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Research Paper

Optimizing the planting density of Bt. cotton varieties for rainfed vertisols of central India

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ABSTRACT

The field experiment was conducted during the monsoon seasons of 2019–20 and 2020–21 at ICAR-Central Institute for Cotton Research (CICR), Nagpur, Maharashtra. Bt cotton (*Gossypium hirsutum* L.) hybrids was introduced in India by the private seed industry in 2002. Hybrid seeds were expensive and its cultivation is input intensive, cotton breeders from the public sector R & D institutes released Bt cotton varieties in 2020 suitable for planting under low input situations. This study evaluated the production potential of four Bt varieties released and notified in India, from the ICAR-Central Institute for Cotton Research, Nagpur. The varieties, ICAR-CICR 'PKV081-Bt', ICAR-CICR 'Suraj Bt', ICAR-CICR 'Rajat Bt', and ICAR-CICR 'GJHV 374 Bt' were evaluated in a split plot design under rainfed conditions on a Vertisol, with four planting densities, viz. 0.37 lakh (90 cm × 30 cm), 0.55 lakh (90 cm × 20 cm), 0.74 lakh (90 cm × 15 cm) and 1.1 lakh plants/ha (90 cm × 10 cm). The results indicated that there were significant differences among varieties and plant densities with respect to seed cotton yield, lint yield, boll weight, days to first open flower and earliness index. ICAR-CICR 'PKV081-Bt' was the most productive variety, yielding 2,639 kg seed cotton/ha at 0.37 lakh plants/ha. The interaction (variety × plant density) was significant for seed cotton yield, lint yield and boll density. Concerning seed cotton yield, for varieties, 'PKV 081 Bt' and 'Rajat Bt', 0.37 lakh plants/ha was optimum whereas for 'Suraj Bt' and 'GJHV 374 Bt', 0.74 lakh plant/ha was optimum plant density. At densities of 0.74 and 1.1 lakh plant/ha, the plant height increased and the maturity was delayed. The study highlights the importance of selecting appropriate Bt varieties and optimizing planting density to increase the productivity of rained cotton on Vertisols of Central India.

***Key words*:** Bt variety, Crop geometry, Earliness index, Plant density, Vertisols

Cotton (*Gossypium hirsutum* L.) is an important commercial crop of India, cultivated in around 13 million hectares area. It provides livelihood to more than 6 million farmers (Waghmare *et al.,* 2022) besides supplying 51% raw material to the Indian textile industry. The Government of India approved the commercial cultivation of Bollgard (BG) cotton containing *cry1Ac* gene in 2002 and subsequently, the Bollgard II containing *cry1AC* and *cry2Ab* conferring resistance to lepidopteron pests was approved in 2006. Bt cotton was rapidly adopted by the Indian farmers and at present, nearly 96% of the cotton area is under Bt hybrids (ISAAA, 2021). As a result, the productivity of cotton increased from 302 kg lint/ha to 566 kg lint/ha during 2002–2013. The Bt technology was introduced in India in the form of hybrids as a 'recurrent value capture mechanism' by the private seed industry whereas pure line varieties are a norm, worldwide (Gutierrez, 2018). Despite saturation of the cotton area with Bt hybrids, cotton productivity in India has stagnated around 500 kg/ha over the last few years whereas the production costs are continuously increasing. Hybrid cotton seeds account for 5.14% of the variable cost of cotton production (Reddy *et al.,* 2021). Hybrid seed production is cost and labour intensive as additional skilled labour is needed for hand emasculation and pollination. A recent study by Patil *et al*. (2024) in the Karnataka, around 2076 labour days was required for the production of hybrid cotton seed in one acre area. Hence, the replacement of hybrids with cotton varieties would be a cost-effective option.

Recently, Bt varieties developed by the public sector containing *cry1Ac* gene were approved for cultivation in India (CICR, 2018) and were gazette notified (vide S.O. 3,482 (E) dated 7th October, 2020). Bt cotton varieties could provide a cheaper to the more expensive Bt hybrids (Vittal, 2018) especially under low input situations like

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rainfed cotton production. Selection of appropriate cultivar (Braunack, 2013) and optimizing the planting density (Zhi *et al.,* 2016) are pre-requisites to popularize the new varieties for increased productivity. Adjusting the planting density optimizes slight distribution in the plant canopy and increases photosynthesis (Yao *et al.,* 2016) and ultimately increases cotton yield.

There is a parabolic relationship between cotton yield and plant density. Thus, optimum planting density is pivotal for optimizing productivity as both too high and too low densities can have negative consequences on cotton productivity (Adams *et al.,* 2019). Optimum plant density is a function of the genotype, soil type, climate and management (Venugopalan *et al.,* 2013; Vinayak *et al.,* 2023). Under dryland conditions, 35,000 plants/ha was identified, which can be interpreted as the minimum population density at which yield may be optimized (Adams *et al.,* 2019). On a non-irrigated Norwood silt loam soil, in Alexandria the lint yields remained stable at plant densities between 33,975 and 152,883 plants/ha and fewer bolls were retained at higher plant densities (Siebert *et al.,* 2006). A density of 55,000 plants/ha is generally recommended for non-Bt cotton varieties of *Gossypium hirsutum* and 15,000 – 20,000 plants/ha is recommended for BG II hybrids (Venugopalan *et al*., 2012). Currently, High Density Planting System (HDPS) is being recommended for cotton grown on marginal soils under rainfed conditions. For HDPS, on sandy loam soils of Telangana, a spacing of 90 cm × 15 cm, accommodating 0.74 lakh plants/ha recommended for high seed cotton yield in 'BG II hybrid', 'RCH 665' (Hemalatha *et al*., 2024). However, planting hybrid cotton at 90 cm × 15 cm would require 6–7 kg seeds/ha as against the normal seed rate of 2–2.5 kg seeds/ha. Considering the high cost of hybrid seeds, Bt varieties would be a cost-effective alternative for HDPS (Kranthi and Stone, 2020).

In this context, this study was conducted to compare the performance of the four Bt varieties with reference to growth parameters, seed cotton yield, lint yield, and earliness indices and to optimize their planting density under rainfed conditions on deep black soils of central India. We hypothesize that owing to the differences in the morphological and phenological traits, the optimum plant density would differ among the four varieties evaluated.

MATERIALS AND METHODS

Field experiment was conducted under rainfed conditions during the monsoon seasons of 2019–20 and 2020–21 on a deep soil belong to Vertisol. Information on important physical and chemical properties of the soil pedon from the experimental site is presented in Table 1. The experimental site is a representative of Agro-Eco Sub-Region 10.2, characterized by hot dry sub-humid bio-climate. The monthly rainfall and number of rainy days during the two experimental seasons is provided in Table 2.

Four Bt varieties, viz. ICAR-CICR 'PKV 081-Bt' (pedigree: 'PKV 081' × 'Bikaneri Naarma Bt'), ICAR-CICR 'Suraj Bt' (pedigree: 'Suraj' × 'Bikaneri Naarma Bt'), ICAR-CICR 'Rajat Bt' (pedigree: 'Rajat' × 'Bikaneri Narma Bt'), and ICAR-CICR 'GJHV 374 Bt' (pedigree: 'GJHV 374' × 'Bikaneri Naarma Bt'), in sub-plots were evaluated at four plant densities, viz. 0.37 lakh (90 cm × 30 cm), 0.55 lakh (90 cm × 20 cm), 0.74 lakh (90 cm × 15 cm) and 1.1 lakh plants/ha (90 cm × 10 cm) as main plots in a split plot design with three replications. The crop was sown on 27 June and on 16 June in *kharif* (monsoon) 2019 and 2020, respectively. All the plots were fertilized with 90 kg N/ha and 20 kg P/ha and 37 kg K/ha. Entire dose of P (Single Super Phosphate) and K (Muriate of Potash) was applied as basal. N (Urea) was applied in 3 equal splits at 15, 45 and 70 days after sowing (DAS). Mean date of appearance of first flower (in eight randomly selected plants) was recorded. Leaf area index (LAI) was measured directly at plant LAI @ 100 days after sowing plant height 100 DAS using a LICOR LAI 2200 Plant Canopy Analyzer. Plant height was measured at plant LAI @ 100 days after sowing plant height 110 DAS and averaged over the eight selected plants. Height was measured from the zero node to

Table 1. Select physical and chemical properties of the soil pedon of the experimental site

Horizon	Depth (cm)	Texture	Bulk density (Mg/m^3)	sHC* (cm/h)	*p*H 1:2	Soil organic carbon (g/kg)	$CaCO_3$ (%)
Very fine smect++itic hyperthermic family of *Typic Haplusterts*							
Ap	0–20	clayey	1.32	0.81	7.7	6.6	5.18
Bw1	20–40	clayey	1.52	0.69	7.9	5.8	6.04
Bss1	40–83	clayey	1.62	0.84	7.9	4.4	5.33
Bss2	83–103	clayey	1.73	0.72	7.9	3.5	6.47
Bss3	103–160	clayey	1.76	0.56	8.0	2.4	6.39

*sHC: Saturated hydraulic conductivity

the node corresponding to the top most fully open leaf on the main stem using a measuring tape. Manual removal of the main-stem growth tip is a recommended practice to break the apical dominance of cotton and allow bolls on the sympodial branches to develop optimally. Therefore, the crop was de-topped (cutting the main shoot at 15 cm from the tip) at 115 DAS. Data on boll weight, boll number/m^2 and number of monopodia were also recorded. Cotton from net plot (4 rows of 4.5 m length) was manually harvested three times at 140, 160 and 180 DAS. Earliness index was determined by weighing seed cotton of first pick (after 140 DAS) and was expressed as a percentage of total seed cotton harvested from all the picks. The formula used to estimate earliness index (Anjum *et al.,* 2010) is given below:

$$\text{Earliness index} = \frac{\text{Weight of seed cotton from first pick}}{\text{Total seed cotton weight from all picks}} \times 100$$

Since the treatment effects were similar during both the crop season, the experimental data was pooled over both the years and statistically analyzed. The pooled data was subjected to ANOVA (Gomez and Gomez, 1984) and wherever F was significant, Student's t test was applied to separate difference among treatment means at 5% level of significance.

RESULTS AND DISCUSSION

The quantum of rainfall received during the crop seasons was 23.8% and 35.5% above the normal rainfall during 2019 and 2020, respectively (Table 2). The number of rainy days were 54 in 2019 and 48 in 2020 as against 48 in the long term normal suggesting a normal distribution throughout the crop season during both the years.

The results presented in Table 3 indicated that the effect of plant density was significant for seed cotton yield, lint yield, boll weight, plant height, LAI, days to flowering and earliness index. On the other hand, the varietal effect was significant for seed cotton yield, lint yield, boll weight, boll number, monopodia, plant height and earliness index. The interaction effect between plant density and genotype was significant for seed cotton yield, lint yield and boll number.

Growth attributes

The growth parameters, viz. plant height, Leaf Area Index (LAI) and number of monopodia were altered significantly due to different plant densities (Table 4). At 110 DAS, the plants of varieties 'PKV081 Bt' (116.4 cm) and Rajat Bt (113.1 cm) were found to be significantly taller than 'Suraj Bt' (108.1 cm) and 'GJHV 374' (109.1 cm) Bt. Averaged over varietal means, significantly taller plants were observed at the 2 higher plant densities, viz. 1.1 and 0.7 lakh plants/ha as compared to the plants sown at 0.55 and 0.37 lakh plants/ha. Earlier it was observed a positive relationship between plant density and plant height in cotton at planting density rates ranging from 33978 to 152883 plants/ha and attributed this difference to an increased inter-nodal distance (Siebert *et al*., 2006).

LAI is an important parameter that characterizes the vegetative vigour of plant (Vinayak *et al.,* 2023). Differ-

Table 2. Rainfall (mm) and number of rainy days at the experimental site

Year	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
				Monthly rainfall				
2019	132.4	398.4	343.4	275	77	0	14.6	1,240.8
2020	234.2	305.3	515.2	201	85.8	16.8	0.4	1,358.7
Normal	163.4	304	275	170.1	61.2	16.8	11.7	1,002.2
				Number of rainy days				
2019	5	15	15	13	4	0	2	54
2020	11	15	16	5	1	0	0	48
Normal	9	14	13	8	3	1	1	49

Table 3. Results of pooled ANOVA (F values and significance) on the effect of plant density and variety on different growth and yield attributes and yield earliness

Effect	Seed cotton yield (kg/ha)	Lint yield (kg/ha)	Boll weight (g)	Open bolls/ m^2	Monopodia/ plant	Plant height (cm)	LAI	Days to flowering	Earliness index
Plant density	5.77*	5.13*	11.33**	3.76^{NS}	14.74**	23.88**	16.52**	35.26**	101.1**
Variety	9.89**	8.79**	17.18**	13.13**	6.03**	10.43**	1.35^{NS}	0.09^{NS}	6.25**
Interaction	3.15*	3.21**	0.91^{NS}	6.29**	1.77^{NS}	1.8^{NS}	1.39^{NS}	1.57^{NS}	1.18^{NS}

**Significant at 1% (p<0.01), *Significant at 5% (p<0.05) and ^{NS} non-significant

Table 4. Effect of spacing on growth attributes of Bt varieties

Treatment	Plant density (lakh/ha)				
	1.1	0.74	0.55	0.37	Mean
Plant height (cm)					
'PKV 081 Bt'	123.7	122.3	106.3	113.3	116.4
'Suraj Bt'	109.2	115.7	102.6	105.4	108.3
'Rajat Bt'	116.1	120.1	110.3	105.8	113.1
'GJHV 374Bt'	112.6	111	106.7	106.1	109.1
Mean	115.4	117.3	106.5	107.7	
CD (P=0.05)	Spacing: 3.85, Variety: 3.41, Interaction: NS				
Leaf area index					
'PKV 081 Bt'	3.21	2.5	2.3	2.12	2.53
'Suraj Bt'	3.04	3.12	2.61	2.3	2.77
'Rajat Bt'	3.18	2.88	2.43	2.36	2.71
'GJHV 374Bt'	3.31	2.35	2.59	2.34	2.65
Mean	3.18	2.71	2.48	2.28	
CD (P=0.05)	Spacing: 0.331, Variety: NS, Interaction: NS				
Monopodia/plant					
'PKV 081 Bt'	1.13	1.67	2.33	2.4	1.88
'Suraj Bt'	1.6	2.07	2.27	2.4	2.08
'Rajat Bt'	1.33	1.07	2.53	2.53	1.87
'GJHV 374Bt'	1.6	2.6	2.67	2.93	2.45
Mean	1.42	1.85	2.45	2.57	
CD (P=0.05)	Spacing 0.475, Variety: 0.33, Interaction: NS				

ences in plant density significantly influenced LAI recorded at 100 DAS. LAI at 1.1 lakh plants/ha was observed to be 17.3%, 28.2% and 39.5% higher than that at 0.74, 0.55 and 0.37 lakh plants/ha, respectively. Within the range of plant densities evaluated, the intra-specific competition for water and nutrients was not a limitation. Under climatic conditions of Henan Province of China, Liu *et al.,* 2019, observed that the LAI in cotton increased as plant density increased from 15000 to 105000 plants/ha and attributed this due to early canopy development at higher plant densities.

Monopodial branches produced at the base of the cotton plants provide a bushy appearance to the cotton plants. Monopodial branching habit is basically a varietal trait characterizing the indeterminate growth habit (Huang *et al.,* 2022). The mean number of monopodia/plant in variety 'GJHV 374 Bt' was found to be significantly higher than rest of the varieties. High planting density (1.1 lakh plants/ha) significantly reduced the number of monopodial branches and provided a compact architecture. Pandangale *et al.* (2020) also observed reduced monopodial branches/plant at increased plant densities.

Yield and yield attributes

The main effect of variety and plant density as well as interaction effect was significant for seed cotton yield and lint yield (Table 5). Averaged over plant density levels, the mean seed cotton yield of the variety 'PKV 081 Bt' (2245 kg/ha) was 14.8% and 16.9% higher than that realized by varieties 'Suraj Bt' (1956 kg/ha) and 'GJHV 374 Bt' (1921 kg/ha), respectively. The yield difference between 'PKV 081 Bt' and 'Rajat Bt' was not statistically significant.

There was no significant difference in the seed cotton yield in the plant density range of 0.37 lakh/ha (2163 kg/ha) to 0.74 lakh/ha (2112 kg/ha) but when the plant density was further increased to 1.1 lakh plants/ha, the seed cotton yield declined significantly to 1907 kg/ha. The lint yield of variety 'PKV 081 Bt' was 14.2% and 19.6% higher than that of 'Suraj Bt' and 'GJHV 374 Bt', respectively.

Significant interaction effect was observed between Bt varieties and plant density for seed cotton yield, lint yield and boll density on rainfed Vertisols (Table 5). Highest seed cotton yield of 'PKV 081 Bt' (2639 kg/ha) followed by 'Rajat Bt' (2338 kg/ha), both at a population density of 0.37 lakh plant/ha. However, a plant density of 0.74 lakh plants/ha was found to be optimum for 'Suraj Bt' (2069 kg/ha) and 'GJHV 374 Bt' (2046 kg/ha). The effect of plant density on lint yield was similar to that of seed cotton yield. Dong *et al.* (2006) also observed a significant interaction between plant density and variety for Bt varieties evaluated at densities of 0.3, 0.4 and 0.6 lakh plants/ha on fertile sandy loam soils of Shandong, China. Bednarz *et al.,* (2000) also observed a stable lint yield over a wide range of planting density and attributed this to the plasticity in

Table 5. Effect of spacing on yield and yield attributes of Bt varieties

Treatment	Plant density (lakh/ha)				
	1.1	0.74	0.55	0.37	Mean
Seed cotton yield (kg/ha)					
'PKV 081 Bt'	1,995	2,099	2,248	2,639	2,245
'Suraj Bt'	1,874	2,069	2,000	1,880	1,956
'Rajat Bt'	1,918	2,055	2,197	2,338	2,127
'GJHV 374Bt'	1,842	2,046	2,001	1,796	1,921
Mean	1,907	2,112	2,067	2,163	
CD (P=0.05)	Spacing: 157.5, Variety: 141.6 Interaction:283.2				
Lint yield (kg/ha)					
'PKV 081 Bt'	705	720	780	945	788
Suraj Bt'	655	748	707	651	690
'Rajat Bt'	655	713	752	804	731
'GJHV 374Bt'	618	710	689	618	659
Mean	658	723	732	754	
CD (P=0.05)	Spacing: 63.2, Variety: 54.8 Interaction:109.7				
Number of bolls/m^2					
'PKV 081 Bt'	79.2	58.5	66.3	78.9	70.72
'Suraj Bt'	74.7	70.9	64.3	55.8	66.43
'Rajat Bt'	80.1	67.7	75.6	83.1	76.62
'GJHV 374Bt'	64.3	71.2	60.6	49.8	61.47
Mean	74.57	67.07	66.71	66.89	
CD (P=0.05)	Spacing: NS, Variety: 5.18, Interaction: 10.35				
Boll weight (g)					
'PKV 081 Bt'	3.46	3.59	3.68	3.79	3.63
'Suraj Bt'	3.38	3.51	3.52	3.61	3.5
'Rajat Bt'	3.06	3.44	3.2	3.34	3.26
'GJHV 374Bt'	3.19	3.25	3.1	3.44	3.24
Mean	3.27	3.38	3.45	3.54	
CD (P=0.05)	Spacing: 0.117, Variety: 0.133, Interaction: NS				

cotton plant architecture and its ability to manipulate boll number and boll weight. Earlier studies from India (Halemani and Hallikeri, 2002) and China (Wang *et al.,* 2004) concluded that the optimum plant density for a variety at a given location is a function of the local soil and climatic characteristics.

Among the yield attributes the boll density, i.e. bolls/m^2 differed significantly among Bt varieties. Averaged over plant densities, the boll density was highest in 'Rajat Bt' (76.62 bolls/m^2) and this was 8.3%, 15.3% and 24.7% higher than the boll density realized with 'PKV 081 Bt', 'Suraj Bt' and 'GJHV 374 Bt'. The boll weight of 'PKV 081 Bt' (3.63 g) and 'Suraj Bt' (3.50 g) was significantly higher than that 'Rajat Bt' (3.26 g) and 'GJHV 374 Bt' (3.24 g).

The boll density did not increase significantly when the plant density was increased from 0.37 lakh/ha to 1.1 lakh/ha. The mean boll weight at 0.37 lakh plants/ha was 8.3% and 4.7% higher than that observed at 0.74 lakh plants/ha and 1.1 lakh plants/ha, respectively and these differences were significant. Zhi *et al.* (2016) also obtained heavier bolls at low plant densities and attributed this to higher retention of early formed first position bolls.

Maturity attributes

The effect of plant densities on indicators of maturity is presented in Fig. 1 and 2. The differences for days to first open flower among the studied Bt varieties was not significant while, significant differences were observed for earliness index. Spacing significantly affected both days to first open flower and earliness index. Among the varieties, highest earliness index with earliest flower initiation was observed under lower plant densities (0.37 and 0.55 lakh plants/ha) than under higher plant densities (1.10 and 0.74 lakh plants/ha). At higher densities, plants across the varieties took more number of days for flower initiation. Increased plant height at higher plant densities observed in the present study would have caused shedding of first formed squares and explains the delay in the days to first open flower and lower earliness index. Across plant densi-

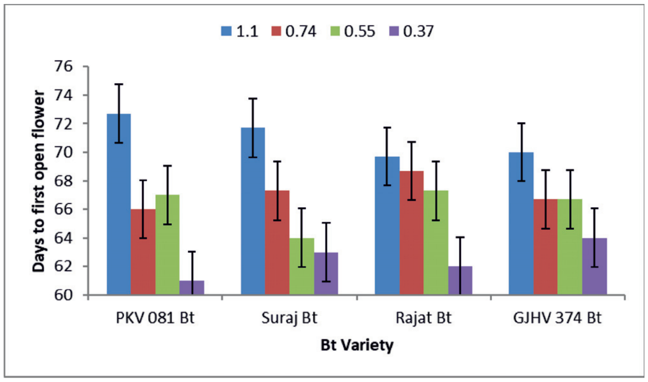

Fig. 1. Effect of plant density on days to first open flower among Bt varieties
[CD (P=0.05): Spacing: 2.04, Variety: NS, Interaction: NS]

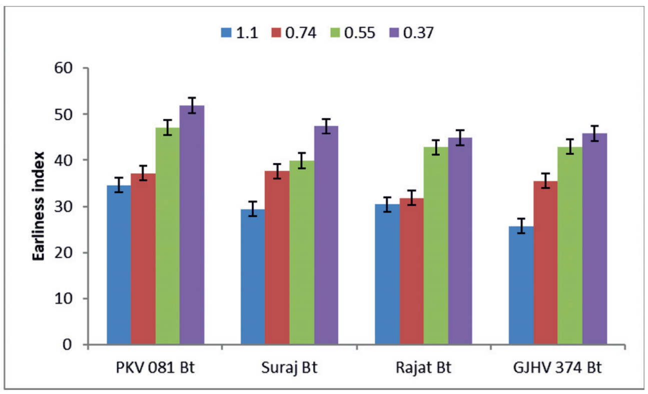

Fig. 2. Effect of plant density on earliness index among Bt varieties
[CD (P=0.05): Spacing: 1.60, Variety: 1.20, Interaction: NS]

ties, PKV081 Bt had better earliness index than the rest of the Bt varieties. Earlier Karunakar *et al.* (2018) observed that under rainfed conditions the non-Bt counterpart of PKV 081 expressed earliness in terms for flowering and maturity. Saleem *et al.* (2009) observed that lesser plant density (wider spacing) took minimum days for flowering with higher earliness index. Siebert *et al.* (2006) was also noted similar observations.

Thus, study concluded that the optimal plant density for high seed cotton and lint yield varied according to the varietal characteristics. However, under rain-fed condition in Vertisols the variety 'PKV081-Bt' should be planted at a density of 0.37 lakh plants/ha by adopting a spacing of 90 cm × 30 cm for fetching the maximum yield.

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