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Assessment of morpho-physiological and yield performance of Bt cotton under HDPS using diverse canopy management techniques

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Abstract
The investigation entitled "Assessment of morpho-physiological and yield performance of Bt cotton under HDPS using diverse canopy management techniques" was conducted using a split-plot design and replicated thrice during the *Kharif* 2023 season at the All India Coordinated Cotton Improvement Project, MPKV, Rahuri, Dist. Ahilyanagar (M.S.), India. The experiment utilized the RCH-659 Bt cotton hybrid. The experimental field was arranged in 48-unit plots, each measuring approximately 6.30 x 6.00 m² for gross plot size, with net plot sizes varying according to spacing. Two factors were considered: spacing, *viz*., S_1 (60x30 cm), S_2 (90x30 cm), S_3 (120x30 cm) and S_4 (120x60 cm) and canopy management techniques *viz*., T_1 (Pruning at 40 DAS and topping at 70 DAS), T_2 (Pruning at 50 DAS and topping at 80 DAS), T_3 (Mepiquat chloride @ 50 ppm at 55 and 75 DAS) and T_4 (No pruning and no topping - control), were used to set up the experiment.
Morphological observations, such as minimum plant height and maximum sympodial length, were recorded in treatment T_1 (pruning at 40 DAS and topping at 70 DAS) under spacing S_4 (120 x 60 cm) compared to all other treatments and spacings. The maximum number of sympodia plant^{-1} was observed in T_3 (Mepiquat chloride at 50 ppm at 55 and 75 DAS) under spacing S_4 (120 x 60 cm) at harvest. Physiological parameters such as chlorophyll index (SPAD) and rate of photosynthesis were recorded superior results under treatment T_1 (pruning at 40 DAS and topping at 70 DAS) with spacing S_4 (120 x 60 cm) at 30, 60 and 90 DAS.
Yield parameters such as seed cotton yield plant^{-1} showed superior results with treatment T_1 (pruning at 40 DAS and topping at 70 DAS) under spacing S_4 (120 x 60 cm). The significantly highest seed cotton yield ha^{-1} at 140 and 165 DAS and total seed cotton yield ha^{-1} was recorded in treatment T_1 (pruning at 40 DAS and topping at 70 DAS) with spacing S_2 (90 x 30 cm).

Keywords: Bt cotton, RCH-659, HDPS, canopy management techniques and spacing

1. Introduction
Cotton (*Gossypium hirsutum* L.) is a dual-purpose crop that is cultivated for both fibre and oil (Ali *et al*., 2019) [34], for this reason, it is known as the "king of fibbers" and one of the most significant textile crops in the world. It is a crucial cash crop in India, significantly contributing to economic growth and employment in rural and urban regions. Approximately 90% of global cotton production is derived from *Gossypium hirsutum* L., the most widely cultivated species in the country. In the 2022-2023 cotton season, India produced over 343.47 lakh bales (5.84 million metric tons), positioning it as the second-largest producer worldwide and accounting for 23.83% of total global production. Nevertheless, India ranks 39th in productivity, with an average yield of 447 kg/ha. According to the COCPC meeting on June 1st, 2023, Maharashtra, a leading cotton-producing state, harvested 84.09 lakh bales from 42.29 lakh hectares, yielding 338 kg/ha (Annexures IV).
Cotton cultivation in India faces numerous challenges that hinder its productivity compared to other countries. Key issues include poor soil health, small farm sizes, limited access to modern technology, reliance on rainfall, low-quality seeds, the impact of climate change, insufficient planting density, fertilizer-related problems and increasing pest and disease pressures. To address these challenges, high-density planting systems (HDPS) have been proposed as a novel approach to cotton cultivation. This method aims to enhance

productivity and profitability by optimizing resource use, reducing costs and mitigating risks. Research suggests that a higher plant density can lead to improved cotton yields, making this technique particularly beneficial for rainfed cotton farmers, especially those on less fertile land. A positive correlation between plant population and seed cotton yield has been noted (Chavan *et al*., 2019) [7].

Cotton plants (*Gossypium hirsutum* L.) typically exhibit apical dominance, which can adversely impact their yield potential. Currently, farmers are facing challenges from excessive vegetative growth along with infestations of bollworms and sucking pests in Bt cotton, largely due to the development of unproductive branches and the dominant upper portions of the plants. This situation results in decreased yields and lower cotton quality. To enhance yields and profitability, farmers are investigating the use of High-Density Planting Systems (HDPS). Canopy management strategies, such as manual and chemical pruning, as well as topping with growth regulators or manual techniques, are employed to manage the growth of plant canopies and prevent plants from toppling when they reach heights of 5-6 feet. These practices can help improve physiological traits in relation to yield.

In Maharashtra, farmers often cultivate cotton hybrids with narrow spacing without adequate canopy management, leading to excessive vegetative growth. This approach serves as a cost-effective strategy to improve cotton yields. To evaluate the effectiveness of optimal planting spacing alongside canopy management techniques, this study aims to investigate the effects of these practices on the morpho-physiological and yield parameters of Bt cotton (*Gossypium hirsutum* L.) under high-density planting systems (HDPS).

2. Materials and Methods

During the *Kharif* season of 2023, an experiment was conducted to assess the effects of plant spacing and canopy management techniques on the morphological, physiological and yield related characteristics of the Bt cotton hybrid RCH 659. The study took place at the All India Coordinated Cotton Improvement Project located at MPKV, Rahuri, Ahilyanagar district, Maharashtra, India. The experimental site is situated at a latitude of 19.380° N and longitude of 74.650° E, with an altitude of 511 meters above mean sea level. The soil is characterized as deep black and slightly alkaline in pH. Throughout the crop growth period, the average weekly maximum temperature was 38.14°C, while the minimum was 17.34°C. The seed material used in the experiment was sourced from the AICIP Cotton Breeder at Mahatma Phule Krishi Vidyapeeth, Rahuri, in the Ahilyanagar district of Maharashtra. Sowing was carried out manually using the dibbling method, with spacing treatments applied as per the experimental design and 2-3 seeds were planted per hill on June 6, 2023, during the *Kharif* season of 2023.

The statistical design adopted for the experimentation was Split Plot design, with three replications and sixteen treatment combinations. The main plots were four spacing viz., S_1 (60x30 cm), S_2 (90x30 cm), S_3 (120x30 cm) and S_4 (120x60 cm). Each of these main plots were divided into four sub-plots. The sub plots consisted of four treatments (canopy management practices) *viz*., T_1 (Pruning at 40 DAS and topping at 70 DAS), T_2 (Pruning at 50 DAS and topping at 80 DAS), T_3 (Mepiquat chloride @ 50 ppm at 55 and 75 DAS) and T_4 (No pruning and no topping - control). Plot size of individual treatment was gross 6.30 x 6.00 m² and the net sizes were 5.70 x 4.80 m² for S_1 (60 x 30 cm), 5.70 x 4.60 m² for S_2 (90 x 30 cm), 5.70 x 3.60 m² for S_3 (120 x 30 cm), and 5.40 x 3.60 m² for S_4 (120 x 30 cm) spacing.

3. Results and Discussion

3.1 Morphological Observations

3.1.1 Plant height (cm)

Plant height is an important visible indicator of plant architecture and growth. It is a function of internode elongation, with the main stem serving as the location for leaves and branches. Plant height was recorded at harvest. The data from *kharif* 2023 season of plant height at harvest are presented in Table 1

3.1.1.1 Effect of spacing

From the Table 1, it was seen that the plant height showed significant difference due to spacing at harvest. Among the spacings, S_4 (120 x 60 cm) exhibited the significantly lowest plant height at harvest as 95.02 cm, which was at par with S_1 (120 x 30 cm) as 102.59 cm. In contrast, the highest plant height at harvest was observed in S_1 (60 x 30 cm) as 81.69 cm, in the year 2023.

The investigation found that plant height was greater in close spacing than in wider spacing, it might be due to increased competition for solar radiation, prompting plants to grow taller in search of light. Venkatkiran Reddy *et al*. (2023) [31] similarly noted that higher densities resulted in taller plants, attributed to competition for resources like nutrients, water and sunlight. In crowded conditions, elongated internodal length leads to taller growth, while narrow spacing limits spread and directs energy upwards. Similar results were also reported by Jagtap and Bhale (2010) [13].

3.1.1.2 Effect of treatment

Crop management practice (treatments), showed significant differences for plant height in the year 2023 (Table 1). Among the treatments, the significantly lowest plant height at harvest was observed in T_1 (Pruning at 40 DAS and topping at 70 DAS) as 81.69 cm which was at par with T_2 (Pruning at 50 DAS and topping at 80 DAS) as 87.19 cm. In contrast, the treatment T_4 (No pruning and no topping - control) recorded the maximum plant height at harvest as 145.72 cm in the year 2023.

The minimum plant height was significantly found in treatment T_1 (Pruning at 40 DAS and topping at 70 DAS) and T_2 (Pruning at 50 DAS and topping at 80 DAS). This may be due to topping, restricts plant growth and reported significantly lower plant height while the maximum plant height observed with control T_4 (No pruning and no topping - control), was due to apical dominance. Similar result was reported by Virdia (2011) [32] that plant height is reduced in early topping mainly due to it arrested further vegetative growth. Similar findings were also observed by Yadav *et al*. (2021) [33], Sisodia and Khamparia (2007) [27].

3.1.1.3 Interaction effects of spacing and treatment

The interaction effects between spacing and canopy management practices were assessed and significant differences were reported. Among the interaction effect of spacing and treatments minimum plant height were recorded in interaction of S_4T_1 (120 x 60 cm with pruning at 40 DAS and topping at 70 DAS) as 73.64 cm, which was at par with

interaction S_3T_1 (120 x 30 cm with pruning at 40 DAS and topping at 70 DAS) were (80.94 cm) and S_4T_2 (120 x 60 cm with pruning at 50 DAS and topping at 80 DAS) were (78.04 cm) in the year 2023. The highest plant height was recorded in interaction S_1T_4 (60 x 30 cm with no pruning and no topping - control)) as 158.75 cm, during 2023 cm at harvest.

The interaction S_4T_1 (120 x 60 cm with pruning at 40 DAS and topping at 70 DAS) recorded the minimum plant height. This mainly due to topping control height by disrupting auxin flow, promoting lateral branching instead of upward growth. With wider spacing, plants may control competition for dominance, enabling topped plants to grow bushier rather than taller. Similar findings also observed by Muller and Leyser (2011) [19] that stem apex removal induces hormone of growth i.e., cytokinin's to stimulate the lateral buds to initiate growth and eventually suppress apical dominance that controls plant height and clears the metabolic pool in plants. The results also agreement with, Shaimaa and Azza. (2023) [26].

Table 1: Plant height(cm), number of sympodia plant^{-1} (no.), sympodial length (cm) of HDPS Bt cotton influenced by different spacing and treatments (Canopy management practices)

Spacing Treatment	2023														
	Plant height (cm)					Number of sympodia plant^{-1} (no.)					Sympodial length (cm)				
	S_1	S_2	S_3	S_4	Mean	S_1	S_2	S_3	S_4	Mean	S_1	S_2	S_3	S_4	Mean
T_1	87.44	84.75	80.94	73.64	81.69	11.25	11.60	11.89	13.57	12.08	32.72	35.75	35.76	45.80	37.51
T_2	91.32	89.63	89.78	78.04	87.19	11.68	12.21	12.65	13.80	12.59	30.30	32.16	35.76	38.59	34.20
T_3	109.41	101.56	103.09	96.29	102.59	12.85	13.20	13.64	14.46	13.54	25.52	29.05	32.10	33.84	30.13
T_4	158.75	149.56	142.47	132.12	145.72	12.32	12.71	13.35	14.13	13.13	23.62	26.15	26.54	28.95	26.31
Mean	111.73	106.37	104.07	95.02	104.30	12.03	12.43	12.88	13.99	12.83	28.04	30.78	32.54	36.79	32.04
	Spacing	Treatment	Interaction			Spacing	Treatment	Interaction			Spacing	Treatment	Interaction		
S. Em. +1	1.802	1.13	2.27			0.221	0.27	0.54			1.448	0.967	1.934		
CD at 5%	6.235	3.31	6.61			0.764	0.79	NS			5.012	2.823	NS		
S. Em.± 2			2.36					0.52					2.214		
CD 2 at 5%			7.46					NS					NS		

CD_1 means between two subplots means at same level of main plot mean. CD_2 Means between two main plots means at same level of subplot mean, Main factor: Spacing: - S_1- 60x30 cm, S_2- 90x30 cm, S_3- 1200x30 cm and S_4- 120x60 cm. Sub factor: Treatments (Crop management practices): - T_1 - Pruning at 40 DAS and topping at 70 DAS, T_2 - Pruning at 50 DAS and topping at 80 DAS, T_3- Mepiquat chloride @ 50 ppm at 55 and 75 DAS, T_4- No pruning and no topping (Control)

3.1.2 Number of sympodia plant^{-1}

Sympodial branches form an important part of the structure of the cotton plant, to which the fruiting bodies develop and contribute to productivity. The data regarding number of sympodia plant^{-1} at harvest, as influenced by spacing, canopy management practices and their interaction are presented in Table 1.

3.1.2.1 Effect of spacing

The results revealed that there was a significant difference among the spacing in both years and on pooled basis. The spacing, S_4 (120 x 60 cm) was recorded significantly maximum number of sympodia plant^{-1} as 13.99, which was followed by S_2 (90 x 30 cm) as 12.43 and S_3 (120 x 30 cm) as 12.98, whereas, the lowest number of sympodia plant^{-1} at harvest was found in S_1 (60 x 30 cm) were (12.03) in the year 2023.

The results, might be due to wide spacing provided more space for lateral expansion of branches and allowed for the enhancement of auxiliary buds in plants compared to plants that were very closely spaced. This is in confirmation of results represented by Yadav *et al.* (2021) [33], Buttar and Singh (2006) [6] reported that better aeration and adequate interception of light and lesser competition for nutrients at wider spacing resulted in higher photosynthesis which in turn helped to produce a greater

number of sympodial branches plant^{-1}, was also observed by Venkatkiran Reddy *et al.* (2023) [31], Tuppad (2015) [30] and Maheswari *et al.* (2019) [18]

3.1.2.2 Effect of treatment

From the data, it was found that significantly maximum number of sympodia plant^{-1} at harvest was observed in T_3 (Mepiquat chloride @ 50 ppm at 55 and 75 DAS) as 13.54, which was at par with, T_4 (No pruning and no topping - Control) were (13.13). While the treatment, T_1 (Pruning at 40 DAS and topping at 70 DAS) was recorded lowest number of sympodia plant^{-1} at harvest were (12.08) during the year 2023.

Canopy management practices significantly affected the number of sympodia plant^{-1} at harvest compared to the control in both seasons. Treatment T_1 (Pruning at 40 DAS and topping at 70 DAS) resulted in the lowest number of sympodia plant^{-1}. These practices reduce vegetative growth and redirect resources toward fruit development, leading to more compact plants with increased fruiting potential. The result is in conformity with the findings of Shaimaa and Azza (2023) [26], found that topping cotton plants prevents new internode formation, reduces height and inhibits further vegetative growth, thereby controlling apical dominance and enhancing fruiting.

3.1.2.3 Interaction effects of spacing and treatment

The interaction effects between spacing and canopy management practices were assessed and nonsignificant differences were reported.

3.1.3 Sympodial length (cm)

Sympodial length is a key factor that affects plant architecture of cotton. refers to the length of the sympodial branches, which are lateral shoots that develop from the main stem of the cotton plant. Studies have shown that these characteristics are influenced by spacing and canopy management practices. The data regarding sympodial length at harvest as influenced by spacing, treatment and their interaction are presented in Table

3.1.3.1 Effect of spacing

Spacing, S_4 (120 x 60 cm) was found significantly highest sympodial length at harvest as 36.79 cm, which was at par with S_3 (120 x 30 cm). While the minimum sympodial length at harvest was found in S_1 (60 x 30 cm) were (28.04) in the year 2023.

The result indicates that with the increase in plant spacing, the sympodial branch length also increased. It might be due to wider spacing provides plants with more resources and better growing conditions, allowing them to expand laterally and produce long sympodial branches. Parallel finding was observed by Ibrahim *et al.* (2022) [12] that an increase in the length of fruit branches per plant in low planting density could be due to less competition and more space available for the growth of plants. Similar result also reported by Brijal *et al*. (2021) [5]

3.1.3.2 Effect of treatment

Among the treatments, T_1 (Pruning at 40 DAS and topping at 70 DAS) (37.51 cm) was found significantly superior to increase sympodial length at harvest. Which was followed by T_2 (Pruning at 50 DAS and topping at 80 DAS) were (34.20 cm. While the lowest sympodial length at harvest was found in T_4 (No pruning and no topping - control) were (26.32 cm).

The findings indicate that early pruning and topping practices result in the longest sympodial lengths, likely due to improved plant architecture and growth potential resulting from these practices. These results are consistent with the findings of Kataria and Valu (2018) [15] and Kumari and George (2012) [17], who reported that detopping inhibited vertical plant growth and subsequently promoted lateral growth, including branching.

3.1.3.3 Interaction effects of spacing and treatment

The interaction effects between spacing and treatment were assessed and nonsignificant differences were reported.

3.2 Physiological Parameters

3.2.1 Chlorophyll index (SPAD)

The chlorophyll index (SPAD) determines the photosynthetic capacity. SPAD readings (chlorophyll content in leaves) increased from 30 DAS to 90 DAS. A perusal of the data reveals that, chlorophyll Index (SPAD) was significantly affected by the spacing and treatment in the experiment at 60 DAS and 90 DAS except at 30 DAS (where only spacing had a significant effect) and interaction.

3.2.1.1 Effect of spacing

The data in Table 2. reveals that at 30, 60 and 90 DAS, significantly highest chlorophyll index (SPAD) recorded in spacing S_4 (120x60 cm) as 34.93, 42.80 and 51.75 respectively, which was at par with S_3 (120x30 cm) as 34.25, 40. 94 and 49.06, respectively. While the lowest chlorophyll index (SPAD) was found in S_1 (60x30 cm) as 29.25, 38.71 and 47.17, at 30, 60 and 90 DAS respectively, during the year 2023, irrespective of treatments.

With respect to plant spacing, wide spacing provided higher chlorophyll content values this is due to the fact that, wide spacing provided with all the natural resources required for their growth and attributed in better performance of individual plant. Similar findings were also reported by Venkatkiran Reddy *et al.* (2023) [31].

3.2.1.2 Effect of treatment

Chlorophyll index (SPAD) in respect to treatment, were observed to be significant at 60 and 90 DAS, except 30 DAS during the year 2023.

At 30 DAS, numerically highest chlorophyll index (SPAD) was recorded in T_4 (No pruning and no topping - control) as 33.40, while, the lowest chlorophyll index (SPAD) was recorded in T_3 (Mepiquat chloride @ 50 ppm at 55 and 75 DAS) as 31.89, during the year 2023 irrespective of spacing.

At 60 and 90 DAS the highest chlorophyll index (SPAD) was recorded in T_1 (Pruning at 40 DAS and topping at 70 DAS) were (42.61 and 51.39) respectively, which was at par with T_2 (Pruning at 50 DAS and topping at 80 DAS) were (41.89 and 49.84) and T_3 (Mepiquat chloride @ 50 ppm at 55 and 75 DAS were (40.74 and 49.12) during the year 2022, While the lowest chlorophyll index (SPAD) was recorded in T_4 (No pruning and no topping - control) were (36.97 and 45.71) respectively, during the year 2022, irrespective of spacing.

The treatment T_1 (Pruning at 40 DAS and topping at 70 DAS) shows highest chlorophyll index (SPAD) than other treatment might be due to early pruning or topping enhances light penetration to the lower parts of a plant. By redirecting nutrients and water from the upper leaves to the lower ones, these practices promote growth and increase chlorophyll production. Additionally, pruning encourages new shoots and expands the overall leaf area, allowing for greater light absorption. With the lower leaves receiving more light and nutrients, growth potential is maximized, thereby improving photosynthesis and chlorophyll synthesis. The results of the present study support the previous findings in *Acer pseudoplatanus* L. Trees by Fini *et al*. (2015) [9]

3.2.1.3 Interaction effect

The interaction effect of spacing and treatment (canopy management practices) on chlorophyll index (SPAD) at 30, 60 and 90 DAS of Bt cotton was found non-significant. Similar reports of non-significant influence of spacing and treatment (canopy management practices) on chlorophyll index (SPAD) was reported by Venkatkiran Reddy *et al*. (2023) [31].

Table 2: Chlorophyll Index (SPAD) at 30, 60 and 90 DAS of HDPS Bt cotton influenced by different spacing and treatment

Spacing Treatment	2023														
	30 DAS					60 DAS					90 DAS				
	S_1	S_2	S_3	S_4	Mean	S_1	S_2	S_3	S_4	Mean	S_1	S_2	S_3	S_4	Mean
T_1	29.03	32.76	35.54	35.64	33.24	41.02	41.65	42.86	44.89	42.61	49.84	50.45	51.65	53.61	51.39
T_2	28.90	30.78	33.05	35.67	32.10	39.92	41.12	42.56	43.97	41.89	47.72	48.78	49.86	53.01	49.84
T_3	27.60	32.18	35.21	32.59	31.89	38.66	39.91	40.93	43.45	40.74	47.01	48.10	48.91	52.44	49.12
T_4	31.45	33.14	33.19	35.81	33.40	35.25	36.33	37.41	38.88	36.97	44.11	44.97	45.82	47.95	45.71
Mean	29.25	32.22	34.25	34.93	32.66	38.71	39.75	40.94	42.80	40.55	47.17	48.08	49.06	51.75	49.01
	Spacing	Treatment	Interaction			Spacing	Treatment	Interaction			Spacing	Treatment	Interaction		
SEM ±	0.335	1.02	SEM ±	2.03		0.746	0.83	SEM ±	1.67		0.871	0.85	SEM ±	1.69	

			1				1				1	
CD at 5%	1.159	NS	CD 1 at 5%	NS	2.583	2.43	CD 1 at 5%	NS	3.015	2.47	CD 1 at 5%	NS
			SEM ± 2	1.79			SEM ± 2	1.62			SEM ± 2	1.71
			CD 2 at 5%	NS			CD 2 at 5%	NS			CD 2 at 5%	NS

CD1 means between two subplots means at same level of main plot mean. CD2 Means between two main plots means at same level of subplot mean, Main factor: Spacing: - S_1- 60x30 cm, S_2- 90x30 cm, S_3- 1200x30 cm and S_4- 120x60 cm. Sub factor: Treatments (Crop management practices): - T_1 - Pruning at 40 DAS and topping at 70 DAS, T_2 - Pruning at 50 DAS and topping at 80 DAS, T_3- Mepiquat chloride @ 50 ppm at 55 and 75 DAS, T_4- No pruning and no topping (Control).

3.2.2 Rate of photosynthesis (umol m^{-2} sec^{-1})

A perusal of the data (Table 3) reveals that, rate of photosynthesis was significantly affected by the spacing and treatment in the experiment at 60 DAS and 90 DAS except at 30 DAS (where only spacing had a significant effect) and interaction.

3.2.2.1 Effect of spacing

At 30, 60 and 90 DAS, the significantly highest rate of photosynthesis was recorded in spacing S_4 (120x60 cm) as 26.27, 30.39 and 31.83, umol m^{-2} sec^{-1}, respectively, which was at par with S_3 (120x30 cm) as 25.02, 29.20 and 31.25 umol m^{-2} sec^{-1}, respectively. Additionally, S_4 (120x60 cm) was also at par with S_2 (90 x 30 cm) were 23.17 umol m^{-2} sec^{-1} at 30 DAS. While the lowest chlorophyll index (SPAD) was found in S_1 (60x30 cm) as 20.47, 25.77 and 28.83 umol m^{-2} sec^{-1}, at 30, 60 and 90 DAS respectively, during the year 2023, irrespective of treatments.

The investigation revealed that wide spacing in Bt cotton can lead to increased rate of photosynthesis primarily due to enhanced light availability, reduced competition for resources, better air circulation and optimized growth conditions. Similar findings were reported by Zaman *et al.* (2021) [34].

3.2.2.2 Effect of treatment

At 30 DAS, effect of treatment shows non-significant result on rate of photosynthesis.

At 60 DAS, the maximum rate of photosynthesis was recorded in T_1 (Pruning at 40 DAS and topping at 70 DAS) as 30.23 umol m^{-2} sec^{-1}, which was at par with T_2 (Pruning at 50 DAS and topping at 80 DAS) as 29.06 umol m^{-2} sec^{-1}. While the lowest rate of photosynthesis was recorded in T_4 (No pruning and no topping - control) as 25.52, irrespective of spacing.

At 90 DAS, the maximum rate of photosynthesis was recorded in T_1 (Pruning at 40 DAS and topping at 70 DAS) as 31.96 umol m^{-2} sec^{-1}, which was at par with T_2 (Pruning at 50 DAS and topping at 80 DAS) were (31.28 umol m^{-2} sec^{-1}) and T_3 (Mepiquat chloride @ 50 ppm at 55 and 75 DAS) were (30.36 umol m^{-2} sec^{-1}), While the minimum, rate of photosynthesis was recorded in T_4 (No pruning and no topping - control) as 28.50 umol m^{-2} sec^{-1}, irrespective of spacing.

The maximum rate of photosynthesis was recorded in T_1 (pruning at 40 DAS and topping at 70 DAS), which may be due to a greater allocation of carbohydrates and resources directed towards the remaining leaves, potentially enhancing their photosynthetic rate and overall growth. The results of the present study support the previous findings of Junjun *et al.* (2021) [14] that the removal of vegetative branches and plant topping enhance the canopy carbon assimilation rate in cotton, leading to an increase in the photosynthesis rate.

3.2.2.3 Interaction effect

The interaction effect of spacing and treatment (canopy management practices) on rate of photosynthesis at 30, 60 and 90 DAS of Bt cotton was non-significant.

Table 3: Rate of photosynthesis (umol m^{-2} sec^{-1}) at 30, 60 and 90 DAS of HDPS Bt cotton influenced by different spacing and treatment (Canopy management practices).

Spacing Treatment	2023														
	30 DAS					60 DAS					90 DAS				
	S_1	S_2	S_3	S_4	Mean	S_1	S_2	S_3	S_4	Mean	S_1	S_2	S_3	S_4	Mean
T_1	17.45	21.67	23.92	27.04	22.52	28.11	29.96	30.62	32.24	30.23	30.13	31.65	33.18	32.89	31.96
T_2	22.18	23.16	25.10	24.88	23.83	26.87	29.08	29.82	30.46	29.06	29.96	30.79	31.92	32.44	31.28
T_3	22.67	23.81	25.81	27.42	24.93	26.14	27.28	29.22	30.12	28.19	28.47	30.11	31.00	31.88	30.36
T_4	19.57	24.05	25.25	25.72	23.65	21.97	24.23	27.14	28.75	25.52	26.76	28.21	28.91	30.10	28.50
Mean	20.47	23.17	25.02	26.27	23.73	25.77	27.64	29.20	30.39	28.25	28.83	30.19	31.25	31.83	30.53
	Spacing	Treatment	Interaction			Spacing	Treatment	Interaction			Spacing	Treatment	Interaction		
SEM ±	0.928	1.11	SEM ± 1	2.22		0.493	0.51	SEM ± 1	1.02		0.522	0.55	SEM ± 1	1.11	
CD at 5%	3.210	NS	CD 1 at 5%	NS		1.707	1.49	CD 1 at 5%	NS		1.807	1.62	CD 1 at 5%	NS	
			SEM ± 2	2.13				SEM ± 2	1.01				SEM ± 2	1.09	
			CD 2 at 5%	NS				CD 2 at 5%	NS				CD 2 at 5%	NS	

CD1 means between two subplots means at same level of main plot mean. CD2 Means between two main plots means at same level of subplot mean, Main factor: Spacing: - S_1- 60x30 cm, S_2- 90x30 cm, S_3- 1200x30 cm and S_4- 120x60 cm. Sub factor: Treatments (Crop management practices): - T_1 - Pruning at 40 DAS and topping at 70 DAS, T_2 - Pruning at 50 DAS and topping at 80 DAS, T_3- Mepiquat chloride @ 50 ppm at 55 and 75 DAS, T_4- No pruning and no topping (Control).

3.3 Yield Parameters

3.3.1 Seed cotton yield plant^{-1}: The data regarding seed cotton yield plant^{-1} at 140 and 165 DAS as influenced by species, treatments and their interaction are presented in Table 4.

3.3.1.1 Seed cotton yield plant^{-1} at 140 and 165 DAS.

3.3.1.1.1 Effect of spacing

The results at 140 and 165 DAS, revealed that there was a significant difference among the spacing. The spacing, S_4 (120x60 cm) was recorded highest seed cotton yield plant^{-1} at 140 and 165 DAS were (104.36 and 113.09 g) respectively, which was followed by S_3 (120x30 cm) were (60.88 and 68.54 g) respectively in the year 2023, while the lowest seed cotton yield plant^{-1} at 140 DAS and 165 DAS was found in S_1 (60x30 cm) were (32.06 and 36.76 g) respectively, in the year 2023.

The S4 spacing (120 cm × 60 cm) significantly increased boll production plant-1 compared to other spacings. This improvement is attributed to reduced competition for resources, which enhances access to sunlight, water and nutrients, leading to larger growth and more branches and flowering sites. Similar results were also observed by Suma (2019) [29], Kumar P. *et al*. (2017) [16], Paslawar *et al*. (2017) [23], Hargrias (2018) [10] and Nehra.

Table 4: Seed cotton yield plant^{-1} (g) of HDPS Bt cotton influenced by different spacing and treatment at 140 and 165 DAS.

Spacing Treatment	2023									
	140 DAS					165 DAS				
	S_1	S_2	S_3	S_4	Mean	S_1	S_2	S_3	S_4	Mean
T_1	37.58	61.35	69.84	114.27	70.76	45.95	68.81	78.96	131.82	81.38
T_2	35.95	58.00	65.17	110.90	67.50	41.29	64.28	76.07	123.01	76.16
T_3	32.74	54.19	61.15	99.25	61.83	35.47	60.35	67.51	108.45	67.94
T_4	21.97	34.67	47.37	93.01	49.25	24.33	38.15	51.62	89.05	50.79
Mean	32.06	52.05	60.88	104.36	62.34	36.76	57.90	68.54	113.09	69.07
	Spacing		Treatment			Spacing		Treatment		
SEM ±	0.574		0.92			3.724		1.28		
CD at 5%	1.986		2.67			12.888		3.75		
Interaction	SEM ±1	CD 1 at 5%	SEM ± 2	CD 2 at 5%		SEM ±1	CD 1 at 5%	SEM ± 2	CD 2 at 5%	
	1.83	5.35	1.69	5.03		2.57	7.50	4.34	14.39	

CD1 means between two subplots means at same level of main plot mean. CD2 Means between two main plots means at same level of subplot mean, Main factor: Spacing: - S_1- 60x30 cm, S_2- 90x30 cm, S_3- 1200x30 cm and S_4- 120x60 cm. Sub factor: Treatments (Crop management practices): - T_1 - Pruning at 40 DAS and topping at 70 DAS, T_2 - Pruning at 50 DAS and topping at 80 DAS, T_3- Mepiquat chloride @ 50 ppm at 55 and 75 DAS, T_4- No pruning and no topping (Control). and Chandra (2001), who reported better development of individual plants in wider spacing, suggesting that widely spaced plants received a favourable microclimate.

3.3.1.1.2 Effect of treatment

Treatments showed significant differences for seed cotton yield plant^{-1} at 140 and 165 DAS, in the year 2023. From the data, it was found that the T_1 (Pruning at 40 DAS and topping at 70 DAS) was recorded highest seed cotton yield plant^{-1} at 140 and 165 DAS as 70.76 and 81.38 g, which was at par with T_2 (Pruning at 50 DAS and topping at 80 DAS) as 67.50 and 76.16 g, respectively. while the lowest seed cotton yield plant^{-1} at 140 and 165 DAS which was found in T_4 (No pruning and no topping -Control) as 49.25 and 50.79 g, respectively, in the year 2023.

Therefore, the treatment T_1 (pruning at 40 DAS and topping at 70 DAS) recorded the highest seed cotton yield plant^{-1}. This is mainly due to early pruning and topping practices, which decreased morphological and physiological characteristics such as plant height, internodal distance, stem girth, and leaf area index while increasing chlorophyll index (SPAD), rate of photosynthesis, and specific leaf weight. Additionally, these canopy management practice also increased the value of yield components, while reducing the boll shedding percentage plant^{-1}. The higher values of yield components lead to an increase in seed cotton yield per plant. These results are consistent with the previous results of Shaimaa and Azza (2023) [26]

3.3.1.1.3 Interaction effect

From the data, it was resulted that the interaction effects of species and treatments on seed cotton yield plant^{-1} (g) of Bt cotton, were significant in the year 2023.

Among the interaction, the interaction S_4T_1 (120x60 cm with pruning at 40 DAS and topping at 70 DAS) recorded highest Seed cotton yield plant^{-1} at 140 and 165 DAS were (114.27 and 131.82 (g)), which was at par with S_4T_2 (120x60 cm with pruning at 50 DAS and topping at 80 DAS) were (110.90 and 123.01 (g)) during the year 2023, whereas, the lowest seed cotton yield plant^{-1} at 140 and 165 DAS was found in S_1T_4 (60x30 cm with no pruning and no topping - control) were (21.97 and 24.33 g) respectively, in the year 2023.

3.3.2 Seed cotton yield ha^{-1}

3.3.2.1 Seed cotton yield ha^{-1} at 140 and 165 DAS

The data on seed cotton yield ha^{-1} at 140 and 165 DAS, as influenced by spacing, treatments and their interaction are presented in Table 5.

3.3.2.1.1 Effect of spacing

The data (Table 5) revealed that, among the spacing, S_2 (90x30 cm) was found significantly highest seed cotton yield ha^{-1} at 140 and 165 DAS, were (1817.86 and 2021.31 kg), which was at par with S_1 (60x30 cm) were (1723.41 and 1977.40 kg) and S_3 (120x30 cm) were (1672.40 and 1882.68 kg) respectively, in the year 2023, while the lowest seed cotton yield ha^{-1} at 140 and 165 DAS was found in S_4 (120x60 cm) were (1438.16 and 1558.64 kg) respectively during the year 2023 with independent of treatments.

Higher seed cotton yield per hectare was recorded under closer spacing S_2 (90 x 30 cm) and S_1 (60x30 cm) as compared to wider spacing. This might be due to it maintain higher values of yield attributes like number of bolls sympodia^{-1}, total number of boll plant^{-1}, number of bolls per square meter etc. and it promotes healthy growth with more

plant population and effective farming practices, leading to increased seed cotton yield ha^{-1}. These findings corroborate the results of Solanki *et al.* (2020) [28], Sarkar (2004) [24], Nehra *et al.* (2004) [21], Buttar and Singh (2006) [6].

3.3.2.1.2 Effect of treatments

Among the treatment, significantly highest seed cotton yield ha^{-1} at 140 and 165 DAS, recorded in T_1 (Pruning at 40 DAS and topping at 70 DAS) were (1929.18 and 2233.29 kg), which was at par with T_2 (Pruning at 50 DAS and topping at 80 DAS) were (1822.23 and 2065.49 kg) respectively in the year 2022, while the lowest seed cotton yield ha^{-1} at 140 and 165 DAS, recorded in T_4 (No pruning and no topping - Control) as (1226.18 and 1301.35 kg) respectively, during the year 2022 with independent of spacing.

Pruning and topping practices increased yield ha^{-1} compared to the control, likely due to improved plant architecture, which allows better sunlight penetration into the canopy due to reduced foliage and lodging. This results in higher photosynthetic activity, as well as a more spread-out plant structure that captures more sunlight and enhances photosynthesis. The result also confirms the findings of Virdia (2011) [32], Selvaraj *et al.* (1977) [25], Ahmed *et al.* (1992) [1] and Aleeva *et al.* (1992) [2].

3.3.2.1.3 Interaction effect

The interaction effects revealed that, significantly highest seed cotton yield ha-1 at 140 and 165 DAS was observed in interaction S2T1 (90x30 cm with pruning at 40 DAS and topping at 70 DAS) were (2340.59 and 2402.21 kg) respectively, during the year 2023, which was at par with S1T1 (60x30 cm with pruning at 40 DAS and topping at 70 DAS) were (2312.39 and 2357.09 kg), S1T2 (60x30 cm with pruning at 50 DAS and topping at 80 DAS) were (2183.22 and 2258.46 kg), S2T2 (90x30 cm with pruning at 50 DAS and topping at 80 DAS) were (2252.99 and 2318.03 kg), S2T3 (90x30 cm with mepiquat chloride @ 50 ppm at 55 and 75 DAS) were (2142.95 and 2162.37 kg), S3T1 (120x30 cm with pruning at 40 DAS and topping at 70 DAS) were (2163.68 and 2221.87 kg) respectively, in the year 2022. The lowest seed cotton yield ha-1 at 140 and 165 DAS was found in interaction S1T4 (60x30 cm with no pruning and no topping - control) were (1376.15 and 1395.67 kg) respectively, during the year 2023.

3.3.3 Total seed cotton yield ha^{-1}

The data on total seed cotton yield ha^{-1}, as influenced by spacing, treatments and their interaction are presented in Table 6.

3.3.3.1 Effect of spacing

According to the data (Table 6) the total seed cotton yield ha^{-1} revealed substantial differences related to the different spacing in 2023. Among the spacing, S_2 (90x30 cm) was found significantly highest total seed cotton yield ha^{-1} were (3839.46 kg), which was at par with S_1 (60x30 cm) were (3700.83 kg) and S_3 (120x30 cm) were (3555.51 kg), during the year 2023, while the lowest total seed cotton yield ha^{-1} was found in S_4 (120x60 cm) were (2996.90 kg) during the year 2023 with independent of treatments.

Higher seed cotton yield per hectare was recorded under spacing S_2 (90 x 30 cm) as compared to other spacing. This might be due to it maintain higher values of yield attributes like number of bolls sympodia^{-1}, total number of boll plant^{-1}, number of bolls per square meter etc. and it promotes healthy growth with more plant population and effective farming practices, leading to increased seed cotton yield ha^{-1}. These findings corroborate the results of Solanki (2020) [28], Nehra *et al.* (2004) [21], Buttar and Singh (2006) [6].

3.3.3.2 Effect of treatments

Among the treatments, significantly highest total seed cotton yield ha^{-1} recorded in T_1 (Pruning at 40 DAS and topping at 70 DAS) were (4162.39 kg) which was at par with T_2 (Pruning at 50 DAS and topping at 80 DAS) were (3888.28 kg), during the year 2023, while the lowest total seed cotton yield ha^{-1}, recorded in T_4 (No pruning and no topping - control) were (2527.82 kg), during the year 2023, with independent of spacing.

In this investigation highest total seed cotton yield ha^{-1} recorded in T_1 (Pruning at 40 DAS and topping at 70 DAS) this might be due to pruning and topping practices have a synergistic effect that maximizes seed cotton yield by reducing excess vegetative growth, which allows for more resources to be allocated to reproductive growth; this not only increases the number of bolls per plant but also enhances the flow of assimilates towards the fruit, resulting in heavier bolls and ultimately higher seed cotton yield ha^{-1}. Such findings were obtained by Obasi and Msaakpa (2005) [22], revealed that pruning, either alone or combined with topping, may redirect the excess flow of assimilates towards the fruit, allowing for more and heavier bolls. This practice also minimizes boll infestation, maximizes boll set, and enhances higher seed cotton yield

3.3.3.3 Interaction effect

The interaction effects revealed that, significantly highest total seed cotton yield ha-1 was recorded in interaction S2T1 (90x30 cm with pruning at 40 DAS and topping at 70 DAS) were (4595.00 kg), in the year 2023, which was at par with S1T1 (60x30 cm with pruning at 40 DAS and topping at 70 DAS) were (4517.45 kg), S1T2 (60x30 cm with pruning at 50 DAS and topping at 80 DAS) were (4165.99 kg), S2T2 (90x30 cm with pruning at 50 DAS and topping at 80 DAS) were (4277.76 kg), S2T3 (90x30 cm with mepiquat chloride @ 50 ppm at 55 and 75 DAS) were (4016.12 kg), S3T1 (120x30 cm with pruning at 40 DAS and topping at 70 DAS) were (4123.94 kg) in the year 2023. The lowest seed cotton yield ha-1 was recorded in interaction S1T4 (60x30 cm with no pruning and no topping - control) were (2454.14 kg) during the year 2023.

In the present investigation, the result might be due to a higher plant population with suitable spacing and early topping and pruning practice allows for better plant growth, enabling the plant to spread out its branches and grow vigorously. This results in improved accumulation and partitioning of photosynthates in the reproductive parts of the plant, contributing to higher seed cotton yield. The relatively higher biomass and enhanced partitioning of photosynthates towards reproductive structures are likely factors leading to increased seed cotton yield. This positive effect is reflected in the physiological parameters and seed cotton yield plant-1. Therefore, seed cotton yield depends on the, higher values of Therefore, seed cotton yield depends on the, higher values of yield components. This is in confirmation with the findings of Donald and Boquet (2003) [8], Shaimaa and Azza (2023) [26] and Hussain *et al.* (2002) [11].

Table 6: seed cotton yield ha^{-1} (Kg) of HDPS Bt cotton influenced by different spacing and treatment

Spacing Treatment	2023														
	140 DAS					165 DAS					Total seed cotton yield ha^{-1} (Kg)				
	S_1	S_2	S_3	S_4	Mean	S_1	S_2	S_3	S_4	Mean	S_1	S_2	S_3	S_4	Mean
T_1	2029.43	2166.10	1936.43	1584.76	1929.18	2488.14	2428.94	2187.85	1828.22	2233.29	4517.45	4595.00	4123.94	3413.15	4162.39
T_2	1939.58	2028.94	1786.01	1534.39	1822.23	2225.67	2248.88	2085.53	1701.87	2065.49	4165.99	4277.76	3873.10	3236.25	3888.28
T_3	1760.15	1900.24	1675.12	1361.49	1674.25	1906.42	2114.53	1850.59	1488.08	1839.90	3665.76	4016.12	3525.67	2849.33	3514.22
T_4	1164.48	1176.19	1292.06	1272.00	1226.18	1289.36	1292.89	1406.76	1216.40	1301.35	2454.14	2468.97	2699.32	2488.86	2527.82
Mean	1723.41	1817.86	1672.40	1438.16	1662.96	1977.40	2021.31	1882.68	1558.64	1860.01	3700.83	3839.46	3555.51	2996.90	3523.18
	Spacing	Treatment	Interaction			Spacing	Treatment	Interaction			Spacing	Treatment	Interaction		
SEM ±	34.116	39.11	SEM ± 1	78.21		45.479	43.69	SEM ± 1	87.39		86.644	88.37	SEM ± 1	176.75	
CD at 5%	118.058	114.15	CD 1 at 5%	228.29		157.379	127.53	CD 1 at 5%	255.07		299.826	257.94	CD 1 at 5%	515.88	
			SEM ± 2	75.84				SEM ± 2	88.29				SEM ± 2	175.89	
			CD 2 at 5%	229.68				CD 2 at 5%	270.40				CD 2 at 5%	536.50	

CD1 means between two subplots means at same level of main plot mean. CD2 Means between two main plots means at same level of subplot mean, Main factor: Spacing: - S_1- 60x30 cm, S_2- 90x30 cm, S_3- 1200x30 cm and S_4- 120x60 cm. Sub factor: Treatments (Crop management practices): - T_1 - Pruning at 40 DAS and topping at 70 DAS, T_2 - Pruning at 50 DAS and topping at 80 DAS, T_3- Mepiquat chloride @ 50 ppm at 55 and 75 DAS, T_4- No pruning and no topping (Control)

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