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Influence of Nitrogen and Growth Regulators on Nutrient Uptake and Final Available Nutrient Status of Paired Row Pigeonpea Intercropping with High-density Cotton in Vertisols of Southern India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The paired row pigeonpea intercropping system, the space between the two paired rows of pigeonpea is effectively utilized for growing high-density cotton. This experiment was conducted at Agricultural Research Station (ARS) Tandur, Vikarabad during *Kharif* 2023-24 and 2024-25. The

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experiment was laid out in a split-plot design with three replications. The main plots (three) with paired rows of pigeonpea combined with three spacings of high-density cotton arranged in six subplots. Among the main plots, at 60 and 90 days after sowing (DAS), and at harvest, the highest nitrogen, phosphorus, and potassium uptake was recorded under the high-density cotton spacing of M_1 (60 cm x 15 cm) during both years of experiment as well as in the mean data whereas the lowest uptake was observed with the wider spacing of M_3(100 x 15 cm). Among the subplots, the highest NPK uptake and final available soil NPK were recorded with the application of 125% RDN + Mepiquat chloride (50 ppm) at square formation and flowering stage (S_3). This was followed by the treatment 125% RDN + Cycocel (60 ppm) applied at square formation and flowering stage (S_6) during both years and in mean data. The lowest values were obtained with the application of 100% RDN + Cycocel (60 ppm) at square initiation, peak square formation and flowering stage. The highest final available NPK (247, 37.7 and 297 kg ha^{-1}) during 2023-24 and (242, 35.1 and 291 kg ha^{-1}) during 2024-25 recorded was spacing of M_3 (100 x 15 cm). Among subplots the highest final available NPK (246, 38.4 and 301 kg ha^{-1} during 2023-24 and 242, 35.7 and 293 kg ha^{-1} during 2024-25) were obtained with the application of 125% RDN + Mepiquat chloride (50 ppm) at square formation and flowering stage (S_3). The results of the current study will contribute efficient nutrient management for the sustainability of productivity in intercropping systems, especially under high-density planting conditions. In a pigeonpea-based intercropping system, optimizing nitrogen levels and growth regulators is crucial for enhancing nutrient uptake and maintaining soil fertility.

Keywords: Paired row pigeonpea; high-density cotton; mepiquat chloride; cycocel; nitrogen management.

1. INTRODUCTION

"Pigeonpea (*Cajanus cajan* L.) is the second most important pulse crop after chickpea in India. Pigeonpea is one of the most important rainy season (*kharif*) grain legume crop, grown predominantly under rainfed conditions in India. In India Pigeonpea is growing in an area of 50.02 lakh ha with the production of 4.34 million tonnes and productivity of 877 kg ha^{-1}" (FAO STAT, 2024).

"In paired row Pigeonpea cotton intercropping system the space between the two paired rows of Pigeonpea is effectively utilized for growing high density cotton. Paired row planting system allows or permits in better light interception by the crop and resource sharing for harvesting better yields" (Sudha Rani et al*.,* 2019). " In addition to that, paired row of Pigeonpea intercropping system enriches the soil by adding nitrogen, improving the soil physico-chemical and biological properties. In intercropping Pigeonpea with other crops such as cotton, provides additional returns to farmers because it is a commercial crop, Pigeonpea also improves soil quality, reduces climatic risks and the likelihood of crop failure, enhances biodiversity and ensures more efficient use of resources and land area" (Maitra et al., 2001; Maitra and Ray, 2019). "Pigeonpea is suitable for inter-cropping with different crops like cotton, sorghum, pearl millet, greengram, blackgram, maize, soybean, and groundnut to enhance production, improve resource-use efficiency and maintain soil fertility" (Maitra and Ray, 2019).

"Plant density plays a very important role in deciding the growth and development and yield of cotton" (Sawan 2016). "In cotton, high density planting is a modern approach, for attaining high productivity, which needs critical planning, proper time of sowing, careful monitoring and prompt investigations. It is one of the best alternative production system with a scope to increase productivity, profitability, resource (inputs) use efficiency, high benefit-cost (B C) ratio and also reduce the problems associated with present production system of India" (Venugopalan et al*.,* 2013). "Higher yields can be achieved by manipulating row spacing and increasing plant density to create a compact arrangement of short-statured plants. There is better light interception, greater leaf area, low weed competition and earliness in crop maturity by adoption of ultra-narrow row spacing cotton" (Wright et al., 2011). When plants density per unit area is increased, plants tends to grow taller, resulting in excessive vegetative growth this can lead to inter-plant competition for various resources, disrupting the balance between vegetative and reproductive stages in cotton. Adequate translocation of photosynthates is essential for proper square and boll development, boll retention and ultimately yield. To address these issues, the source-sink relationship, such as leaf- to-boll connections must be balanced. Plant growth regulators (PGR) are modern agrochemicals that, when applied at low concentrations, can alter plant development by promoting or inhibiting natural growth processes. Application of mepiquat chloride and Cycocel helps maintain compact plant architecture and ensures sufficient photosynthates for optimal proper boll development, retention and good harvest.

2. MATERIALS AND METHODS

The experiment was conducted at Agricultural Research Station (ARS) Tandur, Vikarabad, Telangana. The farm is geographically situated at 350 m above mean sea level at 17º 22ˈ N latitude, 77º 58ˈ E longitude, in the Southern Agro-climatic zone of Telangana. According to Troll's climatic classification, it falls under semi-arid tropics (SAT).

2.1 Crop Establishment and Treatment Details

The experimental plot was clay loamy soil, slightly alkaline in reaction, medium organic carbon, low available nitrogen, high available phosphorus and medium available potassium, respectively.

The experiment was laid out in a split-plot design during *kharif* 2023-24 and 2024-25. The main plot treatments consisted of high density cotton spacings in paired row pigeonpea as follows.

M_1: Paired row of Pigeonpea intercropped with high density planting of cotton at 60 cm x 15 cm (1,11,111 plants ha^{-1}),

M_2: Paired row of Pigeonpea intercropped with high density planting of cotton at 75 cm x 20 cm (66,666 plants ha^{-1}),

M_3: Paired row of Pigeonpea intercropped with normal planting of cotton at 100 cm x 15 cm (66, 666 plants ha^{-1}).

The subplot treatments comprised growth regulators and nitrogen management

S_1: 100% RDN + Mepiquat chloride 50 ppm at square initiation, peak square formation and flowering stage,

S_2: 100% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage,

S_3: 125% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage,

S_4:100% RDN + Cycocel 60 ppm at square initiation, peak square formation and flowering stage,

S_5:100% RDN + Cycocel 60 ppm at square formation and flowering stage,

S_6: 125% RDN + Cycocel 60 ppm at square formation and flowering stage. All treatments are replicated three times.

ADB-39 cotton variety and TDRG 59 pigeonpea variety were selected for the experiment and sown by dibbling at different spacings of high-density cotton. First paired row of pigeonpea was sown with spacing of 45 cm and the space between the two paired rows of pigeonpea was 3 metres and in between the two paired rows of pigeonpea, 60 cm x 15 cm (5 rows of high density cotton), 75 cm x 20 cm (4 rows of high density cotton), and 100 cm x 15 cm (3 rows of high-density cotton) of high density cotton were grown during both years of the experiment. Concerning growth regulators and nitrogen management, Mepiquat chloride 50 ppm and Cycocel (60 ppm) was sprayed at square initiation, peak square formation and flowering stage along with application of 100% The recommended dose of nitrogen (RDN) @ 120:60:60 were applied as per framed treatments, in four equal splits (20, 40, 60 and 80 DAS) while, the entire Phosphorus as basal. 125% RDN of 150:60:60 kg NPK ha^{-1} was applied as per treatments in four equal splits (20, 40, 60 and 80 DAS) and phosphorus was applied as basal dose, and potassium was applied along with urea. Recommended dose of fertilizers (RDF) of pigeonpea is 20:50:00 NPK kg ha^{-1}. Pigeonpea RDF of 20 kg of N and 50 kg of P2O5 were applied as urea and single super phosphate respectively as basal dose to the all the plots of pigeonpea as per treatments. Weeds were controlled by spraying pre-emergence herbicide, pendimethalin @ 0.75 kg *a.i.* ha^{-1} second day of sowing followed by manual weeding at 40 and 70 DAS during both years of study (*kharif*, 2023-24 and 2024-25). The incidence of sucking pests was controlled by spraying Fipronil 5% SC at 4 ml lit^{-1}. Later stages Imidacloprid @ 0.45 ml L^{-1}. To check the incidence of bollworms (*Pectinophora gossipella*), spraying was done with Chlorantraniliprole (10%) + Lambdacyhalothrin 5% ZC @ 0.5 ml lit^{-1} at boll development stage in 2023-24. Emamectin benzoate 5 % SG @ 0.5 g L^{-1} was sprayed against bollworms at 105 DAS and 120 DAS in 2024-25.

2.2 Statistical Analysis

Data on different characters *viz*., growth, yield attributes, yield, soil and plant analysis, economics were subjected to analysis of variance procedures as outlined for split plot design (Gomez and Gomez, 1984). Statistically significance was tested by F-value at p=0.05 (5 %) level of probability and critical difference was worked out where ever the effect was significant. Non-significant treatment differences were denoted as NS. Statistical analysis of data is done by using R Software.

3. RESULTS AND DISCUSSION

3.1 Nitrogen Uptake at 60, 90 DAS and at Harvest

Among the main plots at 60, 90 DAS and at harvest maximum nitrogen uptake (24.2, 22.1 and 23.1), (52.3, 51.0 and 51.7) and mean grain (57.6), straw (21.6) uptake was recorded with the paired row pigeonpea intercropped with high density plant spacing of (60 cm x 15 cm) (M_1), during both years and in mean data. The lowest nitrogen uptake (18.3, 17.9 and 18.1), (48.6, 47.3 and 47.9) and mean grain (51.3), straw (15.9) uptake was recorded with plant spacing of (100 cm x 15 cm) (M_3) during both years and in mean data.

Among the subplots at 60, 90 DAS and at harvest uptake of nitrogen (Table 1.) was not significantly influenced by growth regulators and nitrogen management (M_1) during both years of study. However higher nitrogen uptake (24.0, 22.1 and 23.0), (52.4, 51.8, and 52.2) and mean uptake grain (58.1), straw (22.1) nitrogen uptake of pigeonpea was observed with application of 125% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage (S_3), it was followed by the treatment S6 (125% RDN + Cycocel 60 ppm at square formation and flowering stage) during the both the years of study and in mean data. And the lower nitrogen uptake (18.1, 17.4 and 17.7), (47.8, 46.4 and 47.2) and mean nitrogen (50.3, 15.1 and 32.7) uptake at harvest was recorded with the application of 100% RDN + Cycocel 60 ppm at square initiation, peak square formation and flowering stage during both the years of investigation including the mean data.

The results of the experiment revealed that nitrogen uptake of pigeonpea was not significantly influenced by paired row pigeonpea in high-density cotton spacings, and not influenced by application of growth regulators and doses of nitrogen management. Interaction was also found to be non-significant during both years of the experiment and in the pooled data. This might be the reason of maximum plant height, growth rate, dry matter production and grain yield of redgram by complementary effect of intercrops leading to higher nutrient uptake results as reported by (Shivran and Ahlawat, 2000) and "increasing N level increased the vegetative growth and root biomass and increased the availability of nutrients in soil resulting in higher uptake of nutrients" (Shankarlingappa et al*.,* 2000). Shivakumar et al. (2022) also reported that "NPK uptake in pigeonpea + urdbean might be due to enhanced availability of these nutrients to the plant which raised their content in seed and stalk accompanied by higher total biomass production of pigeonpea". In addition Pandey et al (2013) also revealed "higher NPK uptake by pigeonpea in pigeonpea + urdbean intercropping system than pigeonpea + maize and sole pigeonpea".

3.2 Phosphorus Uptake at 60, 90 DAS at Harvest

The highest phosphorus uptake by pigeonpea (4.81, 4.08 and 4.45 kg ha^{-1}) at 60 DAS, (11.8, 10.9 and 11.3 kg ha^{-1}) at harvest, and in grain (12.6, 11.9 kg ha^{-1}) and straw (8.50, 6.42 kg ha^{-1}) was recorded in the paired-row pigeonpea intercropped with high density cotton spacing of 60 cm x 15 cm (M_1) (Table 2). In contrast, thelowest phosphorus uptake 3.17, 2.97 and 3.07 kg ha^{-1}) at 60 DAS, (9.94, 8.95 and 9.45 kg ha^{-1}) at harvest, and in grain (10.3, 6.06 and 14.69 kg ha^{-1}) of pigeonpea was observed under the wider spacing of 100 cm x 15 cm (M_3) during both the years and in the mean data.

Among the subplot treatments, no significant difference in phosphorus uptake was observed at 60 DAS among the growth regulators and nitrogen management treatments. However, the maximum of phosphorus uptake (4.44, 4.20 and 4.31) at 60 DAS, (11.8, 11.0, and 11.4 kg ha^{-1}) at harvest, and in grain (12.4, 11.8 kg ha^{-1}) and straw (8.44, 6.69 kg ha^{-1}) was registered with application 125% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage (S_3). This was followed by the treatment S_6 (125% RDN + Cycocel 60 ppm at square formation and flowering stage) during both the years in the pooled mean. The lowest phosphorus uptake (3.00, 2.74 and 2.87 kg ha^{-1})

at 60 DAS, (9.78, 8.60 and 9.19 kg ha^{-1}) at harvest, and in grain (8.44, 6.69 kg ha^{-1}) and straw (5.89,3.70 kg ha^{-1}) was recorded with 100% RDN + Cycocel 60 ppm applied square initiation, peak square formation, and flowering stage (S4) during both years and in the mean data. Generally, the results of the current study revealed that phosphorus uptake of pigeonpea was not significantly influenced by paired-row intercropping with high-density cotton, nor by the application of growth regulators and nitrogen management doses during either year in pooled data. Similar findings were reported by Singh and Sekhon (2007), while Singh and Svrivastava (2018) observed Maximum uptake in pigeonpea + groundnut intercropping systems, which was significantly higher than in pigeonpea + rice and pigeonpea + maize systems, mainly due to the greater biomass production in the former system.

3.3 Potassium Uptake at 60, 90 DAS and at Harvest

At 60, 90 DAS and at harvest, the maximum potassium uptake (24.6, 23.5 and 24.1 kg ha^{-1}), (52.1, 50.0 and 51.1 kg ha^{-1}) and mean uptake by grain (28.4, 26.8 kg ha^{-1}), straw (39.7, 37.8 kg ha^{-1}) (Table 3.) was recorded in the paired row pigeonpea intercropped with high density cotton spacing of 60 cm x 15 cm (M_1) However, this treatment was statistically at par with the paired row pigeonpea intercropped with cotton spacing of 75 cm x 20 cm (M_2) during both years and in the mean data. The lowest potassium uptake (21.7, 20.6 and 21.2 kg ha^{-1}), (46.9, 45.4 and 46.2 kg ha^{-1}) and by grain (23.7, 21.8 kg ha^{-1}), straw (35.4, 33.4 kg ha^{-1}) was recorded with the paired row pigeonpea intercropped with high density plant spacing of (100 cm x 15 cm) (M_3) during both years and in the mean data.

Potassium uptake was not significantly influenced among the sub-plot treatments at 60, 90 DAS and at harvest, However maximum uptake of potassium (24.4, 23.6 and 24.1 kg ha^{-1}) was registered with application of 125% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage (S_3), This was followed by S6 (125% RDN + Cycocel 60 ppm at square formation and flowering stage) during the both years and in the mean data. The lowest potassium uptake (21.8, 19.7 and 20.8 kg ha^{-1}), (45.7, 44.5 and 45.2 kg ha^{-1}) and grain (29.2, 27.1 kg ha^{-1}) straw (40.5, 38.1 kg ha^{-1}) was recorded with the application of 100% RDN + Cycocel 60 ppm at square initiation, peak square formation and flowering stage during both years and in the mean data. Enhanced NPK uptake in intercropped pigeonpea systems e.g (pigeonpea + urdbean) might be due to improved nutrient availability, which increases nutrients content in seed and stalk alongside higher total biomass production. Pandey et al (2013) also reported "greater NPK uptake in pigeonpea in pigeonpea+ urdbean intercropping system compared to pigeonpea + maize and sole pigeonpea. Application of 125% RDF significantly enhanced NPK uptake in pigeonpea where as uptake decreased with lower fertilizer levels. This could be attributed to the increased nutrients availability from added fertilizers resulting in vigorous shoot and root growth and greater nutrient absorption from the soil. of these nutrients to the plant. This might has resulted in profuse shoot and root growth and thereby activating greater absorption of these nutrients from the soil". Similarly, maximum NPK uptake occurred in pigeonpea + groundnut intercropping systems which was significantly higher than in pigeonpea + rice and pigeonpea + maize systems, primarily due to higher biomass production (Singh and Srivastava 2018).

3.4 Available Nitrogen (kg ha^{-1})

significantly higher post-harvest available nitrogen status (228, 221 and 224 kg ha^{-1}) was recorded with plant spacing of 100 cm x 15 cm (M_3) during 2023-24, 2024-25 and pooled results, respectively, This, was statistically at par with 75 cm x 20 cm (M_2) for both years and mean results. On the other hand, the lowest available nitrogen status (247,242 and 244 kg ha^{-1}) was observed under the narrow plant spacing of 60 cm x 15 cm (M1) during both years and in mean analysis. This may be attributed the higher plant density cotton system which results in greater overall nitrogen uptake from the soil, leaving less residual nitrogen after harvest, as reported by Shah et al. (2021) and similar results were reported by Malik et al., (2021) who noted that wider spacing with fewer plants per unit area leaves higher residual soil nitrogen while available phosphorus and potassium were largely unaffected spacing. Kumar et al. (2024) also reported that higher planting densities reduce residual nitrogen because the crop utilizes more of the applied nitrogen for growth and yield.

Table 1. Nitrogen uptake (kg ha^{-1}) of pigeonpea in high density cotton in pigeonpea-based intercropping system at 60, 90 DAS and at harvest as influenced by growth regulators and nitrogen management

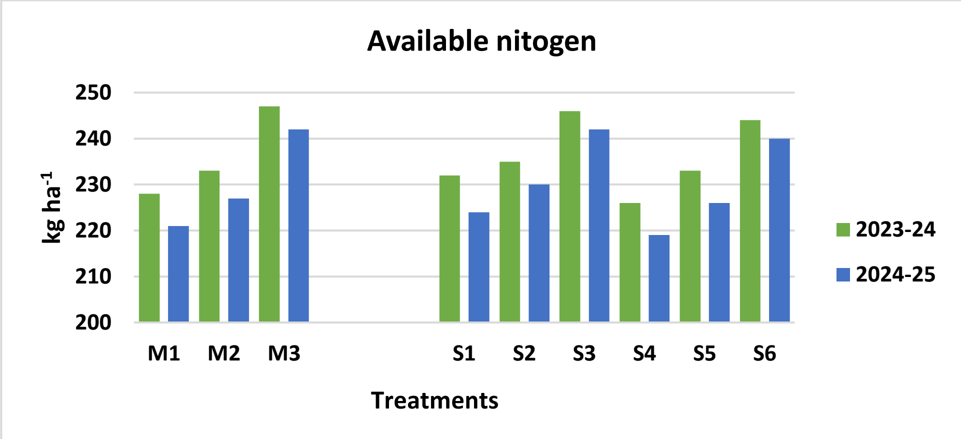
Treatments	60 DAS			90 DAS			At harvest 2023-24			2024-25		
	2023-24	**2024-25**	**Mean**	**2023-24**	**2024-25**	**Mean**	**Grain**	**Straw**	**Mean**	**Grain**	**Straw**	**Mean**
Main plot												
M_1	24.2	22.1	23.1	52.3	51.0	51.7	57.6	21.6	39.6	55.7	18.1	36.9
M_2	20.6	19.6	20.1	50.3	49.0	49.6	54.2	18.4	36.3	53.0	16.3	34.6
M_3	18.3	17.9	18.1	48.6	47.3	47.9	51.3	15.9	33.6	48.9	14.9	31.9
SE(m)±	1.02	0.81	0.67	1.79	1.30	1.47	2.06	1.80	1.90	2.47	1.94	2.17
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Sub plot												
S_1	20.5	19.4	20.0	50.7	48.6	49.7	54.1	18.1	36.1	52.2	16.0	34.1
S_2	21.4	20.5	20.9	51.0	49.7	50.3	54.7	18.8	36.7	53.2	17.1	35.2
S_3	24.0	22.1	23.0	52.4	51.8	52.2	58.1	22.1	40.1	56.3	19.3	37.8
S_4	18.1	17.4	17.7	47.8	46.4	47.2	50.3	15.1	32.7	47.7	14.0	30.8
S_5	19.4	18.4	18.9	48.5	47.2	47.9	53.2	17.6	35.4	50.9	14.7	32.8
S_6	22.7	21.4	22.1	51.7	50.7	51.2	56.0	20.2	38.1	55.0	17.5	36.2
SE(m)±	1.67	1.42	1.42	2.03	2.68	2.17	3.25	20.2	1.90	3.87	2.84	3.30
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction												
M×S												
SE(m)±	2.89	2.46	2.46	3.52	4.65	3.76	5.63	4.7	5.12	2.47	4.91	5.71
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S×M												
SE(m)±	2.83	2.39	1.35	3.68	4.44	3.73	5.54	4.6	5.04	3.87	4.88	5.65
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 2. Phosphorus uptake (kg ha^{-1}) of pigeonpea in high density cotton in pigeonpea based intercropping system at 60, 90 DAS and at harvest as influenced by growth regulators and nitrogen management

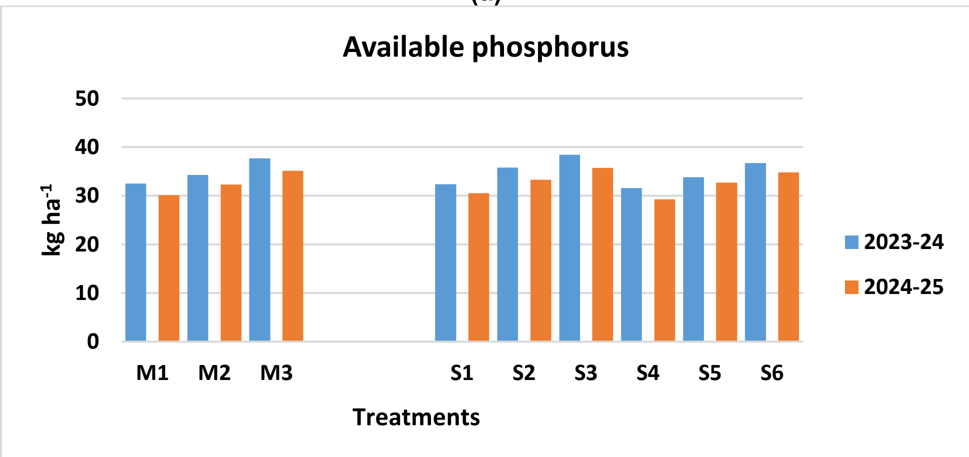
Treatments	60 DAS			90 DAS			At harvest 2023-24			2024-25		
	2023-24	2024-25	Mean	2023-24	2024-25	Mean	Grain	Straw	Mean	Grain	Straw	Mean
Main plot												
M_1	4.81	4.08	4.45	11.8	10.9	11.3	12.6	8.50	10.5	11.9	6.42	9.18
M_2	3.89	3.68	3.78	10.3	9.88	10.11	11.1	7.06	9.10	10.4	4.41	7.42
M_3	3.17	2.97	3.07	9.94	8.95	9.45	10.3	6.06	8.21	9.53	3.62	6.58
SE(m)±	0.30	0.45	0.26	0.28	0.51	0.33	0.48	0.66	0.55	0.41	0.27	0.34
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Sub plot												
S_1	4.11	3.49	3.80	10.3	9.77	10.0	11.1	7.22	9.14	10.5	4.49	7.51
S_2	4.22	3.79	4.01	10.8	10.4	10.5	11.5	7.67	9.61	10.7	4.76	7.76
S_3	4.44	4.22	4.33	11.8	11.0	11.4	12.4	8.44	10.4	11.8	6.69	9.26
S_4	3.00	2.74	2.87	9.78	8.60	9.19	10.4	5.89	8.17	9.48	3.70	6.59
S_5	3.67	3.20	3.44	10.1	9.22	9.67	10.7	6.22	8.50	10.1	4.08	7.08
S_6	4.29	4.01	4.15	11.3	10.5	10.9	11.8	7.78	9.78	11.0	5.19	8.14
SE(m)±	0.42	0.55	0.34	0.78	0.70	0.53	0.92	0.81	0.85	0.69	0.64	1.09
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction												
M×S												
SE(m)±	0.72	0.96	0.58	1.36	1.21	0.91	1.59	1.40	1.48	1.19	1.11	1.13
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S×M												
SE(m)±	0.73	0.98	0.59	1.27	1.22	0.90	1.53	1.44	1.46	1.17	1.05	1.09
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 3. potassium uptake (kg ha^{-1}) of pigeonpea in high density cotton in pigeonpea based intercropping system at 60, 90 DAS and at harvest as influenced by growth regulators and nitrogen management

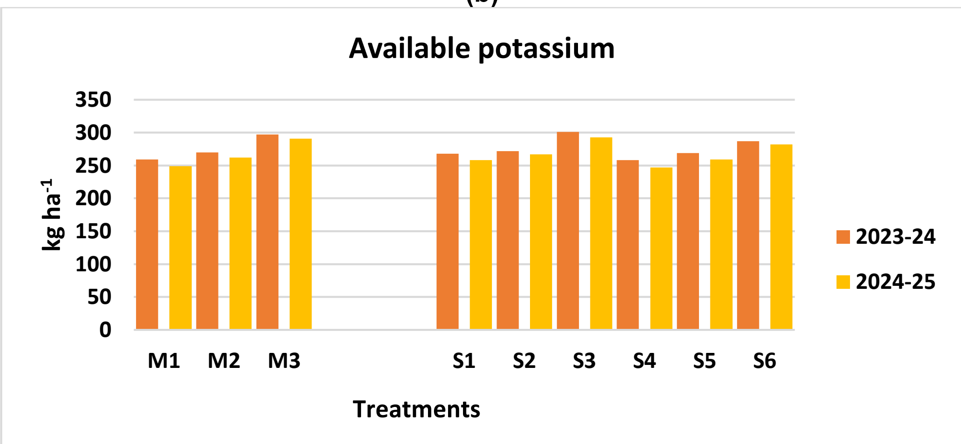
Treatments	60 DAS			90 DAS			At harvest 2023-24			2024-25		
	2023-24	2024-25	Mean	2023-24	2024-25	Mean	Grain	Straw	Mean	Grain	Straw	Mean
Main plot												
M_1	24.6	23.5	24.1	52.1	50.0	51.1	28.4	39.7	34.1	26.8	37.8	32.3
M_2	23.2	22.1	22.6	49.6	48.3	48.9	25.8	37.4	31.6	24.3	36.2	30.7
M_3	21.7	20.6	21.2	46.9	45.4	46.2	23.7	35.4	29.6	21.1	33.7	28.7
SE(m)±	1.26	1.01	1.00	1.70	1.34	1.36	2.38	2.15	2.26	0.82	1.81	1.30
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Sub plot												
S_1	22.8	22.4	22.6	49.4	47.8	48.6	25.2	36.5	30.8	25.0	35.4	30.2
S_2	23.6	22.7	23.2	50.7	48.7	49.7	26.4	37.4	31.9	25.8	36.7	31.3
S_3	24.4	23.6	24.1	52.5	50.1	51.4	29.2	40.5	34.8	27.1	38.1	32.6
S_4	21.8	19.7	20.8	45.7	44.5	45.2	22.8	35.6	29.3	23.2	33.3	28.2
S_5	22.3	21.1	21.7	47.6	46.6	47.2	24.5	36.0	30.2	24.1	34.6	29.3
S_6	23.9	23.0	23.4	51.1	49.4	50.2	27.8	39.0	33.4	26.4	37.4	31.9
SE(m)±	1.58	1.26	1.31	2.61	2.19	2.11	2.49	2.56	2.51	1.38	2.23	1.70
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction												
M×S												
SE(m)±	2.73	2.18	2.28	4.52	3.79	3.65	4.32	4.43	4.35	2.38	3.86	2.94
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S×M												
SE(m)±	2.80	2.23	2.31	4.46	3.71	3.60	4.60	4.58	4.57	2.33	3.96	2.98
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS



(a)



(b)



(c)

Fig. 1. (a,b,c) Final available soil nitrogen, phosphorus and potassium in high-density cotton in pigeonpea-based intercropping system as influenced by growth regulators and Nitrogen Management

M_1: Paired row of Pigeonpea intercropped with high density planting of cotton at 60 cm x 15 cm(111,111 plants ha^{-1}). M_2: Paired row of Pigeonpea intercropped with high density planting of cotton at 75 cm x 20 cm(66,666 plants ha^{-1}). M_3: Paired row of Pigeonpea intercropped with normal planting of cotton at 100 cm x 15 cm (66,666 plants ha^{-1}). S_1: 100% RDN + Mepiquat chloride 50 ppm at square initiation, peak square formation andflowering stage. S_2: 100% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage. S_3: 125% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage. S_4:100% RDN + Cycocel 60 ppm at square initiation, peak square formation, and flowering stage. S_5:100% RDN + Cycocel 60 ppm at square formation and flowering stage. S_6: 125% RDN + Cycocel 60 ppm at square formation and flowering stage.

Among the subplot treatments, the higher post-harvest available nitrogen (246, 242 and 245 kg ha^{-1}) was recorded with the application of 125% RDN + Mepiquat chloride 50 ppm applied at square formation and flowering stage (S_3). This was statistically at par with 100% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage (S_2) and the application of 125% RDN + Cycocel 60 ppm at square formation and flowering stage during both years and in the mean data. The lowest available nitrogen (226, 219 and 223 kg ha^{-1}) was recorded with 100% RDN + Cycocel 60 ppm applied at square initiation, peak square formation and flowering stage (S_4). This may be due the higher nitrogen application in S3, which enhances the residual soil nitrogen compared to 75% and 100% recommended dose of nitrogen. Although, it was statistically comparable to 150% recommended dose of nitrogen. However, as reported by Malik et al. (2021), different spacing and nitrogen doses did not significantly influence the available phosphorus and potassium in the soil.

3.5 Available Phosphorus (kg ha^{-1})

Higher post harvest available phosphorus (32.5, 30.1 and 31.6 kg ha^{-1}) was registered with plant spacing of 100 cm x 15 cm (M_3) during the year of 2023-24, 2024-25 and in the mean data, respectively. This was statistically at par with 75 cm x 20 cm (M_2) for the same years and in mean data. The lowest available phosphorus (37.7, 35.1 and 36.4 kg ha^{-1}) was registered with the narrow plant spacing of 60 cm x 15 cm (M_1) during both years and in the mean results, This may be due to higher plant density in (M1) which leads to increased phosphorus uptake by the cotton crop, as the greater number of plants per unit area exploits more phosphorus from the soil for growth and yield. Consequently, more phosphorus is removed from the soil, leaving less residual phosphorus after harvest, consistent with the finding of Hu et al*.,* (2023). Consequently wider spacing reduces the number of plants per hectare, resulting in lower total phosphorus uptake and higher residual phosphorus post harvest as reported by Prathyusha et al*,* (2022). However, Malik et al*.,* (2021) reported that available P and K in soil were not significantly affected by different spacings or nitrogen doses.

Among the subplots treatments, the maximum post-harvest available phosphorus (38.4, 35.7 and 37.1) was recorded with the application of 125% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage (S_3) This is stastitically at par with the application of 100% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage (S_2) and 125% RDN + Cycocel 60 ppm at square formation and flowering stage (S_6) during both years and in mean data. This trend may be explained by synergistic effect of nitrogen (N) and phosphorus (P) on cotton growth and nutrient uptake which enhances the plant vigor and root development. Increased nutrient uptake can reduce residual soil phosphorus after harvest, as more phosphorus is removed by the crop. Similar observations were reported by (Malik et al*.,* 2021) and Nachimuthu et al*.* (2022). While optimal nitrogen application can improve phosphorus availability and uptake, excessive N may not further enhance phosphorus uptake and can sometimes lead to nutrient imbalances or reduced phosphorus use efficiency.

3.6 Available Potassium (kg ha^{-1})

Among main plots, plant spacing of 100 cm x 15 cm (M_3) recorded significantly higher post-harvest available potassium status in soil (259, 249 and 254 kg ha^{-1}) during 2023-24, 2024-25 and in the mean results, respectively. In contrast, the narrower spacing of 60 cm x 15 cm (M_1) resulted in low available potassium (297, 291 and 294 kg ha^{-1}) during both years and mean results. This may be due to the higher-density cotton in M1, which leads to greater potassium uptake per unit area, resulting in higher removal of available potassium from the soil and lower residual potassium after harvest. These finding is consistent with Monicaa et al*.* (2023). Under wider spacing, fewer plants per hectare, result in lower total potassium uptake, leaving more available potassium in the soil post-harvest.

Higher post-harvest available potassium (301, 293 and 297 kg ha^{-1}) was recorded with the application of 125% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage (S_3). However, this was at par with the application of 100% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage (S_2) and 125% RDN + Cycocel 60 ppm at square formation and flowering stage (S_6) during both years and in mean data. The lowest available potassium (258, 247 and 252 kg ha^{-1}) was recorded with 100% RDN + Cycocel 60 ppm applied at square initiation, peak square formation and flowering stage (S_4).These trends may be attributed to the interaction of plant sapcing and nitrogen doses which influence the available potassium from the soil higher nitrogen application generally enhances the crop uptake of potassium, reducing post-harvest soil potassium as reported by Zhang et al*.,* 2016 while the growth regulator like mepiquat chloride control vegetative growth and improve canopy structure, with minimal direct effect on soil potassium availability (Malik et al*.,* 2021).

4. CONCLUSION

It is concluded that in the paired-row pigeonpea intercropping system in high-desnity cotton spacing of M_1 (60 x 15 cm) recorded the highest uptake of nitrogen, phosphorus and potassium as compared to rest of the other paired row spacings. However, post harvest available soil nitrogen, phosphorus and potassium were recorded with paired row pigeonpea intercropped with cotton (100 cm x 15 cm) during both 2023-24, 2024-25, as well as in mean data. among the subplots, treatments, application of 125% RDN + Mepiquat chloride 50 ppm at square formation and flowering stage (S_3) resulted in the highest uptake of nitrogen, phosphorus and potassium along with the highest available soil NPK as compared to other treatments in both years and in mean data. The lowest nutrient uptake and soil nitrogen, phosphorus and potassium availablility were recorded with the application of 100% RDN + Cycocel 60 ppm at square initiation, peak square formation, and flowering stage (S_4). It is concluded that pigeonpea in paired-row intercropping with high density cotton, along with appropriate growth regulators and recommended fertilizer doses, performed well during both years of the experiment.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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