use of INM demonstrated the maximum nutrient absorption due to the quick availability of nutrients from RDF and the continuous supply of micronutrients from FYM (Rao *et al.,* 2022; Babu

Table 6: Effect of planting pattern and nutrient sources on phosphorous uptake (kg ha^{-1}) by seed and stalk and total phosphorous uptake kg ha^{-1}.

Treatments	Phosphorous uptake by seed kg ha^{-1}		Phosphorous uptake by stover kg ha^{-1}		Total phosphorous uptake kg ha^{-1}	
	2023	2024	2023	2024	2023	2024
Main factor: Planting pattern						
P_1	4.588	5.737	5.729	6.712	10.317	12.449
P_2	3.026	3.993	4.461	5.031	7.487	9.023
P_3	4.762	5.952	6.69	7.391	11.452	13.34
P_4	3.634	4.718	5.067	5.584	8.701	10.301
SE(m)±	0.062	0.068	0.221	0.458	0.204	0.477
CD ($p<0.05$)	0.218	0.241	0.779	1.614	0.718	1.684
Sub factor: Nutrient source						
N_1	2.698	3.558	3.822	3.096	6.52	6.655
N_2	4.383	5.552	5.895	6.853	10.279	12.405
N_3	3.432	4.46	4.782	6.077	8.215	10.534
N_4	5.497	6.829	7.448	8.692	12.945	15.519
SE(m)±	0.091	0.093	0.267	0.479	0.268	0.458
CD ($p<0.05$)	0.266	0.274	0.784	1.406	0.787	1.345
P × N						
Factor (B) at same level of A	0.547	0.565	NS	NS	NS	NS
Factor (A) at same level of B	0.509	0.531	NS	NS	NS	NS

*P_1: 50×25 cm, P_2: 30×25 cm, P_3: Raised bed 67.5cm apart, P_4: 60×20 cm, N_1: Control, N_2: RDF, N_3: FYM, N_4: INM.

Table 7: Effect of planting pattern and nutrient sources on Potassium uptake (kg ha^{-1}) by seed and stover and Total potassium uptake kg ha^{-1}.

Treatments	Potassium uptake (kg ha^{-1})					
	Potassium uptake by seed (kg ha^{-1})		Potassium uptake by stalk (kg ha^{-1})		Total potassium uptake (kg ha^{-1})	
	2023	2024	2023	2024	2023	2024
Main factor: Planting pattern (cm)						
P_1	8.946	9.257	65.44	54.512	74.386	63.768
P_2	7.114	7.294	56.526	46.158	63.639	53.453
P_3	9.771	9.919	67.779	58.159	77.549	68.078
P_4	8.271	8.501	61.219	51.45	69.49	59.95
SE(m)±	0.079	0.128	0.428	0.463	0.476	0.56
CD ($p<0.05$)	0.279	0.453	1.51	1.634	1.681	1.974
Sub factor: Nutrient source						
N_1	6.199	6.09	49.868	40.793	56.068	46.882
N_2	9.259	9.641	68.217	57.882	77.476	67.522
N_3	7.76	8.01	56.504	46.848	64.264	54.86
N_4	10.883	11.23	76.374	64.756	87.257	75.986
SE(m)±	0.083	0.093	0.441	0.591	0.463	0.571
CD ($p<0.05$)	0.243	0.272	1.296	1.734	1.361	1.675
P × N						
Factor (B) at same level of A	0.508	0.587	2.716	3.587	2.864	3.514
Factor (A) at same level of B	0.503	0.651	2.696	3.41	2.885	3.498

*P_1: 50×25 cm, P_2: 30×25 cm, P_3: Raised bed 67.5cm apart, P_4: 60×20 cm, N_1: Control, N_2: RDF, N_3: FYM, N_4: INM.

Table 8: Effect of planting pattern and nutrient sources on quality parameters and microbial population of pigeonpea.

Treatments	Quality				Microbial population					
	Protein content (%)		Protein yield (kgha^{-1})		Bacteria (No. × 10^5 cfug^{-1})		Fungi (No. × 10^4 cfug-^{1})		Actinomycetes (No. × 10^3 cfug^{-1})	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
Planting pattern (cm)										
P1	18.443	18.585	213.783	216.768	56.875	58.223	13.097	13.352	23.018	23.244
P2	16.172	14.992	160.767	149.753	50.659	50.953	9.312	9.581	21.072	21.204
P3	19.745	19.803	237.12	239.919	60.62	60.844	14.751	14.843	25.164	25.345
P4	16.786	17.298	184.636	191.979	54.273	53.633	10.641	10.881	21.885	22.219
SE (m)±	0.154	0.473	1.766	3.953	0.207	0.25	0.199	0.154	0.225	0.242
CD (p=0.05)	0.543	1.669	6.231	13.945	0.729	0.881	0.703	0.543	0.793	0.855
Nutrient source										
N1	15.432	13.388	134.03	116.561	47.983	43.792	7.918	7.438	19.263	18.149
N2	18.714	19.361	220.009	227.393	52.776	54.299	11.073	11.528	21.266	21.728
N3	16.823	17.492	173.842	180.715	62.483	64.817	14.597	15.281	26.971	27.601
N4	20.177	20.438	268.425	273.75	59.185	60.746	14.212	14.41	23.64	24.534
SE (m)±	0.176	0.421	2.503	4.931	0.318	0.203	0.377	0.219	0.4	0.257
CD (p=0.05)	0.516	1.236	7.349	14.479	0.934	0.595	1.105	0.644	1.175	0.754
P × N										
Factor (B) at same level of A	1.075	NS	15.12	NS	1.915	1.27	NS	1.325	2.396	1.578
Factor (A) at same level of B	1.043	NS	14.139	NS	1.771	1.351	NS	1.238	2.181	1.556

*P_1: 50×25 cm, P_2: 30×25 cm, P_3: Raised bed 67.5cm apart, P_4: 60×20 cm, N_1: Control, N_2: RDF, N_3: FYM, N_4: INM.

et al., 2020). It is clear from the data in Table 7 that nutrition sources and planting pattern had a major impact on protein content. The highest protein content (19.74, 19.80%) in seed was found in P_3 for both 2023 and 2024. P_2 has the lowest protein content (16.17, 14.99%). Regarding nutrient management sources, N_4 had the highest protein level (20.17, 20.43%) in 2023 and 2024, while control had the lowest protein content (15.43, 13.38%). Similarly, in both years, P_3 (237.12, 239.91 kg ha^{-1}) and N_4 (268.42, 273.75 kg ha^{-1}) had the highest protein yields. Protein yield and content showed a significant relationship in 2023, while both parameters showed a non-significant interaction in the second year of the trial. The application of INM might have enhanced nitrogen availability and efficiency, which might have accelerated protein synthesis because nitrogen is known to be the basic constituent of proteins (Sarkar *et al.,* 2025; Bansal *et al.,* 2023).

Impact of nutrient management and planting patterns on the microbial population

Planting patterns and nutrient management sources had a major impact on the microbial population, which includes bacteria, fungus and actinomycetes (Table 8). P_3 had the highest number of bacteria (60.62, 60.84), fungi (14.75, 14.84) and actinomycetes (25.16, 25.34) among the planting patterns. P_2 (30 × 25 cm) had the lowest number of bacteria (50.65, 50.95), fungi (9.31, 9.58) and actinomycetes (21.07, 21.20) during the two study years. Similarly, subplot N4 had the highest counts of bacteria (52.48, 64.81), fungi (14.59, 15.21) and actinomycetes (26.97, 27.60) in 2023 and 2024, while control, or no external nutrient application, had the lowest counts of bacteria (47.98, 43.79), fungi (7.91, 7.43) and actinomycetes (19.26, 18.14). With the exception of fungus, which showed non-significant interaction in 2023, interaction between bacteria, fungi and actinomycetes was found to be substantial in both years. Additionally, the addition of FYM would have enhanced nutrient availability, nodulation and root growth by boosting rhizosphere microbial activity (Sarkar *et al.,* 2025; Dash *et al.,* 2024). The similar results found by Bhardwaj *et al.* (2023); Venkatesh *et al.* (2023) in their studies on nutrient management in pigeon pea based intercropping system.

CONCLUSION

This study revealed that planting pattern and nutrient management significantly affect the growth, production, nutrient uptake and quality of Pigeonpea. The combination of raised bed planting (P_3) and Integrated Nutrient Management (N_4) consistently performed better than other treatments by improving yield characteristics, seed and stalk yield, biological yield and nutrient use efficiency throughout both years of the trial. This combination resulted in enhanced protein content and microbial populations, signifying beneficial effects on soil biological health. The exceptional performance of INM is due to the synergistic effect of a balanced nutrient supply from both organic (FYM) and inorganic sources (RDF), which provided continuous nutrient availability and enhanced microbial activity. Raised bed planting improved soil aeration, root development and moisture retention, therefore increasing the utilization of nutrients and crop yield. These findings highlight the possibility of combining raised bed planting with integrated nutrient management as a sustainable agricultural method to improve Pigeonpea yield and maintain soil fertility under agro-climatic conditions of Punjab.

ACKNOWLEDGEMENT

The present study was supported by Lovely Professional University, Phagwara, Punjab.

Disclaimers

The views and conclusions presented in this article, "A Sustainable Approach Towards Pigeonpea Production: Effects of Planting Pattern and Nutrients Supply on Yield, Uptake and Nutritional Quality," are solely those of the authors and do not necessarily reflect the views or policies of their affiliated institutions or funding bodies. The authors are responsible for the accuracy, analysis and interpretation of the information provided. However, they assume no liability for any direct, indirect, incidental, or consequential losses or damages that may arise from the use, application, or interpretation of the content presented in this study.

Informed consent

This study was truly based on crop research only.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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