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Optimization of plant spacing and fertilizer levels for enhanced growth and yield of hybrid pigeonpea (*Cajanus cajan* L.)

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Abstract
To address India's increasing demand for pulses, it is imperative to enhance the productivity of pigeonpea hybrids through the implementation of advanced agronomic practices, specifically modify to optimize their potential across diverse soil types. Therefore, we conducted a field experiment combining plant geometry and nutrient management strategy on hybrid pigeonpea (ICP 15-3) in black soil at Regional Agriculture Research Station, Warangal, Telangana during *kharif* 2024-25. In hybrid pigeonpea, more grain yield (1178 kg/ha) and B:C ratio was recorded with plant geometry 120 x 30 cm (27,777 Plants/ha) and 2.33 respectively and it was at par with 90 x 30 cm (37,037 Pl/ha) (1146 kg/ha) and 2.24. Among the fertilizer doses significantly higher yields and B:C ratio obtained in 25: 50:25: 20 kg NPKS /ha + NPKZn Bio consortia (1276 kg/ha) and 2.47 respectively, which is on par with 20: 40:25: 20 kg NPKS /ha + NPKZn Bio consortia (1247 kg/ha) and B:C ratio of 2.48 when compared other treatments. Interaction between spacing and fertilizer levels was significant. Among fertilizer treatments, F_6 (30:60:30:20 kg NPKS ha^{-1} + bio-consortia) significantly enhanced available soil N, P and K after harvest, indicating improvement in soil fertility status. Higher nutrient uptake by plants under F_4 treatment could be attributed to synergistic effects of inorganic fertilizers and bio-consortia, which enhance nutrient solubilization and absorption efficiency.

Keywords: Hybrid pigeonpea, spacing, bio-consortia, fertilizer doses, integrated nutrient management, production and productivity

Introduction
Pigeonpea (*Cajanus cajan* (L.) Millsp.) is a significant pulse crop extensively cultivated in the semi-arid tropics, notably in India. It plays a crucial role in human nutrition by providing protein, enhances soil fertility through biological nitrogen fixation, and improves soil organic matter content via leaf defoliation during maturity. Consequently, pulses are instrumental in advancing sustainable agricultural practices. (Nagalaxmi *et al.*). Pulses are popularly known as rich source of protein, they maintain soil fertility through biological nitrogen fixation and overall pulse production. On account of biological nitrogen fixation, addition of considerable amount of organic matter through root biomass and leaf fall, deep root-systems, mobilization of nutrients, protection of soil against erosion and improving microbial biomass, they keep soil productive and alive by bringing qualitative changes in physical, chemical and biological properties (Bansal *et al.*, 2011) [1]. As a soil ameliorant, pigeonpea is known to provide several benefits to the soil in which it is cultivated (Murali *et al.*, 2014) [7]. Despite its importance, average productivity of pigeonpea remains relatively low due to sub-optimal agronomic and nutrient management practices. Therefore, improved practices such as optimized plant geometry and balanced nutrient supply are essential to enhance crop performance and productivity sustainably. Plant spacing influences plant population dynamics, light interception, nutrient uptake, branch proliferation, and canopy structure, which directly affect yield attributes and final grain yield. Wider plant spacing can reduce intra-plant competition but may underutilize land area, whereas narrower spacing increases competition for water, nutrients and light, potentially reducing yield contribution per plant (Bathula Venkatesh *et al.*, 2023) [2]. Studies on pigeonpea have shown that plant geometry significantly affects growth parameters,

yield attributes, and productivity, demonstrating the necessity of identifying ideal row and plant spacing for specific agro-ecological conditions.

Balanced fertilizer application is another crucial factor governing the growth and yield of pigeonpea. Fertilizer is a vital input in agriculture to boost the crop yields. (Madhu *et al.*, 2024) [5]. Nitrogen (N), phosphorus (P) and potassium (K), collectively known as NPK, are essential macronutrients crucial for plant growth, supporting key physiological and biochemical processes such as photosynthesis, protein synthesis, and energy transfer. (Nagalaxmi Doddamani *et al.*, 2024) [8]. Integrated nutrient management combining chemical fertilizers with bio-consortia or bio-fertilizers has been reported to improve nutrient availability, soil microbial activity and nutrient use efficiency, resulting in enhanced growth and yield. Biofertilizers such as phosphorus-solubilizing bacteria (PSB), Rhizobium and other microbial consortia play a significant role in mobilizing native soil nutrients, enhancing nodulation and supporting sustainable pulse production by reducing dependency on chemical fertilizers. Integrated nutrient management approaches combining bio-fertilizers with recommended fertilizer doses have been consistently shown to improve yield and maintain soil health in pigeonpea. Despite these documented effects, limited research has focused on the combined influence of plant spacing and integrated fertilizer management (including bio-consortia) in hybrid pigeonpea under field conditions. Therefore, the present field study was designed to standardize optimal plant spacing and fertilizer doses for maximizing growth and yield of hybrid pigeonpea under *kharif* conditions.

Materials and Methods

A field experiment was conducted at D-block, Regional Agriculture Research Station, Warangal, Telangana during *kharif* 2024-25. The experimental site is situated in the Central Telangana Agro-climatic zone. The soil of the experimental site was clay loam in texture with neutral pH level (7.2), an electrical conductivity (EC) of 0.60 dSm^{-1}, the organic carbon (%) was 0.31 and available nitrogen, phosphorus and potassium was 206, 29.5 and 297.4 kg/ha, respectively. The total rainfall received during the crop-growing period was 1082.6 mm.The experiment was laid out in a factorial randomized block design (FRBD), with two spacing's i.e. (S_1: 90 cm x 30 cm and S_2: 120 cm x 30 cm) and six fertilizer doses (F_1 -20: 40: 20: 20 Kg NPKS /ha; F_2 - 25: 50:25: 20 kg NPKS /ha; F_3 - F_1 + Bio consortia @10 g/kg seed (NPKZn); F_4 - F_2 + Bio consortia @10g/kg seed(NPKZn); F_5-15:30: 15: 20 kg NPKS /ha + Bio consortia @10g/kg seed (NPKZn); and F_6 -30:60:30:20 + Bio consortia @10 g/kg seed(NPKZn)replicated thrice.In all there were twelve treatment combinations. Plot size was maintained at 7.2 m × 4.2 m, and seeds of hybrid pigeonpea (IPH-15-3) were sown manually at specified plant spacings, sowing was carried out on 10 July 2024.Bio-consortia included microbial inoculants known to enhance nutrient mobilization (Rhizobium, phosphorus-solubilizing bacteria, potassium-solubilizing bacteria and ZSB), improving nutrient availability beyond conventional fertilization. Fertilizers were applied basally and as per treatment specifications. Weeds were controlled properly with applying of pre-emergence and post-emergence herbicides. Appropriate plant protection measures were proactively implemented as required. Observations on key growth parameters (plant height, branches per plant), yield attributes (pods per plant, seeds per pods and seed weight), and final yield (seed and stalk yield) were recorded at the time of harvest. Soil and plant nutrient analysis, were carried out following standard laboratory protocols. The economics were worked out based on the prevailing market price. Statistical analysis of the data, collected using a factorial randomized block design, was performed via ANOVA.

Results and Discussion

Growth parameters and Yield attributes

Plant spacing did not significantly influence plant height, number of branches and seed index of hybrid pigeonpea (Table 1). However, wider spacing of 120 cm × 30 cm recorded numerically higher number of pods per plant (112) and seeds per 10 pods (49.9) compared to closer spacing (90 × 30 cm). Wider spacing reduces inter-plant competition and improves light interception, nutrient availability, and photosynthetic efficiency, resulting in better reproductive growth (Venkatesh *et al*., 2025; Ganajaxi Math *et al*., (2023) [2, 14, 3]. Among fertilizer treatments, integrated application of inorganic fertilizers along with bio-consortia (NPKZn) significantly improved yield attributes. Treatments F_4 (25:50:25:20 kg NPKS ha^{-1} + bio-consortia) and F_3 (20:40:20:20 kg NPKS ha^{-1} + bio-consortia) recorded significantly higher pods/plant (119 & 120) and seeds/pod (58 & 52.7 respectively) compared to fertilizer-alone treatments. The beneficial effects of biofertilizers are attributed to enhanced biological nitrogen fixation, phosphorus solubilization, zinc mobilization and improved root growth, which collectively enhance nutrient uptake and assimilate partitioning. The significant interaction between spacing and fertilizer levels for yield attributes indicates that optimum nutrient supply expresses its full potential under favorable plant geo-metry, which is in agreement with findings reported in pigeonpea and other pulse crops.

Table 1: Effect of plant spacing and fertilizer doses on growth and yield attributes in hybrid Pigeonpea

Treatments		Plant population (%)	Plant height (cm) at harvest	No of branches at harvest	No of pods /plant	No of seeds /10 pods	Seed yield /plant	Seed index
Factor A: Plant Spacing								
P_1	90cm x 30cm (37,037 Plants/ha)	29440	144	8.0	105	42.5	8.4	8.4
P_2	120cm x 30cm (27,777 Plants/ha)	22033	146	7.7	112	49.9	8.5	8.5
	S.E. (m) ±	147.5	1.8	0.3	1.7	0.8	0.04	0.04
	CD (p=0.05)	NS	NS	NS	5.0	2.2	0.09	0.09
Factor B: Fertilizer Doses								
F_1	20: 40: 20: 20 Kg NPKS /ha	25568	145	7.3	96	39.2	8.3	8.3
F_2	25: 50:25: 20 kg NPKS /ha	25706	147	7.8	106	40.1	8.5	8.5
F_3	F_1 + Bio consortia (NPKZn)	25764	141	8.4	120	52.7	8.4	8.4
F_4	F_2 + Bio consortia (NPKZn)	25785	148	7.2	119	58.0	8.6	8.6
F_5	15:30: 15: 20 kg NPKS kg /ha + Bio consortia (NPKZn)	25818	147	8.0	102	39.7	8.4	8.4
F_6	30:60:30:20 NPKS kg/ha + Bio consortia (NPKZn)	25781	141	8.5	109	47.3	8.6	8.6
	S.E. (m) ±	255.5	3.2	0.4	3.0	1.3	0.1	0.1
	CD (p=0.05)	NS	NS	NS	8.7	3.9	0.15	0.15

	Interaction						
	S.E. (m) ±	361.4	4.5	0.6	4.2	1.9	0.1	0.1
	CD (p=0.05)	NS	NS	NS	12.3	5.5	NS	NS
	CV (%)	2.4	5.3	13.9	6.7	7.0	1.5	1.5

Grain yield and Economics

Wider plant spacing (120 cm × 30 cm) recorded higher seed yield (1178 kg/ha), gross monetary returns, net monetary returns (50769 Rs./ha), and benefit-cost ratio (2.33) compared to closer spacing, although differences were statistically non-significant (Table 2). Improved yield under wider spacing may be attributed to better canopy architecture, higher photosynthate accumulation, and efficient translocation towards flowers and developing pods (Mula, M.G. *et al.*, 2011) [6]. Among fertilizer treatments, F_4 (25:50:25:20 kg NPKS ha^{-1} + bio-consortia) produced the highest seed yield (1276 kg ha^{-1}) and net monetary returns, followed closely by F_3, which recorded the highest B:C ratio (2.48). Integrated nutrient management ensures balanced and continuous nutrient availability throughout the crop growth period, leading to higher productivity and economic returns (Sd Sabeeha Sultana *et al*., 2018) [12]. Phosphorus plays an important role in the higher yield, by stimulation of root development, metabolic processes and energy transformation in the plants, which in turn, resulted in higher translocation of photosynthates towards the sink development. Ultimately the seed yield plant^{-1} was improved which resulted in higher seed yield. The similar results were reported by Goud *et al.*, (2012) [4]. The significant interaction effect on seed yield and economic parameters suggests that appropriate fertilizer management combined with suitable spacing is crucial for realizing higher productivity and profitability in hybrid pigeonpea, corroborating earlier reports by (Venkatesh *et al*., 2023, Venkatesh *et al*., 2025) [2, 14]. The hybrid pigeonpea exhibited a highly favorable environment for effective utilization of available nutrients with maximum root development.

Table 2: Effect of plant spacing and fertilizer doses on yield (kg/ka) and economics in hybrid Pigeonpea

Treatments		Seed yield (kg/ha)	Biological yield (kg/ha)	Harvest Index	GMR (Rs/ha)	NMR (Rs/ha)	B:C Ratio
Factor A: Plant Spacing							
P_1	90cm x 30cm (37,037 Plants/ha)	1146	4466	25.6	86515	47882	2.24
P_2	120cm x 30cm (27,777 Plants/ha)	1178	4559	25.8	88901	50769	2.33
	S.E. (m) ±	20.2	63.7	0.2	1527	1527	0.04
	CD (p=0.05)	NS	NS	NS	NS	NS	NS
Factor B: Fertilizer Doses							
F_1	20: 40: 20: 20 Kg NPKS /ha	1034	4039	25.6	78067	40378	2.07
F_2	25: 50:25: 20 kg NPKS /ha	1166	4541	25.7	88046	49370	2.28
F_3	F_1 + Bio consortia (NPKZn)	1247	4789	26.0	94136	56147	2.48
F_4	F_2 + Bio consortia (NPKZn)	1276	4894	26.1	96325	57350	2.47
F_5	15:30: 15: 20 kg NPKS kg /ha + Bio consortia (NPKZn)	1091	4318	25.2	82358	45353	2.23
F_6	30:60:30:20 NPKS kg/ha + Bio consortia (NPKZn)	1157	4493	25.7	87316	47356	2.18
	S.E. (m) ±	35.0	110.4	0.3	2646	2646	0.07
	CD (p=0.05)	102.8	NS	NS	7759	7759	0.20
	Interaction						
	S.E. (m) ±	49.6	156.1	0.4	3741	3741	0.10
	CD (p=0.05)	145.3	NS	NS	10973	10973	0.28
	CV (%)	7.4	6.0	2.8	7.4	13.1	7.30

Nutrient content in soil and NPK uptakes by plant

Wider spacing (120 × 30 cm) resulted in significantly higher final soil phosphorus (48.8 kg/ha) and potassium content (310.7 kg/ha), likely due to lower nutrient depletion per unit area and improved nutrient recycling through crop residues. Similar observations were reported by Ganajaxi Math *et al.*, (2023) [3] in pigeonpea (Table 3). Among fertilizer treatments, F_6 (30:60:30:20 kg NPKS ha^{-1} + bio-consortia) significantly enhanced available soil N, P, and K after harvest (258.8, 55.4, 320.5 NPK kg/ha respectively), indicating improvement in soil fertility status. Higher nutrient uptake by plants under F_4 treatment could be attributed to synergistic effects of inorganic fertilizers and bio-consortia, which enhance nutrient solubilization and absorption efficiency F_4 (25:50:25:20 NPKS + bio consortia) recorded the highest N (101.4 kg/ha) and P (19.4 kg/ha) uptake, F_6 (30:60:30:20 NPKS + bio consortia) showed maximum K uptake (98.8 kg/ha), bio-consortia treatments consistently outperformed sole fertilizer applications (Sannathimaappa *et al.*, 2023) [11]. Interaction effects were significant only for final soil potassium content, while nutrient uptake remained non-significant, suggesting that fertilizer dose had a stronger influence on nutrient dynamics than plant spacing alone. These findings align with earlier studies emphasizing the role of integrated nutrient management in sustaining soil health and crop productivity (Sharma *et al.*).

Table 3: Effect of plant spacing and fertilizer doses on nutrient uptake (kg/ka) and soil fertility in hybrid Pigeonpea

Treatments		Final N content of soil (kg/ha)	Final P content of soil (kg/ha)	Final K content of soil (kg/ha)	N uptake by plant (kg/ha)	P uptake by plant (kg/ha)	K uptake by plant (kg/ha)
Factor A: Plant Spacing							
P_1	90cm x 30cm (37,037 Plants/ha)	247.9	45.2	297.2	83.7	17.0	**72.2**
P_2	120cm x 30cm (27,777 Plants/ha)	251.2	48.8	310.7	88.4	17.8	70.2
	S.E. (m) $\pm$	2.0	0.7	1.7	2.4	0.3	1.8
	CD (p=0.05)	NS	2.2	5.1	NS	NS	NS
Factor B: Fertilizer Doses							
F_1	20: 40: 20: 20 Kg NPKS /ha	240.6	37.7	290.9	73.8	16.2	49.1
F_2	25: 50:25: 20 kg NPKS /ha	250.8	46.3	295.8	84.5	17.2	63.2
F_3	F_1 + Bio consortia (NPKZn)	256.6	47.8	297.5	97.7	18.1	72.8
F_4	F_2 + Bio consortia (NPKZn)	254.3	47.7	304.7	101.4	19.4	92.9
F_5	15:30: 15: 20 kg NPKS kg /ha + Bio consortia (NPKZn)	236.4	47.3	314.3	71.4	15.3	50.6
F_6	30:60:30:20 NPKS kg/ha + Bio consortia (NPKZn)	258.8	55.4	320.5	87.5	18.5	98.8
	S.E. (m) $\pm$	3.4	1.3	3.0	4.1	0.6	3.2
	CD (p=0.05)	10.0	3.7	8.8	12.1	1.7	9.4
Interaction							
	S.E. (m) $\pm$	4.8	1.8	4.3	5.8	0.8	4.5
	CD (p=0.05)	NS	NS	12.5	NS	NS	NS
	CV (%)	3.3	6.7	2.4	11.8	8.1	11.0

Conclusion

Considering the findings from a year of experimentation, it can be concluded that the wider spacing of 120 x 30 cm (27,777 plants/ha) proved to be the most advantageous plant geometry with highest benefit-cost ratio (2.33) application of inorganic fertilizers (F_3) 25:50:25:20 kg NPKS/ha or (F_4) 20: 40: 20: 20 Kg NPKS /ha along with NPKZn Bio-consortia @10 g/kg seed as seed treatment recorded significantly higher grain yield, net returns of pigeonpea and it may be proved productive, profitable and economically viable to the farmers.

Conflict of Interest

All authors declared that there is no conflict of interest.

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