



RESEARCH ARTICLE

# Agronomic and economic investigation of spatial arrangement and companion crops in pigeonpea based intercropping system in Alfisols

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Received: 13 July 2025; Accepted: 20 October 2025; Available online: Version 1.0: 13 February 2026

**Cite this article:** Laxman N, Atheek URHM, Kamala BS, Anand MR, Anand SR, Somashekar KS, Vishwanath K. Agronomic and economic investigation of spatial arrangement and companion crops in pigeonpea based intercropping system in Alfisols. *Plant Science Today*. 2026; 13(sp1): 1-8. <https://doi.org/10.14719/pst.10617>

## Abstract

A field experiment was conducted to investigate the effect of planting geometry (normal and paired rows) and companion crops (field bean, vegetable soybean and chia) under a pigeonpea-based cropping system in Alfisols under dryland conditions. The experiment comprised 15 treatments, replicated thrice in a randomized complete block design. The trial was conducted for two seasons (kharif, 2020 and 2021). Treatments consisted of sole cropping and intercropping of companion crops (field bean, vegetable soybean and chia) with different row proportions (1:2, 1:3 and 1:4) in pigeonpea. The results revealed that among the different planting geometries, paired-row planting of pigeonpea at 120/60 cm spacing recorded significantly higher plant height (141.05 cm), number of branches per plant (15.61), number of pods per plant (130.90), pod yield per plant (105.25 g plant<sup>-1</sup>), seed yield per plant (40.45 g plant<sup>-1</sup>), seed yield (1483 kg ha<sup>-1</sup>) and stalk yield (3449 kg ha<sup>-1</sup>) as compared to normal row planting. Higher pigeonpea equivalent yield (1666 kg ha<sup>-1</sup>) was recorded with paired-row pigeonpea (120/60 cm) intercropping with chia and higher land equivalent ratio (1.67) recorded with paired-row pigeonpea (150/60 cm) intercropped with vegetable soybean (1:4) compared to other intercropping systems. These treatments were found agronomically superior. Paired-row planting pigeonpea (120/60 cm) intercropped with vegetable soybean (1:3) found to be economically superior, with higher gross returns (Rs. 201992 ha<sup>-1</sup>), net returns (Rs. 160431 ha<sup>-1</sup>) and cost benefit ratio (4.86). From this study it could be concluded that paired pigeonpea intercropped with vegetable soybean is profitable system under dryland conditions and can be recommended for regions with red or light-textured soils.

**Keywords:** intercropping; normal row; paired row; pigeonpea; pigeonpea equivalent yield

## Introduction

Pigeonpea (*Cajanus cajan* L. Millsp.) is an important pulse crop of the semi-arid tropics, cultivated extensively in India for its edible seeds and soil-enriching properties. It occupies a prominent place in dryland agriculture due to its drought tolerance, deep root system and ability to fix atmospheric nitrogen (1). Drylands represents a major pigeonpea-growing region, characterized by erratic rainfall, light-textured soils and low input use. Despite its ecological suitability, pigeonpea productivity in this region remains below the national average, primarily due to suboptimal agronomic practices and mono-cropping (2).

One of the major reasons for low yield is the inefficient utilization of natural resources such as soil moisture, nutrients and sunlight. Traditional planting geometries often result in congested and overlapping canopies, excessive plant competition and inadequate light penetration, leading to reduced photosynthetic efficiency and lower yields. In this context, planting geometry, such as the spatial arrangement of plants, plays a crucial role in determining the crop growth environment. Proper row and plant spacing not only helps in maximizing light interception and aeration but also facilitates better root development, weed control, ease of intercultural operations and alter the microclimate, reducing insect and pathogen buildup and thereby minimizing yield loss (3).

Wider row spacing, for instance, can reduce interplant competition and allow the inclusion of intercrops without adversely affecting the main crop.

Intercropping, another important agronomic strategy, involves growing two or more crops simultaneously on the same field during the same period. In pigeonpea-based systems, intercropping is commonly practiced with cereals (e.g., finger millet, maize), pulses (e.g., green gram, cowpea) and oilseeds (e.g., groundnut). The rationale behind intercropping lies in the complementary use of resources by component crops, which leads to higher resource and land-use efficiency, reduced pest and disease incidence, better weed suppression and income enhancement (4, 5). Short-duration intercrops mature early and utilize the initial slow growth period of pigeonpea, thus making efficient use of resources without competing significantly during the later stages. Moreover, legume intercrops contribute to nitrogen enrichment and soil fertility, promoting the long-term sustainability of the system (6).

The benefits of adopting suitable intercropping systems have been well-documented in several agro-climatic zones. However, the success of an intercropping system is highly dependent on the selection of compatible crops, appropriate planting geometries and the prevailing agro-ecological conditions. The drylands are typified by shallow red soils, erratic rainfall ranging from 600–1000 mm and a short growing season. These constraints call for low-risk, resource-efficient cropping systems that ensure stable yields and profitability under limited water and nutrient availability (7).

In pigeonpea-based cropping systems, the optimization of spatial arrangements (120 cm × 30 cm, 60/120 cm × 30 cm and 60/150 cm × 30 cm) in combination with suitability of intercrops like vegetable soybean, field bean and chia offers an opportunity to increase productivity per unit area. For instance, wider row spacing allows the introduction of one or two rows of intercrops in between pigeonpea rows, resulting in higher land equivalent ratio (LER), improved economics in terms of gross and net returns and a better benefit-cost (B:C) ratio (8). Furthermore, such systems ensure better temporal and spatial complementarity, efficient resource partitioning and overall resilience of the cropping system under dryland conditions.

From an economic standpoint, intercropping reduces dependence on a single crop and distributes production risk, which is particularly beneficial for small and marginal farmers. The addition of intercrops not only improves cash flow but also ensures household-level availability of diverse food commodities. Moreover, practices such as adjusting row spacing, selecting early maturing intercrops and synchronizing sowing time can significantly enhance system profitability and sustainability (9). This system produces two different products at different times, which fetch better market prices and provide additional income compared to a sole crop.

Early harvest of intercrops, such as vegetable soybean at the pod stage within 60 days after sowing, does not interfere with growth of the main crop, as pigeonpea is a slow starter during the early growth phase. On the contrary, the presence of an intercrop during the initial stage suppresses weeds and the incorporation of vegetable soybean residue into the soil after harvest improves water-holding capacity and soil physical properties. It also releases nutrients during the reproductive stage of pigeonpea, when nutrient demand peaks and nodule activity declines after flowering, often expressed by yellowing and shedding of leaves. The slow release of

nutrients at this critical stage ensure adequate nitrogen supply, allowing pigeonpea plant to retain green leaves longer, which enhances the photosynthates production and translocation. This ultimately leads to higher grain yield in intercropped pigeonpea compared to the sole crop.

Normally due to intercropping, pigeonpea yield remains higher, resulting in greater economic benefits. Pod yield of intercrop harvested as a vegetable is season-dependent and often fetches higher market price, while the additional dry matter yield contributes to overall income. Together, these factors can lead to a 150–175% increase in economic returns in intercropping systems to sole pigeonpea cultivation. Given the increasing emphasis on sustainable intensification, integrated approaches that combine optimal plant spacing with suitable intercrop selection hold promise for improving pigeonpea productivity under resource-constrained environments. Therefore, the present investigation was undertaken.

## Materials and Methods

### Experimental site

Two field experiments were conducted under rainfed conditions (annual rainfall: 600–1000 mm) on red sandy loam soils belonging to the Alfisols order during two successive kharif seasons. The experimental field had a deep, sandy loam soil texture with a gentle slope, ensuring effective drainage. The soil was slightly acidic, with a pH of 5.03. It exhibited lower soil organic carbon (0.046%) and available nitrogen (312.5 kg/ha), while available P<sub>2</sub>O<sub>5</sub> (28.5 kg/ha) and K<sub>2</sub>O (295.0 kg/ha) were found to be moderate.

### Experimental design

The experiment consisted of 15 treatments, replicated thrice in a randomized complete block design. The treatments comprised various combinations of planting geometry, sole cropping and intercropping. The details of the treatments are as follows:

- T<sub>1</sub>: normal row (120 cm × 30 cm) pigeonpea (sole crop)
- T<sub>2</sub>: normal row (120 cm × 30 cm) pigeonpea + field bean (1:2)
- T<sub>3</sub>: normal row (120 × 30 cm) pigeonpea + vegetable soybean (1:3)
- T<sub>4</sub>: normal row (120 × 30 cm) pigeonpea + chia (1:2)
- T<sub>5</sub>: paired row (120/60 × 30 cm) pigeonpea (sole crop)
- T<sub>6</sub>: paired row (120/60 × 30 cm) pigeonpea + field bean (1:2)
- T<sub>7</sub>: paired row (120/60 × 30 cm) pigeonpea + vegetable soybean (1:3)
- T<sub>8</sub>: paired row (120/60 cm × 30 cm) pigeonpea + chia (1:2)
- T<sub>9</sub>: paired row (150/60 × 45 cm) pigeonpea (sole crop)
- T<sub>10</sub>: paired row (150/60 × 45 cm) pigeonpea + field bean (1:3)
- T<sub>11</sub>: paired row (150/60 × 45 cm) pigeonpea + vegetable soybean (1:4)
- T<sub>12</sub>: paired row (150/60 × 45 cm) pigeonpea + chia (1:3)
- T<sub>13</sub>: field bean (sole crop – 45 × 15 cm),
- T<sub>14</sub>: vegetable soybean (sole crop – 30 × 10 cm)
- T<sub>15</sub>: chia (sole crop – 45 × 15 cm).

The treatments were randomly allotted in each replication. The trial with the above treatments and the same experimental design was conducted for two consecutive kharif seasons.

## Crop management practices

The experimental field was prepared using tractor-drawn implements. Disc ploughing was done after harvest of the previous crop to remove the stubbles and invert the soil. With the onset of rainfall, harrowing was done to incorporate organic manure (FYM) into the soil, followed by an additional harrowing to break clods and bring the soil to fine tilth. Before sowing, the land was laid out into plots of desired size as per the experimental design and then levelled.

Pigeonpea served as the main crop, while field bean, vegetable soybean and chia were the companion crops of the study. Healthy, certified seeds of suitable varieties were used and the salient features of the varieties are as follows:

### Pigeonpea

The variety Bangalore Red Gram-4 (BRG-4) is short statured, mid-early duration (140-145 days), indeterminate and spreading in type, with a grain yield potential of 12.5–15.0 q ha<sup>-1</sup>.

### Field bean

The variety HA-4 (Hebbal Avare-4), released by the University of Agricultural Sciences, Bangalore, is photo-insensitive, non-viny, compact and determinate. It matures in 95–100 days. Green pods can be harvested in 65–70 days for vegetable use, possessing a unique aroma and taste. Yield potential: 45–50 q ha<sup>-1</sup> (green pods) and 10–12 q ha<sup>-1</sup> (dry seeds).

### Vegetable soybean

The variety Karune (GC-00209-4-1-1), developed by the University of Agricultural Sciences, Bangalore, is short-duration (65-70 days) mainly grown for vegetable use, with a yield potential of 80–90 q ha<sup>-1</sup> (green pods). It is recommended for year-round cultivation.

### Chia

The variety GVKK Chia-1 is a drought-tolerant, high yielding (1–1.25 q ha<sup>-1</sup>), with a duration of 100–120 days. It is rich in Omega-3 fatty acid (60%).

Nutrients–nitrogen, phosphorus and potassium–were applied in the form of urea, di-ammonium phosphate and muriate of potash, respectively. The recommended doses of fertilizers were applied to the sole crops: pigeonpea (25:50:25 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O ha<sup>-1</sup>), field bean (25:50:25 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O ha<sup>-1</sup>), soybean (25:62:25 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O ha<sup>-1</sup>) and chia (100:50:50 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O ha<sup>-1</sup>).

In the intercropping system, fertilizers were applied based on the full dose of the main crop plus half of the recommended dose of the intercrops. The entire quantity of fertilizer was applied as a basal dose in the planting rows at the prescribed spacing (120/60 cm × 30 cm and 150/60 cm × 45 cm). Seeds of pigeonpea, field bean, vegetable soybean and chia were sown at a depth of 5 cm, using the recommended seed rate 15 kg ha<sup>-1</sup>, 30 kg ha<sup>-1</sup>, 62.5 kg ha<sup>-1</sup> and 2 kg ha<sup>-1</sup>, respectively.

The pre-emergent herbicide pendimethalin 38.7 % EC at 2 L ha<sup>-1</sup> was sprayed on the day of sowing to control weeds. Intercultivation was carried out at 30 days after sowing (DAS), followed by earthing up at 60 DAS to manage weeds, aerate the root zone and conserve rainwater. Earthing up also facilitated drainage of excess water and provide physical support against lodging. Need-based plant protection measures were implemented to control insect pest (*Maruca vitrata* - spotted pod borer and *Helicoverpa*

*armigera* - pod borer) and diseases (wilt and sheath blight).

## Growth and yield studies

For growth and yield observations, five randomly selected plants of the main crop within the net plot area were tagged and these plants were used for recording all growth and yield parameters at harvest.

### Pigeonpea equivalent yield (PEY) studies

The seed yields of pigeonpea, soybean, field bean and chia seed were considered and converted into pigeonpea equivalent yield (PEY) based on the prevailing market prices of all component crops. The PEY was calculated using the following formula, applied to the respective treatments for both the years:

$$\text{Pigeonpea equivalent yield (PEY) (q ha}^{-1}\text{)} = \frac{\text{Yield of Fieldbean/ Soybean/Chia (q ha}^{-1}\text{)} \times \text{Price of Fieldbean/ Soybean/Chia (Rs. q}^{-1}\text{)} + \text{Yield of Pigeonpea (q ha}^{-1}\text{)} \times \text{Price of Pigeonpea (Rs. q}^{-1}\text{)}}{\text{Price of Pigeonpea (Rs. q}^{-1}\text{)}} \quad (\text{Eqn. 01})$$

### Land equivalent ratio (LER) studies

Land equivalent ratio (LER) is defined as the relative land area under sole crops that is required to produce the yields obtained in intercropping at the same level of management (10). It is calculated as follows:

$$\text{Land Equivalent Ratio (LER)} = \frac{\text{Yield of pigeonpea in intercropping system}}{\text{Yield of pigeonpea in sole cropping}} + \frac{\text{Yield of intercrop (fieldbean/soybean/chia) in intercropping system}}{\text{Yield of fieldbean/soybean/chia in sole cropping}} \quad (\text{Eqn. 02})$$

## Statistical analysis

The experimental data gathered on the growth parameters, yield parameters and soil parameters were subjected to Fisher's method of analysis of variance (ANOVA) (11). For comparison between the treatment means, an appropriate value of critical difference (CD) was worked out wherever F-test was significant. All the data were analysed and the results are presented and discussed at a probability level of 5%.

## Results and Discussion

### Effect of planting geometry and intercropping on growth attributes of pigeonpea

The pooled data pertaining to growth attributes of pigeonpea as affected by different planting geometries and intercropping systems are presented in Table 1.

Among the different planting geometries, sole paired-row pigeonpea at 120/60 cm spacing recorded significantly higher plant height (141.05 cm) and number of branches per plant (15.61) at harvest. In contrast, the lowest plant height (119.55 cm)

**Table 1.** Effect of planting geometry and intercropping on growth attributes of pigeonpea (pooled data 2020 and 2021)

| Treatments   | Plant height (cm) |       |        | Number of branches per plant |      |        |
|--|-------------------|-------|--------|------------------------------|------|--------|
|  | 2020              | 2021  | Pooled | 2020                         | 2021 | Pooled |
| T <sub>1</sub> : sole pigeonpea NR 120 cm × 30 cm                                  | 138.4             | 117.6 | 128.0  | 13.0                         | 11.0 | 12.0   |
| T <sub>2</sub> : pigeonpea NR 120 cm × 30 cm + field bean 45 cm × 15 cm            | 132.1             | 114.5 | 123.3  | 12.2                         | 10.2 | 11.2   |
| T <sub>3</sub> : pigeonpea NR 120 cm × 30 cm + vegetable soybean 30 cm × 10 cm     | 135.3             | 116.2 | 125.8  | 12.5                         | 10.5 | 11.5   |
| T <sub>4</sub> : pigeonpea NR 120 cm × 30 cm + chia 45 cm × 15 cm                  | 128.7             | 110.4 | 119.6  | 10.9                         | 8.9  | 9.9    |
| T <sub>5</sub> : sole pigeonpea PR 60/120 cm × 30 cm                               | 151.7             | 130.4 | 141.1  | 16.4                         | 14.8 | 15.6   |
| T <sub>6</sub> : pigeonpea PR 60/120 cm × 30 cm + field bean 45 cm × 15 cm         | 144.5             | 125.2 | 134.9  | 14.8                         | 12.6 | 13.7   |
| T <sub>7</sub> : pigeonpea PR 60/120 cm × 30 cm + vegetable soybean 30 cm × 10 cm  | 147.2             | 128.6 | 137.9  | 15.2                         | 13.2 | 14.2   |
| T <sub>8</sub> : pigeonpea PR 60/120 cm × 30 cm + chia 45 × 15 cm                  | 130.6             | 112.4 | 121.5  | 11.6                         | 9.2  | 10.4   |
| T <sub>9</sub> : sole pigeonpea PR 60/150 cm × 30 cm                               | 143.3             | 122.5 | 132.9  | 14.1                         | 12.1 | 13.1   |
| T <sub>10</sub> : pigeonpea PR 60/150 cm × 30 cm + field bean 45 cm × 15 cm        | 139.2             | 119.7 | 129.5  | 13.4                         | 11.4 | 12.4   |
| T <sub>11</sub> : pigeonpea PR 60/150 cm × 30 cm + vegetable soybean 30 cm × 10 cm | 140.3             | 121.2 | 130.8  | 13.9                         | 11.7 | 12.8   |
| T <sub>12</sub> : pigeonpea PR 60/150 cm × 30 cm + chia 45 × 15 cm                 | 134.5             | 114.2 | 124.4  | 11.2                         | 9.4  | 10.3   |
| T <sub>13</sub> : sole field bean  | -                 | -     | -      | -                            | -    | -      |
| T <sub>14</sub> : sole vegetable soybean   | -                 | -     | -      | -                            | -    | -      |
| T <sub>15</sub> : sole chia  | -                 | -     | -      | -                            | -    | -      |
| S.Em. ±  | 4.5               | 4.18  | 4.52   | 0.45                         | 0.38 | 0.42   |
| CD at 5 %  | 13.3              | 12.25 | 13.25  | 1.33                         | 1.13 | 1.23   |

**Note:** NR: normal row, PR: paired row.

and number of branches per plant (9.91) were observed in pigeonpea + chia (1:2) under normal row planting.

The higher plant height and number of branches per plant in the sole-paired row with wider spacing may be attributed to the greater availability of resources, including enhanced solar radiation interception and improved absorption of water and nutrients in the absence of intercrop competition. The increased availability of these resources allow pigeonpea plant to grow taller, develop a larger photosynthetic surface area (greater number of leaves) and subsequently produce more branches per plant (12, 13). In contrast, pigeonpea + chia (1:2) under normal row planting recorded lower plant height and fewer branches due to increased competition between the main crop and the intercrop. Chia plants, when grown at closer spacing and higher density, compete aggressively for light, moisture and nutrients during the early vegetative stages. This competition likely restricted the vegetative growth of pigeonpea,

resulting in reduced plant height and reduced branching (14). Thus, the observed variation in plant height and branching can be primarily attributed to the degree of competition and the available growing space under different planting geometries and intercropping systems (15).

### Effect of planting geometry and intercropping on yield attributes of pigeonpea weight

The yield attributes of pigeonpea as affected by different planting geometries and intercropping systems are discussed here and the two-season data along with pooled data are presented in Table 2.

Among different planting geometries and intercropping systems, sole paired-row pigeonpea at 120/60 cm spacing recorded significantly higher number of pods per plant (130.90), pod weight per plant (105.25 g plant<sup>-1</sup>) and seed weight per plant (40.45 g plant<sup>-1</sup>) at harvest. In contrast, the lowest numbers of pods per plant (80.15), pod weight (47.25 g) and seed weight (26.35 g) were observed in pigeonpea + chia (1:2) intercropping under

**Table 2.** Effect of planting geometry and intercropping on yield attributes of pigeonpea (pooled data 2020 and 2021)

| Treatments   | Number of pods per plant |       |        | Pod weight per plant (g plant <sup>-1</sup> ) |       |        | Seed weight per plant (g plant <sup>-1</sup> ) |      |        |
|--|--------------------------|-------|--------|---|-------|--------|--|------|--------|
|  | 2020                     | 2021  | Pooled | 2020  | 2021  | Pooled | 2020   | 2021 | Pooled |
| T <sub>1</sub> : sole pigeonpea NR 120 cm × 30 cm                                  | 94.5                     | 82.5  | 88.5   | 68.2  | 61.5  | 64.9   | 30.6   | 26.2 | 28.4   |
| T <sub>2</sub> : pigeonpea NR 120 cm × 30 cm + field bean 45 cm × 15 cm            | 98.1                     | 86.8  | 92.5   | 74.0  | 67.0  | 70.5   | 30.7   | 26.5 | 28.6   |
| T <sub>3</sub> : pigeonpea NR 120 cm × 30 cm + vegetable soybean 30 cm × 10 cm     | 102.0                    | 92.4  | 97.2   | 78.8  | 71.4  | 75.1   | 32.0   | 28.0 | 30.0   |
| T <sub>4</sub> : pigeonpea NR 120 cm × 30 cm + chia 45 cm × 15 cm                  | 88.0                     | 72.3  | 80.2   | 50.7  | 43.8  | 47.3   | 28.6   | 24.1 | 26.4   |
| T <sub>5</sub> : sole pigeonpea PR 60/120 cm × 30 cm                               | 137.3                    | 124.5 | 130.9  | 107.9   | 102.6 | 105.3  | 42.5   | 38.4 | 40.5   |
| T <sub>6</sub> : pigeonpea PR 60/120 cm × 30 cm + field bean 45 cm × 15 cm         | 125.4                    | 116.2 | 120.8  | 102.3   | 98.4  | 100.4  | 40.5   | 36.5 | 38.5   |
| T <sub>7</sub> : pigeonpea PR 60/120 cm × 30 cm + vegetable soybean 30 cm × 10 cm  | 116.5                    | 104.4 | 110.5  | 95.4  | 88.4  | 91.9   | 38.6   | 34.4 | 36.5   |
| T <sub>8</sub> : pigeonpea PR 60/120 cm × 30 cm + chia 45 × 15 cm                  | 94.0                     | 76.5  | 85.3   | 61.5  | 64.5  | 63.0   | 30.4   | 25.5 | 28.0   |
| T <sub>9</sub> : sole pigeonpea PR 60/150 cm × 30 cm                               | 115.0                    | 103.2 | 109.1  | 94.7  | 87.6  | 91.2   | 35.1   | 31.2 | 33.2   |
| T <sub>10</sub> : pigeonpea PR 60/150 cm × 30 cm + field bean 45 cm × 15 cm        | 105.5                    | 96.5  | 101.0  | 92.7  | 85.4  | 89.1   | 34.9   | 30.7 | 32.8   |
| T <sub>11</sub> : pigeonpea PR 60/150 cm × 30 cm + vegetable soybean 30 cm × 10 cm | 103.1                    | 93.4  | 98.3   | 82.6  | 75.6  | 79.1   | 32.4   | 28.2 | 30.3   |
| T <sub>12</sub> : pigeonpea PR 60/150 cm × 30 cm + chia 45 × 15 cm                 | 90.0                     | 78.6  | 84.3   | 57.6  | 50.4  | 54.0   | 30.2   | 25.2 | 27.7   |
| T <sub>13</sub> : sole field bean  | -                        | -     | -      | -   | -     | -      | -  | -    | -      |
| T <sub>14</sub> : sole vegetable soybean   | -                        | -     | -      | -   | -     | -      | -  | -    | -      |
| T <sub>15</sub> : sole chia  | -                        | -     | -      | -   | -     | -      | -  | -    | -      |
| S.Em. ±  | 3.48                     | 3.21  | 3.42   | 6.62  | 2.56  | 2.66   | 1.17   | 1.02 | 1.09   |
| CD at 5 %  | 10.21                    | 9.41  | 10.02  | 19.40   | 7.49  | 7.80   | 3.43   | 2.98 | 3.20   |

**Note:** NR: normal row, PR: paired row.

normal row planting.

This superior performance under paired-row sole cropping can be attributed to reduced plant competition and the optimal utilisation of environmental resources. The paired-row arrangement provides more growing space, a better canopy structure, enhanced light interception and improved root development, leading to increased photosynthetic activity and assimilate accumulation. Additionally, the absence of an intercrop ensures uninterrupted availability of soil nutrients and moisture, supporting improved reproductive growth and pod development (16, 17).

In contrast, pigeonpea + chia (1:2) under normal row planting recorded significantly lower values for all yield attributes. This decline in reproductive performance is primarily due to intense interspecific competition between pigeonpea and the closely spaced chia plants. Chia, with its rapid early growth habit and dense canopy, competes strongly for light, nutrients and moisture, particularly during the critical flowering and pod-filling stages. Such competitive stress limits assimilate partitioning toward reproductive organs, resulting in fewer pods, reduced pod weight and ultimately lower seed yield per plant (18). Hence, the differences in yield attributes are closely associated with resource availability, competition intensity and planting geometry, which collectively influence the crop's physiological capacity to support reproductive development.

### Effect of planting geometry and intercropping on yield of pigeonpea and intercrops

The data of seed and stalk yield of pigeonpea and intercrops as

influenced by different planting geometries and intercropping systems including two-season data and pooled data (Table 3).

Among the planting geometries and intercropping systems, paired row (120/60 cm × 30 cm) of sole pigeonpea recorded significantly higher seed yield and stalk yield (1483 kg ha<sup>-1</sup> and 3449 kg ha<sup>-1</sup>, respectively). This was on par with T<sub>6</sub> (1415 kg ha<sup>-1</sup> and 3219 kg ha<sup>-1</sup>, respectively). In contrast, the lowest seed and stalk yield (722 kg ha<sup>-1</sup> and 1826 kg ha<sup>-1</sup>, respectively) were observed in normal row (120 cm × 30 cm) of pigeonpea + chia (1:2).

This superior performance under paired-row geometry is primarily due to enhanced light penetration, improved aeration and efficient utilization of space which favour better vegetative and reproductive growth. The wider spacing between paired rows reduces intra-specific competition, facilitates better canopy management and allows for greater photosynthetic efficiency, resulting in more assimilate production and translocation toward reproductive parts, thereby increasing seed and stalk yield (19–21).

### Yield performance of intercrops

#### Field bean

Higher seed yield (470.5 kg ha<sup>-1</sup>) was recorded under sole field bean, followed by paired-row pigeonpea + field bean at 150/60 cm spacing (312 kg ha<sup>-1</sup>) and paired-row pigeonpea + field bean at 120/60 cm spacing (232 kg ha<sup>-1</sup>). The lowest yield (204.5 kg ha<sup>-1</sup>) occurred under normal row pigeonpea + field bean (1:2).

#### Vegetable soybean

The highest seed yield (768.5 kg ha<sup>-1</sup>) was obtained under sole

**Table 3.** Effect of planting geometry and intercropping on yield of pigeonpea and intercrops (pooled data 2020 and 2021)

| Treatments   | Main crop yield (pigeonpea)       |        |        |                                    |        |        | Intercrops seed yield (kg ha <sup>-1</sup> ) |      |        |
|--|-----------------------------------|--------|--------|------------------------------------|--------|--------|--|------|--------|
|  | Seed yield (kg ha <sup>-1</sup> ) |        |        | Stalk yield (kg ha <sup>-1</sup> ) |        |        | 2020   | 2021 | Pooled |
|  | 2020                              | 2021   | Pooled | 2020                               | 2021   | Pooled |  |      |        |
| T <sub>1</sub> : sole pigeonpea NR 120 cm × 30 cm                                  | 1264                              | 789    | 1027   | 2954                               | 1225   | 2090   | -  | -    | -      |
| T <sub>2</sub> : pigeonpea NR 120 cm × 30 cm + field bean 45 cm × 15 cm            | 1293                              | 810    | 1052   | 3054                               | 1327   | 2191   | 210  | 199  | 204.5  |
| T <sub>3</sub> : pigeonpea NR 120 cm × 30 cm + vegetable soybean 30 cm × 10 cm     | 1312                              | 892    | 1102   | 3218                               | 1702   | 2460   | 389  | 342  | 365.5  |
| T <sub>4</sub> : pigeonpea NR 120 cm × 30 cm + chia 45 cm × 15 cm                  | 768                               | 675    | 722    | 2597                               | 1055   | 1826   | 282  | 263  | 272.5  |
| T <sub>5</sub> : sole pigeonpea PR 60/120 cm × 30 cm                               | 1813                              | 1152   | 1483   | 4218                               | 2680   | 3449   | -  | -    | -      |
| T <sub>6</sub> : pigeonpea PR 60/120 cm × 30 cm + field bean 45 cm × 15 cm         | 1770                              | 1060   | 1415   | 4026                               | 2411   | 3219   | 216  | 248  | 232    |
| T <sub>7</sub> : pigeonpea PR 60/120 cm × 30 cm + vegetable soybean 30 cm × 10 cm  | 1699                              | 1045   | 1372   | 3981                               | 2245   | 3113   | 432  | 412  | 422    |
| T <sub>8</sub> : pigeonpea PR 60/120 cm × 30 cm + chia 45 × 15 cm                  | 1099                              | 785    | 942    | 2868                               | 1232   | 2050   | 293  | 285  | 289    |
| T <sub>9</sub> : sole pigeonpea PR 60/150 cm × 30 cm                               | 1548                              | 1022   | 1285   | 3615                               | 2043   | 2829   | -  | -    | -      |
| T <sub>10</sub> : pigeonpea PR 60/150 cm × 30 cm + field bean 45 cm × 15 cm        | 1479                              | 924    | 1202   | 3460                               | 1797   | 2629   | 316  | 308  | 312    |
| T <sub>11</sub> : pigeonpea PR 60/150 cm × 30 cm + vegetable soybean 30 cm × 10 cm | 1455                              | 895    | 1175   | 3341                               | 1713   | 2527   | 585  | 550  | 567.5  |
| T <sub>12</sub> : pigeonpea PR 60/150 cm × 30 cm + chia 45 × 15 cm                 | 937                               | 750    | 844    | 2705                               | 1114   | 1910   | 332  | 319  | 325.5  |
| T <sub>13</sub> : sole field bean  | -                                 | -      | -      | -                                  | -      | -      | 479  | 462  | 470.5  |
| T <sub>14</sub> : sole vegetable soybean   | -                                 | -      | -      | -                                  | -      | -      | 775  | 762  | 768.5  |
| T <sub>15</sub> : sole chia  | -                                 | -      | -      | -                                  | -      | -      | 548  | 526  | 537    |
| <b>S.Em. ±</b>   | 46.24                             | 34.59  | 38.52  | 104.28                             | 58.01  | 85.96  | NA   | NA   | NA     |
| <b>CD at 5 %</b>   | 135.63                            | 101.45 | 112.99 | 305.85                             | 170.13 | 252.11 | -  | -    | -      |

**Note:** NR: normal row, PR: paired row, NA: not analyse.

vegetable soybean, followed by paired-row pigeonpea + vegetable soybean at 150/60 cm spacing (567.5 kg ha<sup>-1</sup>) and paired-row pigeonpea + vegetable soybean at 120/60 cm spacing (422 kg ha<sup>-1</sup>). The lowest yield (365.5 kg ha<sup>-1</sup>) was observed under normal row pigeonpea + vegetable soybean (1:3).

### Chia

Higher seed yield (537 kg ha<sup>-1</sup>) was recorded with sole chia, followed by paired row pigeonpea + chia at 150/60 cm spacing (325.5 kg ha<sup>-1</sup>) and paired-row pigeonpea with chia at 120/60 cm spacing (289 kg ha<sup>-1</sup>). The lowest yield (272.5 kg ha<sup>-1</sup>) occurred under normal row pigeonpea + chia (1:2).

The higher seed yields of field bean, vegetable soybean and chia under sole cropping can be attributed to the absence of interspecific competition, enabling these crops to fully access light, nutrients, space and moisture for optimal growth and reproductive development. In contrast, yields declined under intercropping due to competition with pigeonpea (22, 23). Among intercropping geometries, paired-row pigeonpea at 150/60 cm spacing resulted in higher intercrop yields compared to 120/60 cm and normal row arrangements. The wider paired-row spacing (150/60 cm) offered better spatial complementarity, reducing competition and allowing improved light interception and resource use by the intercrops (22, 24). Conversely, normal row intercropping systems, with closer spacing and a higher pigeonpea population, exerted strong competition for light and nutrients, resulting in the lowest intercrop yields. These findings demonstrate that planting geometry plays a crucial role in regulating crop competition and productivity in intercropping systems (25).

### Effect of planting geometry and intercropping on yield indices of pigeonpea

The observations pertaining to the yield indices of pigeonpea as influenced by different planting geometries and intercropping systems of the two-season data and pooled data are presented in Table 4.

#### Pigeonpea equivalent yield (PEY)

Among the different planting geometries and intercropping systems, paired-row pigeonpea + chia at 120/60 cm spacing recorded significantly higher PEY (1666 kg ha<sup>-1</sup>), which was on par with paired-row pigeonpea + chia at 150/60 cm spacing (1659 kg ha<sup>-1</sup>). The lowest PEY (1120 kg ha<sup>-1</sup>) was observed in normal row

pigeonpea + field bean (1:2).

The higher PEY in chia-based intercropping systems, despite the lower biomass of chia, may be attributed to the higher market price of chia compared to other intercrops. Similar findings were reported in pigeonpea, soybean blackgram and green gram (16, 17, 26, 27).

#### Land equivalent ratio (LER)

The land equivalent ratio was calculated for all treatments to assess LER under different planting geometries and intercropping systems. All intercropping treatments recorded higher LER values than the sole cropping treatments. The maximum LER of (1.67) was observed in paired-row pigeonpea + vegetable soybean at 150/60 cm spacing, which was on par with paired row pigeonpea + field bean at 150/60 cm (1.61). The lowest LER (1.16) was recorded in paired-row pigeonpea + chia (1:2) at 120/60 cm spacing.

The higher LER obtained with wider paired-row spacing with intercrops such as vegetable soybean may be due to better crop growth facilitated by enhanced spatial complementarity, reduced intra-specific competition and greater inter-specific facilitation within the cropping system. Similar results were reported grain soybean and green gram (13, 17, 20, 28).

### Effect of planting geometry and intercropping on economics of pigeonpea

The economics of pigeonpea-based intercropping system was strongly influenced by different planting geometries and intercropping systems. The two-season data and pooled data are shown in Table 5.

Among all the treatments, paired-row pigeonpea + vegetable soybean at 120/60 cm spacing recorded higher gross returns (Rs. 201992 ha<sup>-1</sup>), net returns (Rs. 160431 ha<sup>-1</sup>) and cost benefit ratio (4.86). In contrast, the lowest gross returns (Rs. 64972 ha<sup>-1</sup>), net returns (Rs. 28978 ha<sup>-1</sup>) and cost benefit ratio (1.81) were recorded in T1 (normal row sole pigeonpea).

### Conclusion

The present study clearly demonstrates that planting geometry and intercropping systems have a significant impact on the growth, yield attributes, productivity and profitability of pigeonpea-based cropping systems. Paired-row planting accommodates a slightly

**Table 4.** Effect of planting geometry and intercropping on yield indices of pigeonpea (pooled data 2020 and 2021)

| Treatments   | Pigeonpea equivalent yield (kg ha <sup>-1</sup> ) |        |        | Land equivalent ratio |      |        |
|--|---|--------|--------|-----------------------|------|--------|
|  | 2020  | 2021   | Pooled | 2020                  | 2021 | Pooled |
| T <sub>1</sub> : sole pigeonpea NR 120 cm × 30 cm                                  | 1264  | 789    | 1027   | -                     | -    | -      |
| T <sub>2</sub> : pigeonpea NR 120 cm × 30 cm + field bean 45 cm × 15 cm            | 1363  | 876    | 1120   | 1.46                  | 1.46 | 1.46   |
| T <sub>3</sub> : pigeonpea NR 120 cm × 30 cm + vegetable soybean 30 cm × 10 cm     | 1441  | 1006   | 1224   | 1.54                  | 1.56 | 1.55   |
| T <sub>4</sub> : pigeonpea NR 120 cm × 30 cm + chia 45 cm × 15 cm                  | 1483  | 1333   | 1408   | 1.13                  | 1.25 | 1.19   |
| T <sub>5</sub> : sole pigeonpea PR 60/120 cm × 30 cm                               | 1813  | 1152   | 1483   | -                     | -    | -      |
| T <sub>6</sub> : pigeonpea PR 60/120 cm × 30 cm + field bean 45 cm × 15 cm         | 1842  | 1143   | 1493   | 1.43                  | 1.45 | 1.44   |
| T <sub>7</sub> : pigeonpea PR 60/120 cm × 30 cm + vegetable soybean 30 cm × 10 cm  | 1843  | 1182   | 1513   | 1.50                  | 1.48 | 1.49   |
| T <sub>8</sub> : pigeonpea PR 60/120 cm × 30 cm + chia 45 × 15 cm                  | 1833  | 1498   | 1666   | 1.14                  | 1.18 | 1.16   |
| T <sub>9</sub> : sole pigeonpea PR 60/150 cm × 30 cm                               | 1548  | 1022   | 1285   | -                     | -    | -      |
| T <sub>10</sub> : pigeonpea PR 60/150 cm × 30 cm + field bean 45 cm × 15 cm        | 1584  | 1027   | 1306   | 1.62                  | 1.60 | 1.61   |
| T <sub>11</sub> : pigeonpea PR 60/150 cm × 30 cm + vegetable soybean 30 cm × 10 cm | 1650  | 1078   | 1364   | 1.69                  | 1.65 | 1.67   |
| T <sub>12</sub> : pigeonpea PR 60/150 cm × 30 cm + chia 45 × 15 cm                 | 1769  | 1548   | 1659   | 1.21                  | 1.28 | 1.25   |
| T <sub>13</sub> : sole field bean  | 1423  | 943    | 1183   | -                     | -    | -      |
| T <sub>14</sub> : sole vegetable soybean   | 1522  | 1043   | 1283   | -                     | -    | -      |
| T <sub>15</sub> : sole chia  | 2636  | 2104   | 2370   | -                     | -    | -      |
| S.Em. ±  | 59.299  | 46.53  | 52.54  | NA                    | -    | NA     |
| CD at 5 %  | 171.782   | 134.79 | 152.19 | -                     | -    | -      |

**Note:** NR: normal row, PR: paired row, NA: not analysed.

**Table 5.** Effect of planting geometry and intercropping on economics of pigeonpea (pooled data 2020 and 2021)

| Treatments   | Cost of cultivation (Rs ha <sup>-1</sup> ) | Gross returns (Rs ha <sup>-1</sup> ) |        |        | Net returns (Rs ha <sup>-1</sup> ) |        |        | C:B ratio |      |        |
|--|--|--------------------------------------|--------|--------|------------------------------------|--------|--------|-----------|------|--------|
|  |  | 2020                                 | 2021   | Pooled | 2020                               | 2021   | Pooled | 2020      | 2021 | Pooled |
| T <sub>1</sub> : sole pigeonpea NR 120 cm × 30 cm                                  | 35995                                      | 77257                                | 52687  | 64972  | 41263                              | 16692  | 28978  | 2.15      | 1.46 | 1.81   |
| T <sub>2</sub> : pigeonpea NR 120 cm × 30 cm + field bean 45 cm × 15 cm            | 40949                                      | 119837                               | 92424  | 106130 | 78888                              | 51475  | 65181  | 2.93      | 2.26 | 2.59   |
| T <sub>3</sub> : pigeonpea NR 120 cm × 30 cm + vegetable soybean 30 cm × 10 cm     | 41560                                      | 211069                               | 119764 | 165416 | 169509                             | 78203  | 123856 | 5.08      | 2.88 | 3.98   |
| T <sub>4</sub> : pigeonpea NR 120 cm × 30 cm + chia 45 cm × 15 cm                  | 43123                                      | 90188                                | 84528  | 87358  | 47065                              | 41404  | 44235  | 2.09      | 1.96 | 2.03   |
| T <sub>5</sub> : sole pigeonpea PR 60/120 cm × 30 cm                               | 35995                                      | 114369                               | 77372  | 95871  | 78375                              | 41378  | 59876  | 3.18      | 2.15 | 2.66   |
| T <sub>6</sub> : pigeonpea PR 60/120 cm × 30 cm + field bean 45 cm × 15 cm         | 40949                                      | 125297                               | 148386 | 136841 | 84348                              | 107437 | 95892  | 3.06      | 3.62 | 3.34   |
| T <sub>7</sub> : pigeonpea PR 60/120 cm × 30 cm + vegetable soybean 30 cm × 10 cm  | 41560                                      | 260591                               | 143393 | 201992 | 219030                             | 101832 | 160431 | 6.27      | 3.45 | 4.86   |
| T <sub>8</sub> : pigeonpea PR 60/120 cm × 30 cm + chia 45 × 15 cm                  | 43123                                      | 111374                               | 95176  | 103275 | 68251                              | 52053  | 60152  | 2.58      | 2.21 | 2.39   |
| T <sub>9</sub> : sole pigeonpea PR 60/150 cm × 30 cm                               | 35995                                      | 94628                                | 68474  | 81551  | 58633                              | 32479  | 45556  | 2.63      | 1.90 | 2.27   |
| T <sub>10</sub> : pigeonpea PR 60/150 cm × 30 cm + field bean 45 cm × 15 cm        | 41019                                      | 148230                               | 116943 | 132586 | 107211                             | 75924  | 91567  | 3.61      | 2.85 | 3.23   |
| T <sub>11</sub> : pigeonpea PR 60/150 cm × 30 cm + vegetable soybean 30 cm × 10 cm | 41630                                      | 259851                               | 138167 | 199009 | 218220                             | 96536  | 157378 | 6.24      | 3.32 | 4.78   |
| T <sub>12</sub> : pigeonpea PR 60/150 cm × 30 cm + chia 45 × 15 cm                 | 43173                                      | 107512                               | 97907  | 102710 | 64339                              | 54734  | 59536  | 2.49      | 2.27 | 2.38   |
| T <sub>13</sub> : sole field bean  | 25863                                      | 74506                                | 64300  | 69403  | 48644                              | 38437  | 43541  | 2.88      | 2.49 | 2.68   |
| T <sub>14</sub> : sole vegetable soybean   | 27055                                      | 187897                               | 99320  | 143609 | 160841                             | 72265  | 116553 | 6.94      | 3.67 | 5.31   |
| T <sub>15</sub> : sole chia  | 31571                                      | 82321                                | 78900  | 80611  | 50749                              | 47329  | 49039  | 2.61      | 2.50 | 2.55   |

**Note:** NR: normal row, PR: paired row.

more plant population than normal row spacing and it facilitates better solar radiation interception, improved microclimate and more efficient moisture management for the main crop. Further, the wider spacing between paired rows creates a spatially compatible environment for both main and companion crops, ensuring balanced light availability, nutrients access and moisture distribution, which supports the normal growth of the initially slow-growing pigeonpea alongside the more vigorous companion crops.

Temporal compatibility is also observed, as the critical growth stages of the main and companion crops do not overlap, enabling unhindered expressions of growth and yield potential in both components. This is particularly evident in pigeonpea + vegetable soybean/ field bean systems, where pigeonpea remains slow-growing during the first 40–50 days, by which time these companion crops approach harvest maturity, thereby avoiding competition during the grand growth phase of pigeonpea. On the contrary, chia, being a long duration crop (~120 days), enters its reproductive stage during the grand growth stage of pigeonpea, which can negatively affect the growth and yield of the main crop. However, this system still records a higher pigeonpea equivalent yield, mainly due to the premium market price chia, which enhances the overall system productivity. This intercropping system is also suitable under extreme weather aberrations, as chia is a hardy and climate-smart crop.

Under normal climatic conditions, intercropping pigeonpea with other pulses (field bean, vegetable soybean and chia) resulted in higher net returns and better return per rupee invested, owing the greater economic yields and better market prices, making it a more profitable intercropping system. Also, the production of multiple crop products promote local processing industries, especially for value-added product such as canned vegetable soybean. Processing pigeonpea seed into dhal or split pulses requires the establishment of pulse-splitting units, which help bridge the gap between producer and consumer while

generating additional income for farmers. The pulse-pulse intercropping system requires less nitrogenous fertilizers, as only a starter dose is needed. This reduces production costs and minimizes environmental pollution, considering that applied nitrogen fertilizers generally have only 20–30 % use efficiency. Legume crops also contribute to climate change mitigation by reducing atmospheric nitrogen levels (a greenhouse gas nearly 300 % more potent than CO<sub>2</sub> in heat retention) by fixing it into plant available forms through biological nitrogen fixation in root nodules. Thus, integrating pulses into pulse-based cropping systems not only enhances farmers' income but also contributes to environmental sustainability mitigating greenhouse gas accumulation. It also supports global protein security by increasing pulse availability within limited areas, thereby promoting sustained pulse production. Overall, this approach provides a sustainable, environmentally friendly and economically viable cropping option for farmers, particularly under rainfed conditions and resource-constrained conditions.

### Acknowledgements

I acknowledge the All India Coordinated Research Project on Pigeonpea, University of Agricultural Sciences, Gandhi Krushi Vignana Kendra, Bengaluru and the Department of Agronomy, University of Agricultural Sciences, Gandhi Krushi Vignana Kendra, Bengaluru, for their support in carrying out this research.

### Authors' contributions

LN carried experiment, analysis and manuscript writing. ARHM carried out supervision and software analysis. KBS carried out the manuscript editing. AMR, ASR, SKS and VK carried out analysis and manuscript editing. All authors read and approved the final manuscript.

## Compliance with ethical standards

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

**Ethical issues:** None

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