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RESEARCH ARTICLE

Integrated agronomic practices and their impact on hybrid pigeonpea productivity

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Abstract

To meet India's growing pulse demand, the productivity of pigeonpea hybrids must be enhanced through advanced agronomic practices tailored to optimize its potential in different soil types. Therefore, we conducted a field experiment combining planting methods, plant geometry and nutrient management strategy on hybrid pigeonpea (ICPH 2740) in black soil at ICRISAT, Hyderabad, during the 2021 and 2022 *kharif* seasons. The objective was to identify the best agronomic practices for yield optimization by examining growth parameters and yield components in relation to seed yield. The study evaluated 30 treatments using Principal Component Analysis (PCA) and correlation analysis to assess substantial variation and relationships among 11 quantitative components. From the mean PCA scoring it was found that higher influential yield components were number of secondary branches plant^{-1} and number of pods plant^{-1} over other components. Higher positive scoring with respect to the number of secondary branches plant^{-1} (2.94) and seed yield (0.32) was recorded with transplanting in the combination of 100 × 100 cm and integrated nutrient approach. However, the number of pods plant^{-1} scoring (0.96) was higher with transplanting in combination with 120 × 120 cm and integrated nutrient management. Similarly, from the correlation studies it was found that seed yield was highly correlated with the number of secondary branches plant^{-1} and the number of pods plant^{-1} (0.96 and 0.86 respectively). Transplanting pigeonpea resulted in a 33.4% higher mean seed yield compared to dibbling. In terms of plant geometry, individual plant yield was highest at 120 × 120 cm spacing; however, on a per-hectare basis, 100 × 100 cm spacing achieved 23.6% higher mean seed yield than 120 × 120 cm. Under transplanting and wider geometry (100 × 100 cm), hybrid pigeonpea recorded a 38% higher seed yield when supplemented with 100% Soil Test-Based (STB) NPK + vermicompost at 5 t ha^{-1} + phosphate-solubilizing bacteria (PSB) + *Rhizobium* seed treatment, compared to STB NPK alone. Ultimately, the combination of transplanting, 100 × 100 cm spacing and integrated nutrient management (100% STB NPK + vermicompost @ 5 t ha^{-1} + PSB + *Rhizobium* seed treatment) proved optimal for yield enhancement and cost-benefit analysis. These findings were consistently supported by PCA and correlation analysis.

Keywords

agronomic practices; hybrid pigeonpea; integrated nutrient management; transplanting; yield optimization

Introduction

To meet the growing demand for pigeonpea in India, efforts have shifted towards improving productivity through advanced agronomic practices and adopting high-yielding hybrids, as expanding the cultivated area is no longer feasible (1). In recent years, irregular monsoon patterns have created significant challenges for farmers, particularly in identifying the ideal sowing window for pigeonpea (2). Additionally, existing pigeonpea hybrids and varieties are photosensitive, causing them to flower simultaneously regardless of differences in sowing time (3). This results in suboptimal source development when planting dates are altered (4).

Ensuring pigeonpea is sown within its optimal planting window is essential for maximizing source development and yield. To overcome the challenges of delayed planting associated with traditional dibbling techniques, transplanting has emerged as a promising alternative. This innovative method helps maintain source-sink balance and ensures proper plant growth by aligning planting with the ideal sowing period (5). However, limited studies have compared the impacts of dibbling and transplanting on pigeonpea growth and yield, leaving a gap in scientific knowledge regarding transplanting's effects on sowing dates, growth parameters and overall productivity.

Another critical agronomic factor influencing pigeonpea performance is crop geometry. Poor crop geometry can lead to reduced plant efficiency, increased flower drop, inadequate ventilation and higher interplant competition (6). Optimizing crop geometry is vital to overcoming these issues. Research has explored various geometries based on factors such as cultivar type (hybrid or inbred), soil conditions, cultivation method (intercropping or sole cropping) and irrigation techniques (drip or surface irrigation) (7). Square planting has gained traction for enhancing the growth of primary, secondary and tertiary branches, thereby increasing leaf area (8). This improvement in leaf area and branching optimizes light interception and supports higher grain yields (9). However, very few studies have evaluated the effect of square planting on dibbling and transplanting on pigeonpea growth and yield, leaving a scientific knowledge gap.

Crop nutrition is another vital factor influencing pigeonpea growth and productivity. Providing nutrients in alignment with crop requirements fosters better growth and increased yields. Integrated nutrient management (INM) has been recognized as an effective strategy for pigeonpea nutrition (10). Organic manure offers a consistent nutrient supply throughout the crop's long growth period, aligning with its demand (11). Furthermore, biofertilizers like phosphorus-solubilizing bacteria (PSB) and *Rhizobium* enhance nutrient uptake efficiency by solubilizing native soil phosphorus and fixing atmospheric nitrogen, respectively (12). However, the impact of different nutrient management practices especially under various planting methods and crop geometry needs to be evaluated scientifically.

The efficient production and distribution of photosynthates to economically important plant parts largely depend on effective light interception (13). Consequently, adopting suitable planting methods (dibbling or transplanting), maintaining proper crop geometry and optimizing nutrient management are key interventions to enhance hybrid pigeonpea productivity. While previous studies have evaluated the individual effects of crop geometry (14), planting methods (15) and nutrient management (16) on pigeonpea growth, there is a lack of research on the combined influence of these factors. An integrated study is critical, as pigeonpea growth and yield are simultaneously affected by all these elements. This study aims to evaluate how different planting methods, combined with varying crop geometries and nutrient management strategies, impact the yield and growth components of hybrid pigeonpea.

Materials and Methods

A two-year field study was conducted at ICRISAT, Hyderabad, located at 17°51’04.7’’ N latitude and 78°26’91.7’’ E longitude, during the 2021 and 2022 *kharif* (rainy) seasons. The experimental site received a rainfall of 998.4 mm in 2021 and 1000 mm in 2022. The soil at the site is clay-textured, containing 49% clay, with a moderately alkaline pH of 8.1 and low organic carbon content (0.42%). The available soil nitrogen is 231 kg ha^{-1}, phosphorus is 29.8 kg ha^{-1} and potash is 350.5 kg ha^{-1}. The experiment was conducted using a split-split plot design to evaluate the combined effects of three key factors: planting method (dibbling vs transplanting), crop spacing (square planting vs conventional transplanting) and nutrient management (a combination of soil test-based fertilizers, biofertilizers and vermicompost). The treatment details are presented in Table 1. Here we have three factors with more emphasis on nutrient management (sub-sub factor), to assess whether the recommended dose of fertilizer is sufficient for hybrids under wider plant geometry in black soils, for that we have used split-split plot design. The impact of these treatments on growth, development and yield of pigeonpea was recorded at regular intervals and analyzed to find the best treatment combination for hybrid pigeonpea under black soil.

Table 1. Treatment details

Factors	Treatments
Main plot (Planting method)	M_1: Dibbling, M_2: Transplanting
Subplot (Spacing)	S_1: 100 cm × 100 cm S_2: 120 cm ×120 cm S_3: 150 cm × 60 cm (Normal transplanting)
Sub-sub (Nutrient Management)	N_1: Control; N_2:100% STB NPK (25:37.5:8.5 kg ha^{-1}); N_3: 100% STB NPK + vermicompost + PSB + seed treatment with *Rhizobium*; N_4: 150% STB NPK; N_5: 150% STB NPK + vermicompost + PSB + seed treatment with *Rhizobium*

The seedlings were raised in pro-trays filled with cocopeat and vermicompost in a 1:1 ratio and transplanted when they were 23-25 days old. Dibbling (seeds are placed in holes made at definite depths at fixed spacing and covered with soil) was performed on the same day as transplanting. The sowing was done on 20th June and 23rd June during 2021 and 2022 respectively. Vermicompost and PSB were mixed one week before application at 5 t ha^{-1} and 5 kg ha^{-1}, respectively and applied one day before sowing after the layout of fields in respective treatments. *Rhizobium* seed treatment at 500 g ha^{-1}, was done one hour before sowing. The pigeonpea hybrid "ICPH 2740 (Mannemkonda Kandi)," an indeterminate, photosensitive hybrid with a growth duration of 180–190 days, was used for this study. It is known for producing many secondary and tertiary branches under wider spacing, with a yield potential ranging from 2407 to 3652 kg ha^{-1}. The fertilizer application was done based on a soil test approach. All other agronomic practices like weed management, irrigation and insect pest and disease control were carried out as per the standard state recommendations. Growth parameters and yield components were recorded from five tagged plants in each plot and the average was used for analysis. Dry matter production, stover yield and seed yield were measured from net plot areas: S_1 (2.0 m × 4.0 m = 8.0 m^2), S_2 (3.6 m × 3.6 m = 12.96 m^2) and S_3 (3.0 m × 3.6 m = 10.8 m^2).

Statistical analysis

To better understand treatment effects, Principal Component Analysis (PCA) and correlation were conducted on the mean data using R software (Version 4.3.3) to evaluate relationships between growth parameters, yield components and overall seed yield. An angle of less than 45 degrees between the vectors of PCA indicates a significant relationship among them. Individual treatment-wise PCAs were also developed to identify which growth and yield components most influenced overall seed yield, with the scoring summarized in Table 2.

Results and Discussion

The results of the present study indicate that the number of pods per plant and the number of secondary branches per plant were significantly affected by different agronomic management practices (Fig. 1). Transplanting resulted in a significant increase in both the number of pods per plant (31.8%) and the number of secondary branches per plant (32.6%) compared to dibbling. This could be attributed to the vigorous and healthy seedlings planted within the optimal sowing window, which likely promoted better growth (4). Plant geometry also had a significant impact on pigeonpea yield in both years. The highest mean per-plant seed yield was observed with the 120 × 120 cm plant spacing, which was statistically similar to the 100 × 100 cm spacing (Table S1). However, the 100 × 100 cm crop geometry resulted in 17.5% and 30.1% more pods per plant and secondary branches per plant, respectively, compared to the 150 × 60 cm spacing (normal transplanting). The increased number of pods and branches in wider and square plant geometry could be due to better light distribution across the plant canopy (17). Regarding nutrient management, the combination of 100% soil test-based NPK with an integrated approach resulted in significantly higher pod and branch numbers (16.5% and 21.5%, respectively) compared to 100% soil test-based NPK alone. This improvement is likely due to the steady and sustained nutrient supply provided by the integrated nutrient management approach, which supported the better development of yield components compared to the sole use of soil test-based NPK (18).

Table 2. PCA scoring 30 treatment combinations

Treatment	No. of secondary branches $plant^{-1}$ (NSB)	No. of pods $plant^{-1}$ (NPP)	Seed yield (SY)
$M_1S_1N_1$	-2.635	-0.152	-0.037
$M_1S_1N_2$	-0.918	-0.123	-0.038
$M_1S_1N_3$	0.167	-0.422	0.064
$M_1S_1N_4$	-0.792	-0.123	-0.034
$M_1S_1N_5$	0.46	-0.583	0.025
$M_1S_2N_1$	-2.553	-0.418	0.127
$M_1S_2N_2$	-0.85	0.332	0.23
$M_1S_2N_3$	0.271	0.073	-0.091
$M_1S_2N_4$	-0.391	0.394	0.078
$M_1S_2N_5$	0.4737	0.169	0.084
$M_1S_3N_1$	-2.839	-0.309	-0.126
$M_1S_3N_2$	-1.414	-0.333	-0.272
$M_1S_3N_3$	-0.206	-0.678	0.053
$M_1S_3N_4$	-0.954	-0.163	-0.153
$M_1S_3N_5$	0.023	-0.613	0.192
$M_2S_1N_1$	-2.066	0.048	0.219
$M_2S_1N_2$	0.788	0.226	0.028
$M_2S_1N_3$	2.85	0.544	0.273
$M_2S_1N_4$	1.417	0.349	-0.328
$M_2S_1N_5$	2.94	0.31	0.322
$M_2S_2N_1$	-2.61	0.255	0.158
$M_2S_2N_2$	0.66	0.688	-0.014
$M_2S_2N_3$	2.54	0.884	0.221
$M_2S_2N_4$	1.51	0.813	-0.427
$M_2S_2N_5$	2.76	0.963	0.078
$M_2S_3N_1$	-2.279	0.17	0.175
$M_2S_3N_2$	0.083	-0.058	-0.372
$M_2S_3N_3$	1.28	-0.944	-0.14
$M_2S_3N_4$	0.325	-0.193	-0.185
$M_2S_3N_5$	1.48	-0.81	0.189

Table S1. Influence of agronomic practices on mean yield parameters and yield (two years)

Treatment	Seed yield (kg ha^{-1})	Stover yield (kg ha^{-1})	No. of secondary branches plant^{-1}	No. of pods plant^{-1}
Planting method				
M_1: Dibbling	1377	5270	19	412
M_2: Transplanting	1824	6156	26	595
SE(m)±	29	115	0.7	12
CD (P=0.05)	176	698	4.0	72
Plant geometry				
S_1: 100 × 100 cm	1751	5923	23	512
S_2: 120 × 120 cm	1431	5425	26	545
S_3: 150 × 60 cm	1619	5791	18	453
SE(m)±	44	49	0.8	11
CD (P=0.05)	142	160	2.5	35
Nutrient management				
N_1: Control	666	3458	12	230
N_2 :100 % STB NPK	1437	5729	21	511
N_3: 100 % STB NPK + vermicompost + PSB + *Rhizobium*	2158	6611	27	607
N_4: 150 % STB NPK	1536	5980	23	539
N_5: 150 % STB NPK + vermicompost + PSB + *Rhizobium*	2203	6787	28	630
SE(m)±	39	89	0.7	13
CD (P=0.05)	113	258	2.0	36

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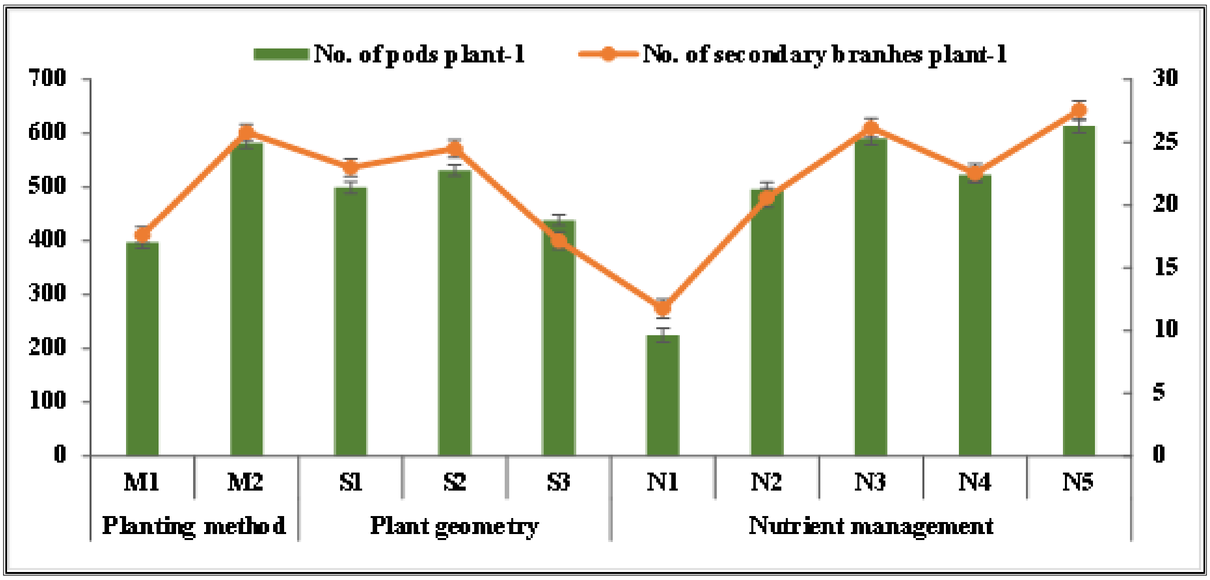

Fig. 1. Effect of agronomic practices on yield components of hybrid pigeonpea (Mean of two years).

The mean seed yield was 25.1% higher under transplanting compared to dibbling (Fig. 2). Although per-plant yield components and yield were higher with a 120 × 120 cm spacing, on a hectare basis, the 100 × 100 cm spacing resulted in 22.9% higher yield. Previous studies have indicated that square geometry allows for the development of more secondary and tertiary branches per plant, which is directly linked to higher yield (13). The combination of transplanting with 100 × 100 cm spacing and a 100% soil test-based NPK integrated approach resulted in 38% higher mean seed yield compared to the same spacing with only 100% soil test-based NPK. While seed yield under the 150 × 60 cm crop geometry was similar to that of the 100 × 100 cm geometry, transplanting with 100 × 100 cm spacing combined with integrated nutrient management led to a significantly higher seed yield (14.2%) compared to the same management approach under 150 × 60 cm spacing.

The biplot analysis (Fig. 3 & 4) highlighted the relationships between yield components, overall yield and effects of various treatments. The components closest to yield in the biplot were most strongly correlated with it. The biplot showed a strong positive correlation between the number of pods per plant, number of primary branches and the number of secondary branches per plant with seed yield. These findings align with the results of (19). On the other hand, the number of root nodules per plant was negatively correlated not only with seed yield (kg ha^{-1}) but also with all other growth parameters of hybrid pigeonpea. This could be because, in the control plots, nodule formation was high to meet the minimum nitrogen requirements, but this did not lead to a proportional increase in yield, especially when compared to the integrated nutrient management approach, particularly under wider plant geometry.

To visualize the impact of treatments on the most influential yield components (number of pods per plant and number of secondary branches per plant), PCA was performed using the mean data from the two years (Fig. 4),

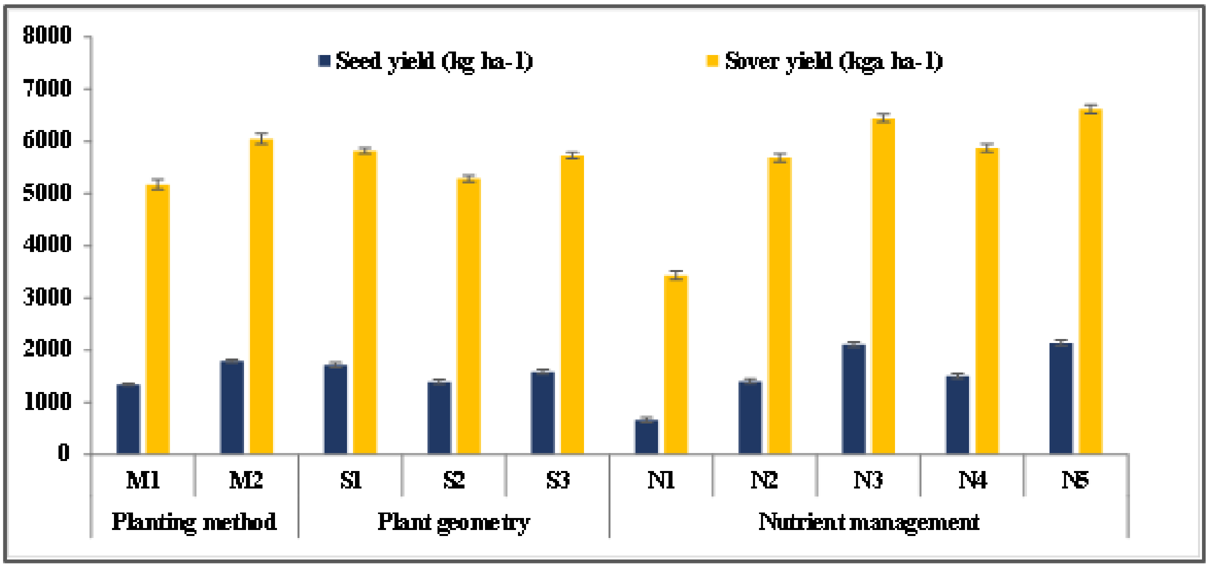

Fig. 2. Effect of agronomic practices on yield of hybrid pigeonpea (Mean of two years).

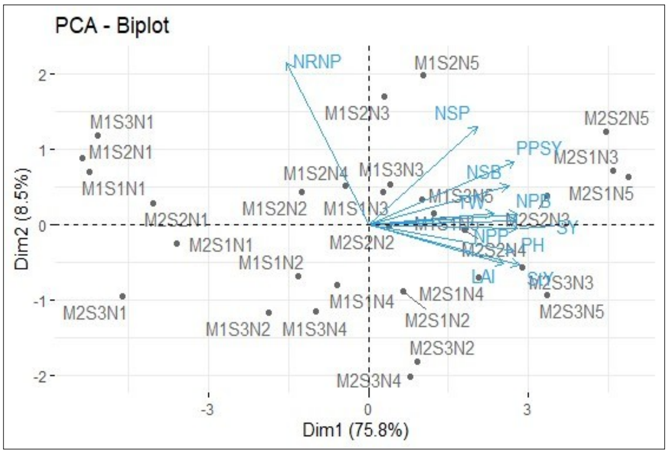

Fig. 3. Mean data PCA biplot with 11 quantitative variables among 30 treatment combinations of hybrid pigeonpea during *kharif*.

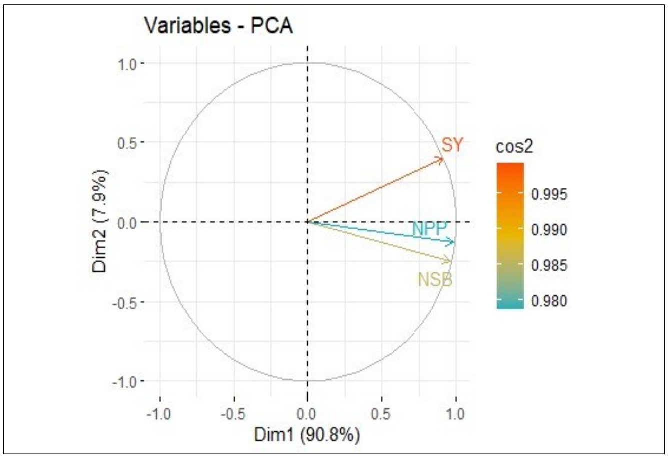

Fig. 4. Mean data PCA graph showing the relationship of seed yield with key components.

with the respective PCA scores presented in Table 2. The results showed that most treatments involving dibbling had negative PCA scores compared to transplanting. For the number of pods per plant, higher positive values were observed with the 120 × 120 cm plant geometry combined with transplanting and the integrated nutrient approach (0.96 and 0.88). However, when considering number of secondary branches plant^{-1} and seed yield, the highest positive PCA scores were recorded with the 100 × 100 cm plant geometry combined with transplanting and the integrated nutrient approach (Scores of 2.94 and 2.85; 0.27 and 0.32, respectively).

Additionally, correlation analysis was conducted among the 11 characters and the results are presented in Table 3. The plant height (PH) trait showed a positive correlation with leaf area index (LAI), number of primary branches per plant, seed yield (SY) and stover yield (STY), but had minimal influence on the number of secondary

Table 3. Correlation coefficients of growth, yield components and yield of hybrid pigeonpea during *kharif*, 2021 and 2022

	Correlations										
	PH	NPB	LAI	NSB	NRNP	NPP	NSP	TW	PPSY	SY	STY
PH	1	.858**	.948**	.754**	-.423*	.808**	.602**	.704**	.802**	.803**	.941**
NPB	.858**	1	.756**	.943**	-.453*	.950**	.596**	.685**	.924**	.851**	.883**
LAI	.948**	.756**	1	.626**	0	.708**	.494**	.636**	.689**	.943**	.905**
NSB	.754**	.943**	.626**	1	-.378*	.960**	.629**	.671**	.952**	.963**	.817**
NRNP	-.423*	-.453*	0	-.378*	1	-.532**	0	-.434*	0	-.374*	-.572**
NPP	.808**	.950**	.708**	.960**	-.532**	1	.633**	.727**	.927**	.867**	.892**
NSP	.602**	.596**	.494**	.629**	0	.633**	1	.576**	.717**	.635**	.610**
TW	.704**	.685**	.636**	.671**	-.434*	.727**	.576**	1	.713**	.744**	.786**
PPSY	.802**	.924**	.689**	.952**	0	.927**	.717**	.713**	1	.859**	.847**
SY	.803**	.851**	.943**	.963**	-.374*	.867**	.635**	.744**	.859**	1	.961**
STY	.941**	.883**	.905**	.817**	-.572**	.892**	.610**	.786**	.847**	.961**	1

****. Correlation is significant at the 0.01 level (2-tailed).**

***. Correlation is significant at the 0.05 level (2-tailed).**

branches per plant. The per-plant seed yield was strongly influenced by the number of secondary branches and pods per plant (r = 0.95 and 0.93 respectively). The leaf area index (LAI) was closely related to both seed yield and stover yield, likely due to the leaf surface's role in light interception and photosynthate production (20). On a hectare basis, the ultimate yield was most strongly correlated with the number of pods and secondary branches per plant. This is likely because flowering and pod formation primarily occur on secondary and tertiary branches (21, 22). As per (14), under wider plant geometry, the flower drop percentage was less, which could lead to increased pod formation. In wider plant geometries, the number of secondary branches and pods per plant are crucial yield-contributing factors (23) and special attention should be given to maximizing hybrid pigeonpea expression and yield. A similar correlation pattern was observed using the PCA biplot technique.

Conclusion

The combined use of different statistical methods, including correlation and PCA biplot techniques, offers a more reliable estimation than relying on individual approaches when selecting the best agronomic interventions to enhance hybrid pigeonpea yield. The present field study found that the number of pods per plant and the number of secondary branches per plant were the most influential variables affecting seed yield. Transplanting with square and wider plant geometry (100 × 100 cm), combined with integrated nutrient management, emerged as the optimal agronomic strategy for maximizing the hybrid pigeonpea's growth, yield components and overall yield. These findings highlight the importance of planting methods, appropriate plant geometry and effective nutrient management in boosting hybrid pigeonpea expression and productivity in deep black soils, which is crucial for addressing future food security challenges. Further research in diverse climatic conditions like medium to deep black soils with availability of one or two irrigation facilities could refine these practices and expand recommendations for pigeonpea cultivation in different regions, ensuring that the benefits observed in this study can be applied more widely, contributing to sustainable global pigeonpea production.

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Authors' contributions

BV conceptualised, conducted data curation, conducted formal analysis, investigated, carried out methodology, as well as wrote the original draft preparation. MMR contributed to conceptualisation, design of experimentation, funding acquisition, reviewing and editing. CS did the statistical analysis, reviewing and editing. VK participated in the idea of PCA analysis, reviewing and editing. NVK supported in collecting field data. MY gave final improvements in data reviewing and editing. BP contributed to the data reviewing and editing.

Compliance with ethical standards

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

Ethical issues: None

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